THE EFFECT OF TEMPERATURE AND DROUGHT STRESS ON BAMBARA GROUNDNUT (*Vigna subterranea* (L.) Verdc) LANDRACES

Ibraheem Alshareef

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University of Nottingham

School of Biosciences

Sutton Bonington Campus

Leicestershire, LE12 5RD

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A CO_2 assimilated during photosynthesis

C_i Inter-cellular CO2

CO_2 Carbon dioxide

D Sowing date

DAS Days after sowing

D1 First date of sowing

D3 Third date of sowing

D5 Fifth date of sowing

E Leaf transpiration

E_s Soil surface evaporation

E_t Evapotranspiration

ƒ Fractional intercepted radiation

g Gram

GH glasshouse

g m^{-2} gram per square meter

g_s Stomatal conductance

h Hour

HI Harvest index

HT High temperature

kg Kilogram

KPa Kilopascal

LAI Leaf area index

LDM Leaf dry matter

LRWC Leaf relative water content

LT Low temperature

MJ Megajoule

°C Degree Celsius

$°C^d$ degree days

PAR photosynthetically active radiation

PDM Pod dry matter

RUE Radiation use efficiency

SD Saturation deficit

SED Standard error of difference

S_i Incident radiation

S_t Transmitted radiation

T Transpiration

T_b Base temperature

T_c Ceiling temperature

T_o Optimum temperature

TDM Total dry matter

WUE Water use efficiency

% Percent

ε_{s-} The ratio of dry matter produced to solar radiation intercepted

ε_w The ratio of dry matter produced to water transpired

Θ Thermal time

ABSTRACT

Five experiments were conducted to investigate the effect of drought and high temperature stress on the growth and development of bambara groundnut (*Vigna subterranea* (L.) Verdc) Three glasshouse experiments were conducted at the University of Nottingham, Sutton Bonington Campus, UK, and two field experiments were conducted at the Botswana College of Agriculture, Gaborone, Botswana. In the glasshouse experiments, two landraces were grown, S19-3 (from hot, dry environment/ Namibia) and Uniswa Red (from cool, wet environment/ Swaziland) under two different temperatures, 33±5 ^{o}C and 23±5 ^{o}C. In the first experiment (2006), soil moisture was non-limiting. In the second experiment (2007) drought was imposed at pod filling stage (77 DAS). In the third experiment (2008), the same two landraces were grown under the same temperatures, but the drought was imposed at flowering (30 DAS). In the first field experiment, two landraces were grown under three sowing dates and two water regimes; rain fed and drought. The two landraces were Dip C (from hot, dry environment/ Botswana) and Uniswa Red. Drought was imposed approximately at pod filling (63 DAS). In the second field experiment, the same landraces were grown under the same sowing dates and water regimes with drought imposed at 30 DAS.

Canopy development and growth were affected by temperature and water stress. In the glasshouse experiments, Uniswa Red always gave the highest leaf number at the high temperature and S19-3 had the lowest at the low temperature. Leaf number decreased with drought, it reached over 100 in the full irrigation treatment, and less than 100 in late season drought treatment and a maximum of 60 in the early season drought treatment. Crops grown under high temperature always had higher leaf area

index and total dry matter. The highest yield (306 gm^{-2}) was produced by S19-3 at 33°C in 2007 and the lowest (31.1 g m^{-2}) by Uniswa Red at 33°C in 2008. Comparison of regressions showed no significant difference in water use efficiency (WUE) between treatments in 2007. However, there were significant differences in 2008 when S19-3 (1.80 g kg^{-1}) had a greater WUE than Uniswa-Red (1.09 g kg^{-1}) at the high temperature, but both landraces had similar WUE at the low temperature (S19-3 2.28 g kg^{-1}, Uniswa Red 2.23 g kg^{-1}). This indicates that, despite being from a hot, dry environment, S19-3 performs well at the low temperature, and this is supported by data from 2007 when S19-3 maintained the highest soil moisture content and the lowest evapotranspiration at the low temperature.

For the field experiments, where the temperature decreased with delay in sowing, there was a reduction in development, growth and yield. The effect of sowing date on leaf number was significant in both field experiments. In the first field experiment, the four treatments mean of leaf number of leaves declined from 62 per plant in the first sowing date (D1) to 52 leaves per plant in the third sowing date (D3) and 46 leaves per plant in the fifth sowing date (D5) and it was 64, 52, and 37 for D1, D3, and D5 respectively in the second field experiment. WUE decreased with delay in sowing from average of 1.9 g kg^{-1} in D1 to average of 0.45 g kg^{-1} in D5.

The landraces varied in their response to temperature and drought stress with respect to growth, development and resource capture and conversion. The landraces used different mechanisms to resist drought and temperature stress, that include high leaf water content, reduction in leaf area to reduce transpiration surface and avoidance through faster growth rate.

1 Introduction

1.1 General introduction

There are three main reasons for carrying out agriculture; food production, fibre production and biofuel production. The production of food for human consumption is the most important. Farming in the tropics is carried out mostly by smallholders who usually practice it for subsistence using traditional methods of cultivation. That will not be enough to face the increasing demands for food due to population pressure (Holmes, 1998). In 1900, the world population size was 1.5 billion, in 2050 it is expected to be 9 billion (McMichael, 2001). The highest rate of population growth will be in the zones which already suffer from poverty and food shortage; for example, the population of Ethiopia (62 million in 2001) is expected to increase to 213 million in 2050, and the population of India is likely be 1.6 billion in 2050 (Bantilan *et al*., 2001).

Growing sufficient food to sustain an increasing population has always been difficult because of the limited available resources. The continuous increases in population forces people to use fragile soils for intensive and extensive crop production. Unreliable rain in semiarid and arid lands, lack of surface and ground water also contribute to crop failures in some years (Twomlow, 2002).

Crop improvement targets include increased yield, disease and drought resistance and improved quality. To achieve the main objective of yield increase and stability, crop improvement should be applied in areas which suffer from food shortage, like Africa and some places in Asia, where certain crops have the ability to stand the harsh conditions like drought and heat. In these conditions concentrating on a crop that can be drought and heat tolerant, and at the same time has a high nutritional value has been very important.

Although over 10000 plant species have been cultivated over time, globally, 90% of the world food needs is provided by 15 plant species and eight animal species (Jones, 2003). This makes it necessary to expand the number of food plants which are cultivated by small holder farmers in the marginal areas, and to investigate the possibility whether it is manageable to elevate the breeding status similar to ones which have been used as main sources of food (Jones, 2002).

Agriculture in arid lands cannot depend on rainfall alone, it is necessary to depend on stored water to get yield, while in semi-arid lands, reasonable and good yield is possible with rainfall alone if the distribution of rainfall meets crop requirements. The arid and semi-arid regions of the world constitute almost 44.7 million km^2 and approximately 39 % of this area is semi arid (Arnon and Gupta, 1995). The semiarid climate is not always intermediate between dry and humid. It can be totally dry in a season and fairly humid in the next season, like Botswana which has rainy summer and dry winter. In crop production, it is not only crop survival that is the target, but also yield; sometimes rainfall is sufficient for crop growth, but not yield if the crop suffers from stress throughout the season or at a critical time of development (Arnon and Gupta, 1995).

In semi-arid regions, both seasonally and diurnally, soil temperature is extremely variable. Temperature requirements differ between species. The effect of soil temperature persists beyond germination into the growth of the seedling. The composition of seeds and the permeability of the seed coat, determine the extent at which a seed imbibes water from soil during the initial stage of germination.

1.2 Bambara groundnut

Bambara groundnut is well-known in sub-Saharan Africa, but is little known or sometimes unknown in other parts of the world. The crop belongs to the family leguminosae. The crop is bunch type, leaves are trifoliate. Pods are on the soil surface or immediately under the surface. A pod contains 1-2 seeds, but most landraces have a single-seeded pod. The crop is known to be pest resistant; it buries its pods in the soil, which makes them safe from damage by flying insects that usually destroy pulses like cowpeas and beans (National Academy of Science, 1981).

Bambara groundnut is essentially grown for human consumption, the seed considered as a complete food because of the high nutritional value (Linnemann and Azam-Ali, 1993). The seeds can be consumed in different ways; they can be grilled, boiled or eaten fresh. In Botswana for example, they are boiled with salt and eaten as a snack.

One of the most important characteristics of bambara groundnut is its ability to produce some yield in soils which are too poor for cultivation of other, more favoured, species such as groundnut (Linnemann and Azam-Ali, 1993). Growth and development of bambara groundnut varies according to landraces and environmental conditions. Germination and emergence takes about 7-15 days, while flowering take 30 to 55 days depending on daylength, temperature and landrace (Gonapa, 2002).

Bamabra groundnut is a short day crop grows at elevations up to 1600 m. The optimum temperature for bambara groundnut range from 20- 28 °C (Linnemann and Azam-Ali, 1993). To grow successfully and to give good yield, the crop needs evenly distributed and

moderate rainfall from sowing until flowering. The crop is usually harvested between 90 to 170 days after sowing (DAS) (Linnemann and Azam-Ali, 1993).

The previous studies on bambara groundnut have been carried out on landraces because no varieties of bambara groundnut have been developed. A landrace is locally adapted, selected through traditional methods, and not developed by breeding. The landraces S19-3, which originated from a hot and dry environment (Namibia) and Uniswa Red, which originated from wet and cool environment (Swaziland) have been extensively used for several studies at The Tropical Crops Research Unit (TCRU), Sutton Bonington, University of Nottingham. The two landraces were chosen as representative landraces of two contrasting environments. However, relatively little work has been published on drought and heat stress.

It has been demonstrated that bambara groundnut has the ability to produce high yield under both controlled environments and in the field. For example, pod yield was 3.66t ha^{-1} in a study of Mwale *et al*. (2007a) in controlled environments. In a field study in Ivory Coast, bambara groundnut produced 4.8 t ha^{-1} (Kouassi and Zoro, 2010). A considerable number of studies on the crop in controlled environments have been carried out, but more efforts should be made to improve the management of the crop in the field. Because this crop grows in semi-arid areas and gives higher yield under drought compared to the other species, it is very important to conduct trials using this crop in semi-arid zones along with studies in the controlled environments.

2. Literature review

Drought, cold and heat have major effects on the growth, development, gas exchange and resource capture and use in bambara groundnut. Previous studies on these aspects will be reviewed.

2.1 Soil moisture and crop growth

Stimulation of crop growth can be achieved by moderate quantities of soil moisture and inhibited by either deficit or excessive amounts (Israelsen and Hansen, 1962, Figure 2.1). The soil water concentration and the volume of soil explored by the roots are the factors which control the amount of water available to a crop. Water uptake and water loss must be balanced to avoid an excessive water deficit in the plant (Shamudzarira, 1996). Soil moisture deficit affects several plant processes from cell to the canopy such as leaf expansion and leaf production rate. Water stress restricts vegetative growth of bambara groundnut resulting in decreased total dry matter (TDM) (Mwale *et al*., 2007a).

2.2 Evapotranspiration (E_t)

Because E_t is a combination of a single process (evaporation) from two surfaces, i.e. soil and plant, and because it is affected by different factors, measuring E_t can be very complicated. Many methods use atmospheric and thermodynamic parameters to calculate E_t, like vapour pressure of the air and net radiation, but in reality, sometimes it is difficult to measure all the parameters required, therefore parameters related to E_t are often used for calculation. For example, atmospheric humidity which is needed for measuring E_t, which can be estimated by measuring temperature or dew point (Burman and Pochop, 1994).

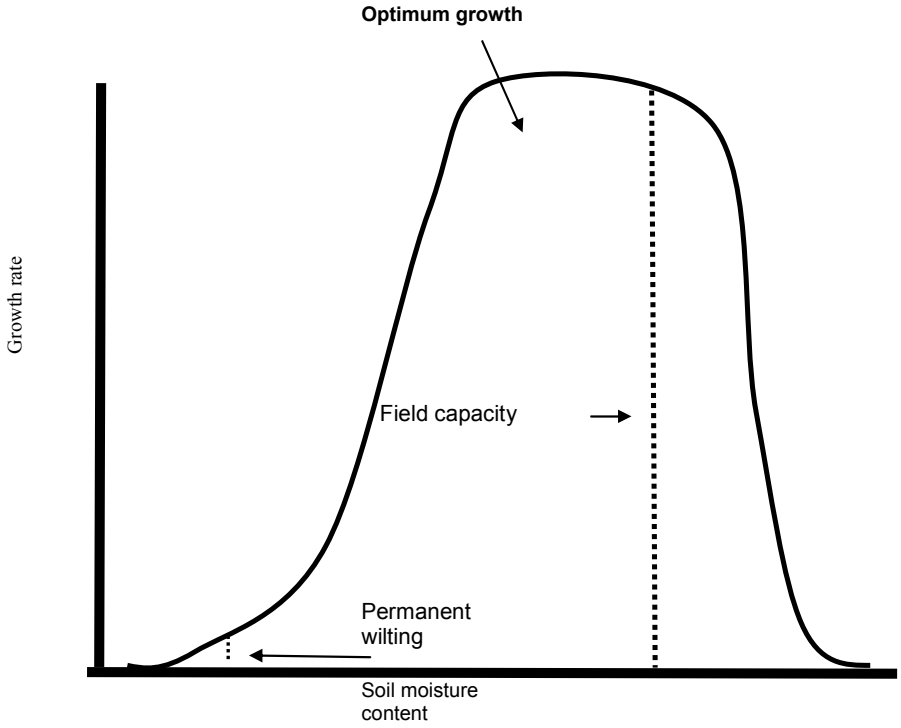

Figure 2.1 Relationship between soil moisture content and growth rate, optimum growth varying somewhat with aeration, water holding capacity of soil and crop grown. Adapted from Israelsen and Hansen (1962).

Physical factors play a very important role in E_t, but in addition to that, plant communities have a physiological impact on the E_t through the process of transpiration which is determined by a combination of stomatal conductance and the total surface area of their leaf canopies (Azam-Ali and Squire, 2002).

Soil evaporation (E_s) and transpiration (T), which are the two components of evapotranspiration are usually measured simultaneously. Therefore combined measurement of E_t is common, but for plant growth model studies and irrigation management practices, it is preferable to measure E_s and T individually (Klocke, *et al*., 1985).

Many researchers use the temperature of the crop canopy to estimate water stress of a crop, by using infrared thermometry. The crop uses transpiration to cool leaves to a temperature below that of the surrounding air, and infrared thermometry gives a measure of temperature. Usually, the stressed crop will have higher temperature and transpire less, and its temperature will reach or exceed that of surrounding air. Crop canopy temperature-air temperature differential (*Tc-Ta*) has been related to seasonal water use and yield (Mitchell and Hanks, 1985). Vapour pressure deficit of air, wind speed and net radiation have been added to this model of crop water stress to normalize (*Tc-Ta*) for environmental variability (Mitchell and Hanks, 1985).

A large portion of the world's land used for agriculture is arid or semi arid. A large component of the hydrological balance of the earth is represented by those areas. In the arid and semi arid zones evaporation and transpiration back 90% of the precipitation to the atmosphere (Burman and Pochop, 1994). Studies of water use by dry land crops, used to rely on the soil water balance, often with neutron scattering method used to estimate available soil water. This method allows E_t to be measured at intervals greater than daily. Usually arid or semi-arid crops have a big soil surface area exposed throughout the growing season. Because of that it is very important to measure E_s along with T (Hatfield and Wanjura, 1985).

Squire (1990) indicated that E_t can be calculated as $E_t = RI$, where E_t units are volume of water transpired per unit of ground surface per unit time, R is length of root per unit area of ground surface, and I is volume of water per unit length of root per unit time.

2.3 Evapotranspiration and soil moisture

E_t is estimated from the changes in soil moisture content which can be measured by the gravimetric method (Burman and Pochop, 1994). However, this method cannot be carried out repeatedly at the same location because it is destructive and also takes a long time. Various instruments are now used to estimate soil moisture, such as the Neutron probe, PR2 (Delta-T Devices) and a tensiometer, which means that the gravimetric method is now usually used for calibration only.

The process of water relocation in the soil after a rainstorm or irrigation makes soil moisture movement very important in consideration of evapotranspiration. Water is moved to the soil surface to supply E_t. This movement is caused by plant roots or by unsaturated flow through soil particles (Azam-Ali and Squire, 2002). In a study of two bambara groundnut landraces, Shamudzarira (1996) found that soil water supply had a strong effect on water use. He reported seasonal E_t ranges between 318mm and 440mm under irrigation and 81mm to 102mm under drought. In a study on two landraces and four cultivars of dry bean grown under two water regimes (Munoz-Perea *et al*., 2007); irrigated and droughted (four irrigations through the season), E_t decreased by 3% to 40 %. When they repeated the experiment with more severe drought (irrigation twice throughout the season), reduction in E_t ranged from 20% to 50%.

2.4 Transpiration (T)

To carry out photosynthesis, plants must absorb CO_2 from the atmosphere through stomata, while losing water through the same pores. Leaves absorb energy from the sun for photosynthesis, 1% of this energy is used for photosynthesis the rest tends to heat the leaves. Plants usually dissipate the excess energy by transpiration, convection or radiation to prevent the increase of leaf temperature (Azam-Ali and Squire, 2002). Transpiration rate from most dry land crops is usually more limited by resistance from vegetation than the atmosphere. The vegetation effect on transpiration rate can be divided into two categories: the movement of water vapour from the sub-stomatal cavities of leaves to the air above the canopy, which is determined by the physiology and structure of the canopy, and the supply of water from the soil to the conducting vessels in the plant (Squire, 1990). In a study on bambara groundnut, seasonal transpiration of Dip C was 241mm in the irrigated treatments and 168mm in the droughted treatment (Mwale *et al*., 2007b)

2.5 Surface evaporation (E_s)

Soil evaporation in temperate environments can be a very small portion of E_t, and sometimes can be ignored in calculations of E_t, but this case is rare in tropical areas for two reasons: firstly crops cannot achieve full ground cover, secondly, rainfall rewets the soil surface frequently by small amounts of water which may not be enough to reach the roots. In this case E_s can form a big portion of E_t (Azam-Ali and Squire, 2002).

Gharres (1990) divided the evaporation from soil into three stages:

. Stage 1, the evaporation from soil is equal to the potential rate.

. Stage 2, during which evaporation from soil constitutes a rapidly decreasing fraction of the potential rate

. Stage 3, during this stage the soil becomes very dry and the rate of evaporation is very slow and almost has a stable rate.

Different techniques are used to estimate evaporation from soil surface or standing water. Commonly, it is determined from the change in the soil weights by using small containers, such as plastic trays or metal cans filled with soil or water and placed at the level of the evaporating surface and weighed daily (Lascano *et al*., 1987; Simmonds and Williams, 1989; Shamudzarira, 1996 and Mwale *et al*., 2007b). Squire (1990) pointed out that this method can be accurate only during the first days after the soil gets wetted, because with time the water will move to the soil surface and that will underestimate E_s. Because of this usually after a long period E_s is estimated by measuring soil moisture content by gravimetric method or by using any instrument measures that soil moisture, such as the Neutron probe or PR2.

2.6 Growth analysis and crop productivity

Growth can be measured by leaf area, shoot, root and total weight or plant height (Fageria *et al*., 2006). Plant growth and biomass partitioning determine crop productivity. In turn, developmental stages of crops affect growth and partitioning between vegetative and reproductive components. To maximize crop yield, knowledge of physiological processes of growth, development, and partitioning into yield is necessary.

The two terms, *growth* and *development* sometimes are confused with each other. In fact they are two separate processes. Development can be defined as the sequence of ontogenetic events, involving both growth and morphology. Sparkes (2003) defined development as the progression in the structure or number of individual organs through a

series of discrete changes. Developmental measurements include process of organ initiation and include leaf and flower emergence (Fageria *et al.,* 2006). Growth is quantitative process and includes irreversible changes in the length, area, or weight of individual organs (Sparkes, 2003). Salter (1967) indicated that, several studies on groundnut found that water requirements reached a peak during flowering and pod development, when most dry matter was being accumulated.

Usually when drought is not severe, the only gross morphological attribute affected is leaf size, when drought increases, the rates of leaf initiation and branching both are reduced (Squire, 1990). Growth analysis is a very useful method to quantify the impact of stress on crops. Leaf growth and development are usually affected by water stress and this is usually expressed as leaf area index for the growth and for development as the total leaf number. All of these are used useful to estimate the surface area available for transpiration and productivity (Rosenthal *et al*., 1985). Generally in crops, both the time to floral initiation and the time duration from floral initiation to flowering increase under drought (Blum, 1997). Blum (1997) reported that the impact of drought on flowering is due to abscisic acid accumulation under the effect of water stress.

2.7 Environmental effect on growth and development

When the rate of transpiration exceeds the rate of water absorption by the roots, the plant becomes under water stress (Kramer and Boyer, 1995). The effect of water deficit on growth and development of bambara groundnut was reported by several studies; Mwale (2007a) reported that drought decreased the production rate and the total leaf number produced by bambara groundnut. A reduction of 60% in leaf production followed by reduction of 32% in leaf area index (LAI) was reported by Collinson *et al*. (1999).

Shamudzarira (1996) reported that drought slowed the rate of canopy development where LAI never exceeded 1.5 in the droughted treatment while it went up to 5.5 in the irrigated canopies. Phenology was also reported to be affected by water deficit, Collinson *et al*. (1999) found that cumulative flower production was reduced by 50% due to drought, while (Mwale, 2005) reported that pod number was reduced under drought.

Damage to the plants caused by exposure to high temperature differs from crop to crop, and depends on growth stage and type of plant tissue. Some growth stages are more sensitive to high stress than others. In pearl millet, for example, the seedlings are most vulnerable to heat during emergence, because of the rise of soil surface temperature (Klueva *et al*., 2001). Heat stress can reduce crop yield or change quality. Heat stress can be severe or moderate, and usually when the term high temperature is used, it refers to rise in temperature which stresses the crop (Stone, 2001). Agonga (2006) indicated that the heat stress delays pod formation in bambara groundnut. McDonald and Paulsen (1997) studied the response of Alaska pea to elevated temperature during flowering, where one week after start of flowering, the plants were exposed to 20/15 or 30/25 °C day/night temperature for 7 days, after exposure to high temperature, plants were transferred to 20/15 °C until physiological maturity. They found that high temperature reduced plant height by 15% , TDM by 49%, seed yield by 54% and HI by 8%. During flowering, pollen development, fertilization and asynchrony of stamen are sensitive to temperature stress. The loss of pollen or stigma viability under heat stress might be the main reason for lowered number of seeds produced in the legumes (Thuzar *et al*., 2010).

It is more common for tropical species to experience temperatures near the upper limit of their range than the lower, especially at the emergence stage in drier regions (Squire, 1990). Most of the tropical species survive between 15-40 °C, though few stay alive above

50°C or below 10°C. Most of the studies on the effect of temperature on bambara groundnut germination were carried out in the laboratory. The base temperature (T_b) of bambara groundnut was reported to be 10°C (Kocabas *et al*., 1999). However, Massawe *et al*. (2003a) found, in a study of 10 landraces of bambara groundnut, that T_b ranged from 11.5 °C to 12.3 °C. Massawe *et al*., (2003b) found that the rate of leaf appearance was related linearly to temperature. The optimum temperature for germination of bambara groundnut ranged from 30.2 to 35.3 °C (Massawe *et al*., 2003). The optimum temperature for crop development might differ between developmental stages. For example, the suitable temperature for soybean is 15-22 °C at emergence, 20-25 °C at flowering and 15-22°C at maturity (Thuzar, 2010)

The effect of photoperiod on flower production in bambara groundnut was reported by Linnemann and Craufurd (1994) who found that photoperiod longer than 11.33 h d^{-1} delayed flowering. The same study indicated that bambara groundnut did not produce any pods at photoperiods greater than 16 h d^{-1}. Photoperiod and temperature are generally assumed to be the main environmental factors influencing reproductive development in annual crops. The onset of flowering is photoperiod-insensitive and the onset of podding is retarded in most bambara groundnut landraces (Brink, 1999).

Most crops show negative response to water stress in terms of yield. Aspects of plant behaviour relative to drought can be divided into four categories; modification of leaf area, root growth, efficiency of exchange or water for CO_2 by leaves, and processes involved in setting and filling of seeds (Fageria *et al*., 2006). In crop species, it is not only the ability to survive periods of water deficit which is important, but also the ability to produce a harvestable yield (Turner, 1979). The impact of drought differs according to the plant's developmental stage. Seed yield and size will be small if the drought occurs during

seed formation. For that reason, if drought follows favourable meteorological conditions which produce abundance of vegetation, the crop will face the worst conditions for high yield (Hounam *et al*., 1975).

Soil moisture deficit has a huge effect on total dry matter (TDM) production in bambara groundnut. Mwale (2005) reported a reduction of 50% in accumulated total dry matter under drought. Collinson *et al*. (1996) reported that TDM ranged from 2.5 to 9.3 t h^{-1} under droughted and irrigated treatments respectively. Pod number per plant was reduced by 43% due to drought while HI was not affected by drought (Mwale *et al*., 2007a). However, Kumaga *et al*. (2003) reported a decline in HI in three droughted legumes species and a decrease of 75% in yield. Shamudzarira (1996) reported a pod yield of 450 g m^{-2} under irrigation and a yield of 25 g m^{-2} in bambara groundnut droughted from establishment. The ability of partitioning dry matter into harvestable yield under limited water supply is an important trait for drought tolerant crops. In a study on groundnut (Vorasoot *et al*., 2004), four cultivars were grown under three soil water regimes; field capacity (FC), half field capacity and quarter field capacity. Depletion in available soil water from FC to quarter FC reduced HI significantly.

Reproductive growth leading to seed yield is commonly decreased by the same rise in temperature that improves vegetative growth and development, but this increase in the vegetative growth and development will be only up to a certain temperature where any further increase in temperature will decrease TDM (Thuzar, 2010). Wheeler et al. (1997) investigated the effect of heat stress on two genotypes of cow pea; a high temperature tolerant genotype and a high temperature sensitive genotype. At 49 DAS (12 days after flowering), each genotype was divided into four groups. One group was left at 30/24 °C. Each of the remaining groups were placed at a programmed controlled environment to

give three high temperature treatments for six days; 35/24, 40/24 and 45/24 °C for three days then 50/24°C for three days. All the plants were then returned to 30/24 °C. The photoperiod was set to 12 h d^{-1} for all the temperature regimes with vapour pressure deficit of 1.4 kPa during the day and 0.9 kPa at night. They found that TDM and seed yield in both genotypes were significantly affected by temperature. They found also TDM and seed yield of the high temperature genotype were greater than for the high temperature sensitive genotype. The highest TDM for the high temperature tolerant genotype was 61.3 g $plant^{-1}$ at 35/ 24 °C day/night regime and the lowest was 30.2 g $plant^{-1}$ at 45/24 °C. In the high temperature sensitive genotype, the highest TDM was 37.4 g $plant^{-1}$ at 40/24 and the lowest was 26 g $plant^{-1}$ at 35/24 °C. Seed yield decreased with increase in temperature for the high temperature tolerant genotype where the highest seed yield 13.9 g $plant^{-1}$ was obtained at 30/24 °C and the lowest (7.1 g $plant^{-1}$) was obtained at 45/24 °C . This pattern did not exist in the high temperature sensitive genotype where they produced 5.7, 3.5, 4.9 and 1.1 g $plant^{-1}$ at 30, 35, 40, and 45 °C respectively. TDM, pod and seed dry matter produced at mean temperature of 30°C was significantly higher than the TDM, seed and pod dry matter produced at mean of 25°C (Craufurd *et al*., 2002).

In a study on the interaction effect of drought and temperature stress on groundnut, plants were grown at 30/24 °C day/night temperature (mean of 27°C) until 50 % of the genotypes had flowered when they were transferred to two different temperature regimes, mean of 27 °C and 40/28 °C day night (mean of 34 °C) and under two soil water regimes; 100% available soil water and 50% available soil water. They found substantial effects of temperature and significant effects of water deficit on TDM, WUE and SLA, but no interaction effect was found. TDM was reduced by high temperature and that was associated with a lower WUE. At 100% available soil water, WUE values of 2.8 g kg^{-1} and 2.2 g kg^{-1} at 27°C and 34°C respectively. At 50% available soil water, WUE values

were 3.3 and 2.7 g kg^{-1} at 27 °C and 34 °C, respectively (Craufurd *et al*., 1999). Prasad *et al*. (2000) reported that imposing high temperature stress at flowering, but not at podding, reduced total dry matter and pod weights were reduced by high air temperature at both flowering (18%) and podding (26%). In a study conducted by Bagnall and King (1987), cowpea was grown at 27/22 °C day/night regime until flowering. After which the plants were grown in different temperatures regime; 21/16, 24/19, 27/22, 30/25 and 33/28°C day/night. The highest number of pods was produced at 24/19 and the lowest was produced at 33/28°C. The authors attributed this to high temperature reducing the duration of leaf formation as they found a high correlation between leaf area formed after first flower appearance and seed yield of plants grown at 27/22°C or above.

The effect of sowing on crop yield and dry matter production was reported in several studies (El Mahdi *et al*., 2007; Miah *et al*, 2009 and Ouda *et al*., 2005). In a study by Wajid *et al*. (2004) on the effect of three sowing dates (10 November, 25 November and 10 December) on wheat, they reported that early sowing enhanced grain yield over the late sowing by 60.6 %.

2.8 Gas exchange, plant water status, heat and drought

Leaves have the ability to change the pressure of CO_2 at the sites of carboxylation and, in turn, the transpiration rate by stomatal movements. Changes in leaf temperature and leaf water potential can be caused by the change in transpiration (Farquhar and Sharkey, 1982). A reduction in stomatal conductance is a common response to lack of water but at the same time, when the plant is exposed to high temperature, the stomatal conductance increases by the plant as a way to reduce the leaf temperature by increasing transpiration.

Because of that, when the plant is exposed to high temperature and drought, the plant tries to balance water loss and leaf temperature. Chickweyeye (2006) indicated that bambara groundnut showed a higher stomatal conductance in high temperature than low temperature under unlimited water supply.

In arid and semi arid lands, bare soil surfaces are usually exposed to high radiation loads. That exposes many crops to severe heat stress even before they have started germination. Much of the incident energy is lost through latent heat of vaporization if the soil is moist, but dry lands keep soil temperature much higher than the ambient air temperature. High temperature is widely reported to cause stomatal closure, that is an indirect response to the effect of temperature on vapour pressure deficit and leaf respiration, which raises the CO_2 concentration leading to stomatal closure (Stone, 2001). Different physiological characters are used to determine drought resistance of crops. The regulation of water loss by stomata is a very important indicator which has received a considerable amount of studies from plant physiologists and breeders in their attempts to improve crop yield in dry environments (Jones, 1979).

Plant water status controls the stomatal movement. When a plant suffers from water deficit, the stomata start to close, but it has been demonstrated that in some plant species, especially legumes, stomata start to close in dry soils even though the plant water status has not changed. This has been shown to be due to root signals (Squire, 1990). A partial root drying experiment was carried out, where part of root was kept wet, and another part was droughted, the stomata closed even though the plant water status was not affected (Schulze, 1993). Rending and Taylor (1989) indicated that three factors control the extent to which plant water potential decreases during the daily stress period: (1) the amount of energy into the leaves which is used to convert liquid water to vapour; (2) the ability of

water vapour to move from internal evaporating surface through the stomata and cuticle to the ambient atmosphere and; (3) the water supply from the soil to the sub-stomatal evaporating sites within the leaves.

Different environmental factors control stomatal movements, water availability, water vapour pressure deficit, CO_2 concentration and temperature. The interaction between these factors which are working at the same time makes studies on one factor difficult. For example, leaf temperature will increase because of increasing leaf irradiance, but at the same time will lower leaf water potential. Photosynthesis rate will change because the intercellular CO_2 concentrations will be modified due to the temperature increase (Willmer, 1983).

Photosynthesis, which is the primary factor controlling total dry matter production, is the best indicator of plant function (Planchon, 1987). Turner (1979) indicated that two main factors determine the capacity of plants to maintain active photosynthesis under drought stress:

-The maintenance of a high leaf water status, which is assessed by the leaf water potential and relative water content.

- The ability of the plant to tolerate the internal water deficit.

McDonal and Paulsen (1997) studied the effect of elevated temperature during flowering on P_n of pea, faba bean and cowpea grown at 20/15°C, 30/15°C and 30/25 °C day/night temperature where P_n responded similarly to temperature and after 4 days of being grown at the temperature regimes, the highest P_n was at 30/15 °C in cowpea (13.3 mmol CO_2 m^{-2} s^{-1}) while the lowest P_n was at 30/25 °C in pea (5.33 mmol CO_2 m^{-2} s^{-1}). P_n decreased from 17.45 mmol m^{-2} s-1 to 1.8 mmol m^{-2} s^{-1} in soybean grown at 100% available soil

water and 25% available soil water respectively. This reduction was associated with reduction in leaf area from 991 cm^2 to 725 cm^2 (Purwanto, 2003).

The first measurements on gas exchange in bambara groundnut were carried out in the TCRU, University of Nottingham, by Deswarte (2001). He found drought reduced P_n at 32 °C to values as low as 6 µmol m^{-2} s^{-1}, while the irrigated treatment ranged from 18.1 to 24.3 µmol m^{-2} s^{-1}. Chickweyeye (2006) reported higher photosynthesis for bambara groundnut at 23 °C than 33 °C. He reported seasonal values of 10.6 µmol m^{-2} $s^{-1}$and 11.1 µmol m^{-2} s^{-1} for Uniswa Red and S19-3 respectively at low temperature and seasonal values of 9.8 and 8.7 µmol m^{-2} s^{-1} at high temperature. However, he found that the two landraces had lower g_s under low temperature compared to high temperature. In general, increase in P_n capacity following growth at low temperatures is associated with increase in orthophosphate availability (Antolin *et al*., 2005). Shamudzarira (1996) reported values of g_s of 0.2 cm s^{-1} and 0.1-0.6 cm s^{-1} for droughted and irrigated stands of bambara groundnut, respectively. Values of g_s as low as 0.09 , 0.1 and 0.04 cm s^{-1} were reported for droughted Dip C, S19-3 and Uniswa Red at 115 DAS, respectively (Mwale, 2005).

Drought resistance can be defined as the ability of a crop to stay alive, grow, and produce seeds when part of its life cycle has been under stress (Fageria *et al*., 2006). When water supply is terminated, plant water relations undergo three main stages of development; in the first stage transpiration and assimilation continue normally until the soil moisture is decreased to a limit where water uptake is unable to cover the transpirational demand, this will lead to the stage II; in this stage transpiration and assimilation are decreased below the potential level. As soil moisture is decreased, water and heat stress progress. In stage III the stomata are fully closed and water loss from plant is not stomatal, here the crop

reduces water use to stay alive. The time that crop is able to survive in stage III differs from one species to another (Blum, 1997).

The response of the plants to drought stress could be divided into these categories, drought escape, drought avoidance, and drought tolerance (Collinson *et al*., 1997). Drought escape represents the ability of plants to complete the life cycle before the existence of the drought. Drought avoidance is shown when the plant shows a high ability to reduce water loss by stomatal control, and maintaining a high plant water status by maximising water uptake through deep roots. The plants which are classified as drought tolerant, such as groundnut, maintain positive turgor at low water potential.

Although bambara groundnut is known as a drought resistant crop, the shortage of quantitative evidence regarding the mechanism of its response means that it has not been classified into one of the drought resistance groups (escape, avoidance and tolerance). Seventy two landraces of bambara groundnut were examined by Begemann (1988) under two water stress regimes in Ibadan, Nigeria. In the first regime, where the plants were droughted from 2 weeks after sowing, the highest-yielding landraces were those which reached maturity early, as they managed to escape drought by producing some yield before drought became severe. In the second, where the plants were droughted for the first 35 DAS, the highest-yielding were those with extensive roots able to avoid drought by extracting water from deeper soil layers. The expansion of cells is highly sensitive to drought mainly because of reduction in the hydrostatic pressure or potential of turgor necessary for expansion (Collinson *et al*., 1997).

Plant water status can be described in terms of leaf relative water content (LRWC) or leaf water potential. In a study on water status of bambara groundnut droughted at 36 DAS,

LRWC decreased from 92-96% under non limiting soil moisture to 83% at 137 DAS, and average leaf water potential of $16x10^{-3}$ MPa in droughted stands and average of $5.3x10^{-3}$ M Pa in irrigated stand (Collinson *et al*., 1997). The same study reported a decline of g_s from 0.46-0.79 cm s^{-1} in non droughted stands to 0.13-0.48 cm s^{-1} in the droughted stand. Mwale (2005) reported a decrease in g_s due to drought and found no effect of drought on LRWC where values did not go below 90% in either irrigation or drought treatments. On a study on groundnut and bambara groundnut grown in the TCRU at 27 °C, Nuer (1989) found that LRWC in groundnut decreased from 79% under irrigation to 50% under drought, while in bambara groundnut the decrease was from 83-70% in the same treatments.

Prolonged heat stress causes an increase in transpiration resulting in high water loss from the plant leaves and hence low RWC (Farkhutdinov *et al*., 2003). Tsukaguchi *et al*. (2003) investigated daily changes in LRWC under heat stress in four cultivars of groundnut under field conditions. No differences were found between the heat sensitive and heat-tolerant cultivars at 12:00 h and LRWC in heat-tolerant cultivars was significantly lower than in heat-sensitive cultivars in the morning and evening.

2.9 Resource use efficiency

2.9.1 Radiation use efficiency

Radiation use efficiency (RUE) is the relation between the accumulated dry matter and the amount of intercepted solar radiation. The ratio of dry matter produced to solar radiation intercepted (ε_s) which can be derived from linear regression of dry matter on intercepted radiation for a number of samples during a growing season (Squire, 1990). The difference

between received solar radiation at the canopy surface and that transmitted at the soil is known as intercepted radiation. The incoming radiation itself differs throughout the tropics. Seasonal means of total solar radiation (in the wavelength range 0.4-3 μm) range from 12 MJ m^{-2} d^{-1} in cloudy upland to more than 24 MJ m^{-2} d^{-1} during cropping seasons in some semi-arid regions. Therefore, it is more constructive to compare canopies using fractional intercepted radiation (*f*), because this fraction is little affected by the absolute values of the incoming radiation (Squire, 1990).

In a study on soybean, green gram (*Vigna radiate* cvs), black gram (*Vigna mungo* cv Regur), cowpea, lablab bean and pigeon pea in Australia, (Muchow, 1985), the crops were grown under three water regimes; wet, dry and wet/dry. The wet regime received irrigation weekly. The dry regime received irrigation until establishment and then no further irrigation was applied. The wet/dry regime received weekly irrigation until 6 weeks after sowing when drought was imposed. All grain legumes attained peak values of fractional intercepted radiation (*f*) greater than 0.9 under the wet regime. Under the dry regime, peak values ranged between 0.5 and 0.6 for lablab bean, cowpea and soybean and between 0.4 and 0.5 for the rest of the crops except for pigeon pea where *f* ranged between 0.3 and 0.4. The minimum values of for all species under wet/dry regime were higher than maximum value of f under the dry regime. This pattern of *f* was associated with similar pattern of LAI and TDM. Dry matter production at 42 DAS was significantly reduced under the dry regime compared with the wet regime. The authors attribute reduction in *f* at the dry regime to reduction in leaf production, leaf loss and erect leaf orientation.

A considerable number of studies have been carried out on bambara groundnut to evaluate the effect of drought stress on *f* and radiation use efficiency (RUE). Collinson *et al*. (1999) reported that seasonal *f* ranged from 0.2-0.37 for droughted bambara groundnut and 0.62-

0.74 for irrigated bambara groundnut. The same authors reported ε_s 1.00 g MJ^{-1} under non-limiting soil moisture and 0.51 g MJ^{-1} under drought. In a similar study, Mwale *et al*. (2007b) reported values of 1.51 g MJ^{-1} and 1.02 g MJ^{-1} under irrigation and drought conditions, respectively.

In a study on the effect of temperature on *f* and ε_s in bambara groundnut, Chickweyeye (2006) found that landraces at 33 °C intercepted more radiation than stands at 23 °C. The study reported ε_s values of 1.07 g MJ^{-1} and 1.02 g MJ^{-1} for S19-3 and Uniswa Red grown at 33 °C, respectively, and 1.01 and 0.74 g MJ^{-1} for Uniswa Red and S19-3 at 23 °C. In cowpea, ε_s ranged from 0.73-1.15 g MJ^{-1} to 0.07-0.5 g MJ^{-1} under irrigation and drought, respectively (Craufurd and Wheeler, 1999). The reduction of ε_s due to drought was also reported in finger millet where Maqsood and Azam-Ali (2007) reported values of 2.1g MJ^{-1} and 2.8 g MJ^{-1} under drought and irrigation, respectively. Light extinction coefficient was not affected by drought (Mwale, 2005).Values of 0.6 (Berchie, 1996); 0.55 (Nuer, 1989) and 0.46 (Mwale, 2005) were reported for irrigated bambara groundnut grown at mean air temperature of 28°C at TCRU. Collinson *et al*. (1999) reported a mean *k* value of 0.62 for bambara groundnut grown at mean air temperature of 27°C at TCRU.

Chickweyeye (2006) reported that Uniswa Red and S19-3 under 33 °C and 23°C gave a mean extinction coefficient (*k*) value of 0.62 for all treatments. The smallest (0.52) and highest (0.68) *k* values for S19-3 were both observed under low temperature at 68 and 75 DAS, respectively. At 33 °C, S19-3 had reached a maximum *k* value of 0.66 by 75 DAS and this was almost four weeks earlier than Uniswa with *k* value of 0.66 at 102 DAS at the high temperature.

2.9.2 Water use efficiency

Water use efficiency (WUE) is the relationship between any of yield, biomass or assimilation and amount of water used (Jones, 1993). Total dry matter has a linear relationship (determined by photosynthetic efficiency, saturation deficit, water potential and supply of nutrients) with transpiration with a slope ε_w (g kg^{-1}) known as dry matter/transpired water ratio. This relationship depends on gas exchange, when leaves transpire water through opening stomata and take CO_2 from the atmosphere. (Squire, 1990). Water use efficiency is a physiological trait, usually associated with drought tolerance, and it can contribute to crop productivity for crops grown under drought. Because of that, WUE improvement of crop, should improve the yield performance (Fageria *et al*., 2006). WUE is more useful than RUE in semi-arid climates as radiation is rarely limiting but water is.

The dry matter of a stand (W) is related to its cumulative transpiration by

$$W = \varepsilon_w \Sigma E_t$$

Where ε_w is the amount of dry matter produced per unit transpired water (the dry matter / transpired water ratio) (Squire, 1990).

Tanner and Sinclair (1983) indicated that WUE can also calculated from

$$P = KT / D$$

where P is the dry matter production, T is the crop transpiration, K/D is the dry matter: water ratio (dry mass produced per unit mass of water transpired) and D is the average vapour deficit of the air. The same reference pointed out that this equation is very reliable especially in more arid environments, when crop production is limited by water availability.

The number of studies on WUE of bambara groundnut is very limited. Values of 2.2 and 3 g kg^{-1} were reported for irrigated bambara groundnut stands and 1.8-2.6 g kg^{-1} for droughted stands (Shamudzarira, 1996). Mwale (2005) reported values of 2.05 and 1.65 g kg^{-1} for irrigated and droughted bambara groundnut stands, respectively. As the main aim for most of the crop improvement studies is to enhance yield, some studies use seed yield WUE which is the ratio of seed yield to water utilized, which is generally inversely proportional to the severity of drought. In a study on two landraces and four cultivars of dry bean grown under two water regimes (Munoz-Perea *et al*., 2007), drought reduced HI by 17% to 60% and reduced seed yield between 34% to 76% and the values of seed WUE were higher in the irrigation treatment than the droughted treatment except for one genotype.

Objectives

The overall objective of this study was to investigate the effects of drought and temperature stress on the growth and development of three landraces of bambara groundnut. The study was designed to address the following objectives:

1. To uncouple effects of temperature and soil moisture deficits on the growth and yield of bambara groundnut.

2. To investigate the differences in the drought and heat tolerance and partitioning efficiency of bambara groundnut landraces.

3. To quantify the impact of drought and temperature on resource capture and conversion coefficients.

Hypotheses

. There are differences in the drought and heat tolerance of bambara groundnut landraces based on physiological characteristics.

. Heat stress affects the onset of reproduction, crop yield and harvest index of bambara groundnut.

. Responses of RUE and WUE to drought and temperature stress will depend on the physiological characteristics of the landraces.

3 Materials and methods

3.1 Sites and experiments conducted

Two types of experiments are described in this thesis; glasshouse experiments and field experiments. The glasshouse experiments were conducted over three years between 2006 and 2008 at the University of Nottingham, Sutton Bonington Campus (52^0 50' N, $1^0$15'W) United Kingdom. The field experiments were conducted over two years in 2007-2008 and 2008- 2009 at Botswana College of Agriculture, Gaborone, Botswana (24°33' S; 25°54' E). The experiments formed part of the EU-funded BAMLINK project (INCO-CT-2005-015459).

3.2 BAMLINK

In 1981, a report of the National Academy of Science described bambara groundnut as one of the crops most neglected by science, but nowadays, and after twenty years of research at the University of Nottingham and its collaborating partners, this description might not be applicable any more. During those twenty years, three projects were carried out on bambara groundnut led by the University of Nottingham and funded by the European Union (EU). The third project (BAMLINK) started in January 2006 and has continued for four years. The project is investigating the physiology and the genetic characteristics of bambara groundnut and its nutritional and food processing potential in semi-arid Africa and India. Ten partners (two European, three Indian and four African) have cooperated in this project. The author was not physically involved in the 2006 glasshouse experiment which was carried out by Asha Karunaratne; a PhD student, and Wedson Chickweyeye; an MPhil student. The raw data were provided by Ms Karunaratne and they were analyzed and interpreted by the author. In the 2007 glasshouse experiment,

gas exchange measurements were carried out by Kaonika Rashid; an MSc student until 118 days after sowing when the author took over and carried out the measurements until the end of the season. The author was fully responsible for soil moisture and leaf relative water content measurements and irrigation, while he shared the rest of the measurement responsibilities with the team members. In the 2008 glasshouse experiment, soil moisture content measurements and irrigation were carried out by Stanley Noah (PhD student), while the author was responsible for gas exchange, leaf relative water content and soil evaporation measurements. The author carried out the rest of the measurements with technical assistance from the team members.

Field experiments were designed by Prof Abu Sesay (BAMLINK Principal Investigator, at Botswana College of Agriculture,). The author was physically involved in the first field experiment during the first three months of the season. The rest of the experimental results were provided by Prof Sesay. In 2008-09, the author was involved in the field experiment from the beginning until the end of the season.

In the two field experiments, the author collaborated with Prof Sesay to measure stomatal conductance. Soil moisture content measurements and irrigation requirements were carried out by Dr Scott Morake (a researcher at Department of Agriculture, Gaborone, Botswana) and T.Mpuisang (a Lecturer at Botswana College of Agriculture)**.** All the rest of the measurements were carried out by the author with technical assistance from trained workers.

3.3 Glasshouse experiments

3.3.1 Glasshouse constitution and location

The experiment was carried out in the five controlled-environment glasshouses at the Tropical Crops Research Unit (TCRU), University of Nottingham, Sutton Bonington, UK (Plate 3.1). The glasshouses are aligned in a north-south direction to prevent mutual shading. Each glasshouse measures 10.1m long by 4.7m wide, with height of 2.3m at the eaves, reaching 3.5m height at the centre. Each glasshouse contains two separate plots, north plot and south plot. Each plot measures 4m by 4m. More details about the glasshouses structure are given in Monteith *et al*. (1983) and Clifford *et al*. (1993). Four profile probe (PR2 Delta-T Devices) access tubes were located at least 1m from the edges in each plot. The access tubes allow soil water content to be measured to a depth of 100cm.

Each house contains a gravely sandy loam soil to a depth of 1.25m with heavy duty butyl liner installed to prevent vertical and lateral infiltration of water.

Plate 3.1 Tropical Crops Research Unit glasshouses, University of Nottingham

3.3.2 Monitoring and control of the glasshouses environment

Copper constantan (38 swg) Type t thermocouples were used to monitor the wet and dry bulb temperature. The thermocouples were sited in an aspirated psychrometer unit mounted 2.3m above the ground level. The temperature was recorded every two minutes for both bulbs. The values were used to compute the atmospheric saturation deficit (kPa) in the glasshouses.

Air was drawn through the psychrometer at a rate of $3ms^{-1.}$ The wet bulb was supplied with deionised water using a peristaltic pump. Water was injected where required to maintain the saturation deficit (SD) below 4 kPa. To maintain the air temperature at the required level, a gas-fired hot air blown boiler (Powermatic model CA-A9-150) was used. Cooling and ventilation of the glasshouses was achieved through automatically controlled vents that run the full length of the glasshouses on either side of the central ridge.

In each plot, incident solar radiation (S_i) was measured using two tube solarimeters located 2.3m above ground level, and radiation transmitted through the canopy (S_t) was measured using two solarimeters at ground level. The incident and transmitted radiation were measured every hour and the intercepted radiation for each day was computed as the sum of the hourly differences between S_i and S_t. (Plate 3.2). Fractional intercepted radiation (f) was calculated as $f = (S_i - S_t)/S_i$. Thermal time (Squire, 1990) accumulation on each day was computed from the air daily mean temperatures as:

$$\Theta = (T - Tb)$$

Where T is the daily mean temperature in the glasshouse and T_b is the base temperature. Cumulative Θ was calculated as the sum of daily values of Θ.

In a study of ten bambara groundnut landraces, Massawe (2000) found that T_b temperature was between 11.5 ^oC to 12.3 °C. On the other hand, Kocabas *et al*., (1999) found that the physiological T_b for a bambara groundnut landrace was 12.9 C, but when they calculated the base temperature by using a regression analysis of the germination rate against temperature, they found that Tb is 9.9 °C which they suggest can be used as a constant value in the thermal time calculations. Mwale (2005) suggested T_b for bambara groundnut to be 10°C. In the present study T_b was taken as 10^{o}C.

Plate 3.2 Glasshouse facilities and structures used to control the inside environment.

3.3.3 Plant materials

In the glasshouse experiments, two native African landraces of bambara groundnut were used; Uniswa Red, which originates from Swaziland, a relatively cool and wet environment, and S19-3, which originates from the hot and dry environment of Namibia.

3.3.4 Experiment 1: Effect of high and low temperature on growth and development of bambara groundnut landraces under non limiting soil moisture conditions

Two bambara groundnut landraces were grown over the summer of 2006 (April to September). The experimental design was split plot (two landraces; Uniswa Red and S19-3 and two temperatures; 33 ±5 ^{o}C and 23 ±5 ^{o}C (Figure 3.1). The soil moisture was non-limiting and the plots were irrigated weekly to field capacity (see later).

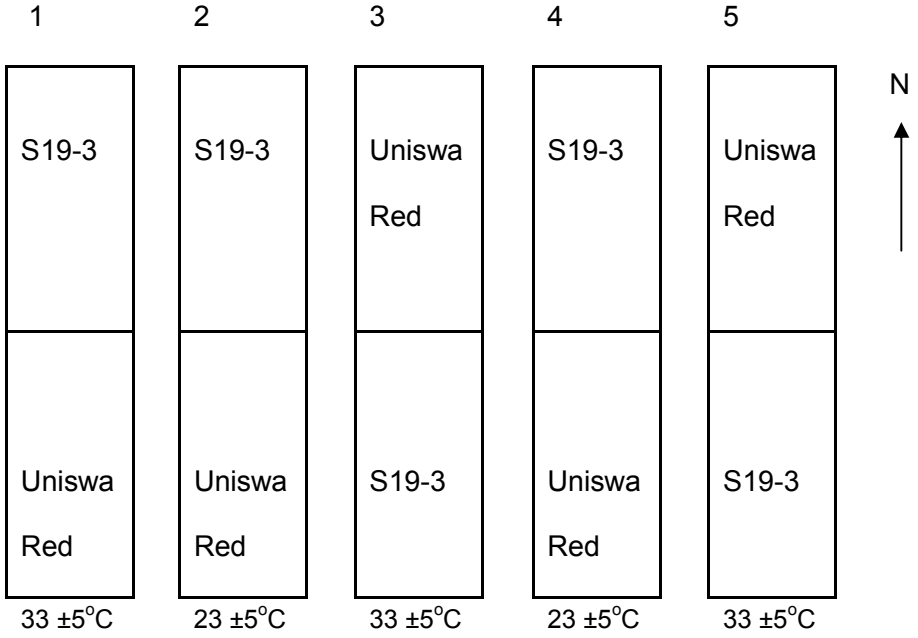

Figure 3.1 Design for the bambara groundnut experiment 2006 in the TCRU glasshouses.

3.3.4.1 Soil preparation and sowing

Prior to planting, soil samples were taken in each plot and analysed. Based on the analysis results, single fertilisers were applied to the plots to raise the quantities to equivalent of 300 kg ha^{-1} potassium and 100 kg ha^{-1} of nitrogen at 57 days before sowing (DBS) and 34 days after sowing (DAS). On 11 May, 2006, the seeds were sown; three seeds per hole at a depth of 5 cm, 10cm within rows and 35cm between rows to get population of 432 seeds per plot. Thinning was carried out at 19 and 22 DAS to provide an established population of 216 seeds per plot i.e. 15 plants m^{-2}.

3.3.4.2 Photoperiod control and crop protection:

All glasshouses received natural daylight, and because bambara groundnut is a short day plant for pod filling, the day length was controlled by covering the crop stands in each plot with a black polythene screen at 2000 and uncovering at 0800 to maintain 12h photoperiod from 21 DAS until 113 DAS.

To protect the crops from red spider mites (*Tetranychus cinnabarinus*) , biological pest control, *Phytoseiulus persimilis* was distributed at 26 DAS then weekly from 47 DAS until 96 DAS in all glasshouses.

3.3.4.3 Irrigation

All plots were irrigated weekly to field capacity using trickle irrigation system from 0 to 97 DAS (Table 3.1).

Table 3.1 Amounts of irrigation (mm) applied to each glasshouse at different dates (expressed in DAS) during the 2006 bambara groundnut glasshouse experiment.

	Temperature	**23±5°C**		**33±5°C**		
	G/house Number	**2**	**4**	**1**	**3**	**5**
	00	10	10	10	10	10
	04	10	10	10	10	10
	07	10	10	10	10	10
	12	07	07	10	10	10
	19	07	07	10	10	10
	22	10	10	10	10	10
	25	10	10	10	10	10
DAS	27	22	22	22	22	22
	34	25	25	25	25	25
	41	30	30	30	30	30
	48	30	30	30	30	30
	55	40	40	40	40	40
	62	40	40	40	40	40
	69	30	30	40	40	40
	76	30	30	40	40	40
	83	30	30	40	40	40
	91	20	20	30	30	30
	97	20	20	30	30	30
TOTAL		381	381	437	437	437

3.3.4.4 Measurements:

Developmental measurements

Every morning between 5 and 16 DAS, emerged seedlings were counted in the central five rows of each plot. Each emerged seedling was tagged to not be counted again. After 16 DAS, in each plot ten plants were randomly tagged and used for counting leaves, flowers and pods twice a week until 127 DAS.

Growth analysis

Every two weeks, 10 plants were collected randomly from each plot for eight sequential growth analyses. On every occasion leaves, flowers and pods were counted. The green leaf area of each plant was measured using LI-1300 Leaf Area Meter. Leaves, stems and pods were dried in the oven at 80^{o}C for 48h and weighed. The mean of 10 plants represent the value of a particular replicate.

For yield measurements, 40 plants were taken from the untouched central 3.6 m^2 of each plot. The plants were separated into leaves, pods and stems before drying them in the oven at 80^{o}C for 48h. Pod dry weight was used to calculate the yield. The harvest index was calculated as the fraction of pod dry weight to the total dry weight at harvest.

Gas exchange

Gas exchange measurements; photosynthesis and stomatal conductance were taken weekly by CIRAS 1 photosynthesis system, from 36 DAS until 113 DAS. All the measurements were taken between 1000 and 1500h.

Solar radiation

The incident solar radiation (S_i) and the transmitted solar radiation (S_t) below the canopy were measured from 20 DAS until final harvest. The measurements were taken hourly every day between 0800 and 2000 at 10 minute intervals using a data logger (Campbell Scientific CR10). Intercepted daily radiation was calculated as the hourly difference between Si and St. The sum of the daily values of the intercepted radiation represented the cumulative intercepted radiation.

In addition, daily maximum and minimum temperature, saturation vapour pressure deficit and amount of applied water were recorded for each plot.

Data analysis

Growth analysis data were analysed statistically using the software package Genstat 12th edition (Lawes Agriculture Trust, Rothamsted Experimental Station, UK) by analysis of variance. The difference was considered significant when probability was equal or less than 0.05. Because the raw data of gas exchange results were not provided, the data were not analysed statistically, but are presented for comparison with 2007 and 2008 results

3.3.5 Experiment 2: Effect of high and low temperature on growth and development of bambara groundnut landraces experiencing late season drought

3.3.5.1Soil preparation and seed selection

At the end of March 2007 the soil was irrigated and dug over by using spades to create a fine seedbed. All glasshouses were fertilized with the equivalent of 105 kg ha^{-1} nitrogen and 325 kg ha^{-1} potassium.

Before sowing, seeds selected from a previous experiment conducted in TCRU glasshouses in 2001 were germinated in controlled environment room at 28 ^{o}C to check their viability. Two landraces were sown on 12 April 2007, S19-3 and Uniswa Red, at depth 5cm (one seed for each hole) at space of 10 cm between each hole and 35cm between rows. As in the previous season, there were 12 rows in each plot and 36 holes in each row to give a total of 432 plants per plot. This gave a total of 864 plants in each house. At 26 DAS the crops were thinned to 18 plants per row (approximately 20cm between plants) which again gave an established population of 15 plants m^{-2}

All glasshouses were irrigated using sprinklers for three weeks after sowing and then trickle tapes were fixed in all glasshouses to provide water lost each week by evaporation. Drought was imposed at 77 DAS. The amount of applied water is shown in Table 3.2.

3.3.5.2 Experimental design

The experiment was designed as a split plot (two bambara groundnut landraces and two different temperatures). Each landrace was allocated randomly in each house (Figure 3.2), with three replicate houses at 33^{o}C ±5 (GH1,GH3,GH4) and two at 23^{o}C ±5 (GH2,GH5)

Despite applying irrigation, soil moisture content in GH1S was unable to reach field capacity during the initial irrigation period. The reasons for this failure are not known, but this plot was excluded from all the measurements.

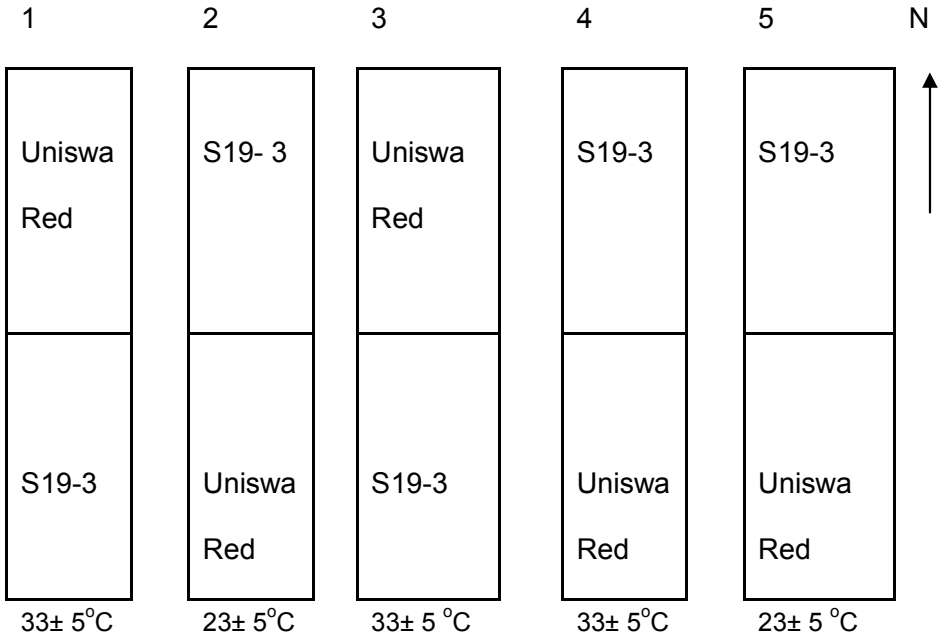

Figure 3.2 Design for the bambara groundnut experiment 2007 in the TCRU glasshouses.

3.3.5.3 Measurements

Soil moisture content

Soil moisture content was measured throughout the growing season. Azam-Ali and Squire (2002) indicated that determining the gravimetric soil moisture is a sufficient basis to determine how much water is available for use by plants if the soil moisture release characteristics of any particular soil type are known. Water content can be expressed on a mass basis as $W = mw / ms$

Where *mw* and *ms* are the masses of soil water and dry solids respectively, but because determining the gravimetric soil moisture is a destructive method, it was not possible to use it to monitor the soil moisture content during the whole season. However, it was measured three times during the season (48 DAS, 76 DAS, and 168 DAS) to calibrate the equipment used to monitor soil moisture content (PR2 probe Delta T Devices).

Soil moisture content in the soil profile was monitored in all plots using a PR2 probe. Measurements were taken weekly starting from 55 DAS. Unfortunately the PR2 broke down after 119 DAS and the measurements were stopped between 119 and 168 DAS. The PR2 probe measures the soil moisture at 10cm, 20cm, 30cm, 40cm, 60cm, and 100cm. Each plot has four access tubes. The average of the access tube readings represents the mean amount of water in the soil for each plot. When an electric current is applied to the Profile Probe it creates a 100MHz signal (similar to FM radio).The signal is applied to pairs of stainless steel rings which transmit an electromagnetic field extending about 100mm into the soil. The field passes easily through the access tube walls, but less easily through any air gaps. The water content of the soil surrounding the rings dominates its

permittivity. The permittivity of the soil has a strong influence on the applied field resulting in a stable voltage output that act as a simple, sensitive measure of soil moisture content.

Table 3.2 Irrigation (mm) applied to each plot during the 2007 glasshouse experiment.

	Temperature	**23±5°C**				**33±5°C**				
	G/house									
	Number	**2**		**5**		**1**	**3**		**4**	
DAS	**Plot**	**N**	**S**	**N**	**S**	**N**	**N**	**S**	**N**	**S**
0		5	5	5	5	5	5	5	5	5
5		5	5	5	5	5	5	5	5	5
8		5	5	5	5	5	5	5	5	5
12		5	5	5	5	5	5	5	5	5
15		10	10	10	10	10	10	10	10	10
19		10	10	10	10	10	10	10	10	10
22		15	15	15	15	15	15	15	15	15
28		10	10	10	10	10	10	10	10	10
29		10	10	10	10	10	10	10	10	10
33		10	10	10	10	10	10	10	10	10
36		10	10	10	10	10	10	10	10	10
40		10	10	10	10	10	10	10	10	10
43		10	10	10	10	10	10	10	10	10
47		10	10	10	10	10	10	10	10	10
50		10	10	10	10	10	10	10	10	10
54		10	10	10	10	10	10	10	10	10
60		10	20	10	30	10	20	30	10	40
64		10	20	10	30	10	20	30	10	40
68		10	20	10	30	10	20	30	10	40
71		10	20	10	30	10	20	30	10	40
74		10	20	10	30	10	20	30	10	40
77		20	20	20	20	20	20	20	20	20
	Total	215	265	215	315	215	265	315	215	365

Evapotranspiration (E_t)

Weekly evapotranspiration was measured as $Et = (\theta tp + \theta Ip) - \theta tc$ (Mwale, 2005)

Where θtp is the profile water content (mm) measured the previous week, θIp is the amount of irrigation (mm) applied the previous week, and θtc is the current water content of the profile.

Soil surface evaporation (E_s)

Evaporation was measured from weight change of soil in small plastic trays (Squire, 1990; (Kijoji, 2003; Mwale, 2005). Soil was dug over carefully between rows to make a hole exactly the same dimension as the tray. Two trays (18cm ×18cm and 9cm deep) were filled with soil, weighed (Ti) and placed at the level of the soil surface between adjacent plant rows in each plot after 24 h from the last irrigation. The weight of the trays was measured every day for 10 days to ensure that all the evaporation from the soil surface was included.

The E_s was calculated as : $Es = 10(Ti - Tf) / At$, where Ti is the initial weight of the tray with soil in grams, Tf is the final weight of the tray with soil in grams , and At is the tray surface area (cm^2).

Leaf relative water content (LRWC)

LRWC measurements were carried out weekly from 62 until 147 DAS. The technique was based on the method used by Brown (1991). Every week, 10 plants were chosen randomly, three middle green leaflets of leaves were collected randomly from each plant

and punched with a steel borer (1cm in diameter). Every three leaflet represent one replicate. The fresh weight of the leaf discs (Fw) was taken immediately after coring, then the discs were immediately put in a Petri dish containing distilled water for 6 h. A 60 W bulb was used to illuminate the Petri dishes to keep the discs as close to their light compensation point as possible (Brown, 1991). After 6 h the leaf discs were dried carefully with tissue paper and the hydrated weight (Hw) was obtained immediately. The leaf discs were put in an oven at 80^{o}C for 48h to obtain the dry weight (Dw). RWC was calculated as: $LRWC = (FW - DW)/(HW - DW) * 100$

Growth analysis

Sequential growth analysis, at two to three weeks intervals, was carried out on 10 plants per plot on nine occasions through the season. Plants to be harvested were pre-determined to avoid selecting plants adjacent to previous harvesting locations. No plants were taken from the two edge rows in each plot to avoid edge effects, nor the central areas where light interception measurements and final harvest were taking place. Leaves and pods were counted at growth analysis. Leaf, stem, and pod dry weights were obtained after oven-drying at 80^{o}C for 48h. The mean of 10 plants for each variable were taken as a representative value for a particular replicate. Green leaf area and stem area was measured by using LI-1300 Leaf Area Meter.

Thirty plants were sampled from the central area in each plot at the final harvest, 10 were used for the usual growth analysis, and then the other 20 were used to measure the shoot weight and calculate the harvest index as the fraction of pod weight to shoot weight.

Final harvest date was estimated from visual observation of leaf senescence and pod maturity. Pods were oven dried for one week at 35^{o}C and shelled to get the fraction of shell/pod weight. All the remaining plants in each plot (between 165-167 DAS) were harvested, and the pod weight of each plant was obtained to see the yield performance of each plant.

Developmental measurements

Seedlings were counted daily, in three rows for each plot, from emergence until thinning. A seedling was considered emerged when the first two leaves were visible on the soil surface. By thinning to exactly to 18 plants per row, a final population of 15 plant m^{-2} was achieved in all plots at establishment (26 DAS). After 26 DAS six plants were randomly selected and tagged in each plot and used for counting leaves and flowers twice a week until 151 DAS.

Gas exchange

Gas exchange measurements started at 56 DAS and continued until 144 DAS. Ten plants were tagged and the measurements were made weekly on four plants from the 10 tagged plants. The measurements were made on the middle leaflet of one leaf from each plant. In case of the death or damage of the tagged leaf, a new leaflet was tagged to carry on the measurements. Because it was not possible to finish all the glasshouse measurements on the same day, the measurements were carried out on two days every week. A Portable Gas Exchange Fluorescence System (GFS-3000- WALZ) was used to measure stomatal conductance, photosynthesis, transpiration and sub-stomatal CO_2. All the measurements were taken between 0900-1500. The leaf was placed in the chamber for an average of

three to four minutes before any readings were taken, and the first reading could be recorded after five minutes. The cuvette CO_2 concentration was maintained at 380 μL L^{-1} by mixing incoming air with a source of CO_2.

Solar radiation

The method described in 2006 experiment (3.3.4.4) was followed to measure solar radiation from the first day of sowing until the final harvest.

Water use efficiency

Water use efficiency (WUE g kg^{-1}) was determined from the regression of cumulative above dry matter (gm^{-2}) against cumulative transpiration (mm).

Radiation use efficiency

Radiation use efficiency (g MJ^{-1}) was determined from the regression between the accumulated above ground dry matter (g m^{-2}) and the total cumulative intercepted radiation (MJ m^{-2}) estimated from the above and below canopy solarimeters.

Thermal time required for leaf production

Thermal time required for leaf production was computed as the inverse of the slope of the regression between leaf number against the cumulative thermal time (Mwale, 2005)

Data analysis

Emergence, establishment, gas exchange parameters and the growth analysis were analysed following the procedures used in 2006 (3.3.4.4).

3.3.6 Experiment 3: Effect of high and low temperature on growth and development of bambara groundnut landraces experiencing early season drought.

The same protocols established in 2006 and 2007 were repeated in 2008 (April to September) with the same experimental design and different temperature and landrace allocation in the glasshouses; two landraces (Uniswa Red and S19-3, sown on 17 April) and two temperatures (33^{o}C ±5; GH1, GH2, GH5 and 23^{o}C; ±5, GH3, GH4) Figure (3.3). Soil moisture was non-limiting with irrigation applied weekly or twice a week to field capacity until 29 DAS where the drought was imposed. A CIRAS-1 portable photosynthesis system was used to measure gas exchange because of technical faults in GFS-3000- WALZ. Table (3.3) shows the amount of irrigation applied to each plot.

Assessments of growth and development were as described in 3.3.6.3

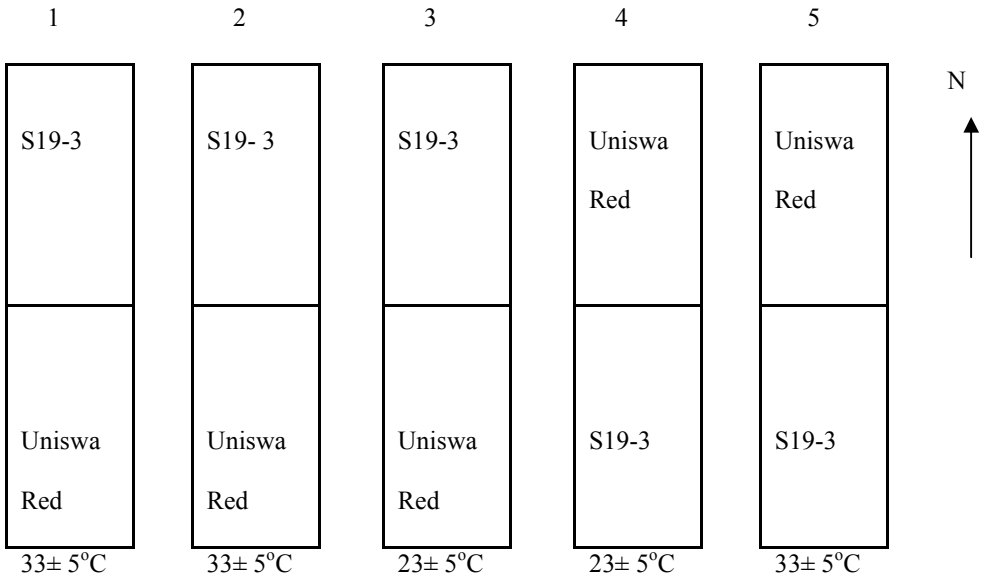

Figure 3.3 Design for the bambara groundnut experiment 2008 in the TCRU glasshouses

Table 3.3 Amounts of irrigation (mm) applied to each plot at different dates (expressed in days after sowing, DAS) during the 2008 bambara groundnut glasshouse experiment.

	Temperature	23±5°C				33±5°C					
	G/house Number	3		4		1		2		5	
DAS	plot	N	S	N	S	N	S	N	S	N	S
0		15	15	15	15	15	15	15	15	15	15
1		15	15	15	15	15	15	15	15	15	15
4		20	20	20	20	20	20	20	20	20	20
7		10	10	5	10	15	15	15	15	5	10
12		10	10	0	10	15	10	10	10	0	10
16		20	20	10	20	20	10	10	15	5	15
19		10	15	0	15	10	0	0	0	0	10
22		25	25	15	25	10	10	10	10	10	20
26		5	15	0	15	15	0	0	0	0	5
29		20	20	20	20	25	25	25	25	25	25
	Total	150	165	100	165	160	120	120	125	95	145

3.4 Field experiments.

This study was part of the experiments run by the BAMLINK project at its partner location in Botswana. The measurements were conducted at Notwane Farm, Botswana College of Agriculture, Gaborone, Botswana (Plate 3.3).

3.4.1 Experiment 1: The interaction of temperature, late season drought and photoperiod on growth and development of bambara groundnut landraces.

3.4.1.1 Field site, experiment preparation and sowing

The field experiment (2007-2008) was designed to examine six landraces with two water regimes; rainfed and irrigated, and five dates of sowing December 21, January 4, January 18, February 1 and February 18. The experiment was designed as split-split plot (sowing dates as the main plot, water treatment on the sub-plots, and landraces on the sub-sub plots).

Plots were hand-planted**,** and, **e**xcept for the December 21 sowing in which two seeds were planted per station, in all other sowing dates, seeds were sown at double spacing (10cm) along the row and all plots were thinned to 1 plant per station at 25 DAS.

The soil was dug over and levelled to make a fine seedbed . The gross sub-sub plot size was 4 x 3.5 m that gave 320 plants per sub-subplot. At 25 DAS the plants were thinned to 20 plants in each row to give a plant population of 160 plants in each subplot with an equivalent plant density of 11 plant m^{-2}.

Adjacent sub-sub plots were spaced 1m apart, in addition to two border rows of plants to minimize lateral infiltration of water from irrigated plots to moisture stressed plots. At planting, all plots were fertilized with a basal application of single super phosphate at the rate of 25 kg P ha^{-1}.

For the first date of sowing only, two Neutron probe access tubes were installed in each sub-subplot, one between rows and one within the row. All plots were irrigated using trickle tape. The irrigation for the rainfed treatment was terminated at 63 DAS.

3.4.1.2 Plant materials

In the field experiments, six landraces were examined. The author was responsible for measurements on two landraces, Uniswa Red and DipC. Originally, the field experiment had been designed to be carried out on the same landraces used in the glasshouses. However, the lack of S19-3 seeds in Botswana meant that this landrace had to be replaced by Dip C, which originates from a similar environment in Botswana to S19-3 which comes from Namibia. The seeds used in this experiment were collected from previous BAMLINK field experiments in Botswana.

3.4.1.3 Crop protection

To control seedling disease, seeds were dressed with Captan (N-trichloromethylthio-4-cyclohexane-1, 2-dicarboximide) applied at the rate of 250g of product per 100 kg of seed. A nematicide (Nemacu**r** 10 GR, Bayer AG) was applied at the rate of 1.5 g m^{-1} of row, at planting, to prevent root-knot nematode infestation. Cutworm bait (KOMBAT) was applied along the rows at emergence. Plots were hand weeded during the season. To

control insects and foliar pathogens, plants were sprayed with the insecticide Malathion 50% EC (*S*-1,2-bis(ethoxycarbonyl)ethyl *O,O*-dimethyl phosphorodithioate) and the systemic fungicide Eria (triazole, binzimidazole) , using a knapsack sprayer. Earthing-up was done after 100 % flowering.

Plate 3.3 Experimental site, Notwane Farm, Botswana College of Agriculture 2007-2008

3.4.1.4 Irrigation

All plots were irrigated from first day of sowing to 90% of field capacity using a trickle irrigation system which was terminated from the rainfed treatment at 63 DAS (Table 3.4).

Table 3.4 Amounts of irrigation (mm) applied to each sowing date at different dates (expressed in days after sowing, DAS) during the 2008-2009 bambara groundnut field experiment.

Date of sowing		1	2	3	4	5
	0					21
	1					
	2					
	3					
	4					
	6					21
	11					14
	14				21	
	15			18	21	
	16			18		
DAS	26			21		
	27			21		
	29		18			
	30		18			
	34			21		
	39			14		14
	40		21			
	41		21			
	43	18				
	44	18				
	48	18				
	53	21				
	54	21			21	
	55	21				
	67	14				
	81		21			
	95	21				
	Total	152	99	113	63	70

3.4.1.5 Measurements

Soil moisture content

Soil moisture content in the soil profile was monitored using Neutron Probe (CPN, Model 503). Measurements were taken weekly starting from 40 DAS. The Neutron probe measured the soil moisture at 0-20, 20-40, 40-60, 60-80, 80-100 and 100-120 cm. The sum of readings represents the total amount of water in each location. Each sub-subplot had two access tubes; the average of readings represents the mean amount of water in each subplot.

Before starting the measurements, the probe was calibrated for the experimental site at the same soil type. For each depth measured by the probe, two soil samples were taken to measure soil moisture content by gravimetric method. Readings of Neutron probe as count number were converted to count ratio which equals count number divided by the standard count(standard count is the average of 4 or five neutron probe readings taken after placing the probe over the access tube preparing to be lowered into the hole). A graph was plotted to get a linear regression between count ratio and gravimetric soil moisture to calculate the coefficients a and b, which are slope and intercept respectively. Water content

(V %) = a×count ratio +b

Soil surface evaporation

Evaporation was measured from weight changes of soil in small cans (Mwale, 2005; Gharres, 1990; Squire, 1990; Villalobos and Fereres, 1990 and Azam-Ali, 1983). A soil

sample was taken after each irrigation or rain event (W1) and another sample before the next irrigation (W2), the difference in weight between W1 and W2 gives the amount of water evaporated from the soil surface in grams which can be converted to mm as:

.

Density of water = 1 gcm^{-3}

Density= Weight/volume,

1 g cm^{-3}(density of water) = water lost by gram/volume

Volume= gram lost of water /1 g cm^{-3}

(Depth*area) = g (lost water)

Depth= g(lost water)/ area

Evapotranspiration *(E_t)*

Weekly evapotranspiration was measured as described in section.3.3.6.3

Emergence

Seedlings were counted daily in the central 4 rows for each subplot from emergence until thinning. A seedling was considered emerged when the first two leaves were visible on the soil surface.

Leaf Relative water content (LRWC)

LRWC measurements were carried out weekly from 52 DAS. The technique was based on a method used by Equiza *et al*., (2001). Every week, three plants were chosen randomly from each sub-subplot, one leaf was collected from each plant, the three leaflets of each

leaf were cut to get 3 cm segment from the central portion of the leaf. The fresh weight of the leaf segments (Fw) was taken immediately after cutting, then the segments were put in a Petri dish containing distilled water overnight under the fluorescent light to keep the samples as close as possible to their CO_2 compensation point (Brown, 1991). Next morning the leaf segments were dried carefully with tissue paper and the hydrated weight (Hw) was obtained immediately .The leaves were put in an oven at 80^{o}C for 48h to obtain the dry weight (Dw). RWC was calculated as: $RWC = (FW - DW)/(HW - DW) * 100$

Growth analysis

Sequential growth analysis at 25, 45, 60, 89, 105, 112, 120 DAS was carried out on 5 adjacent plants per sub-subplot, which were taken from one row. Every growth analysis was carried out on a different row. No plants were collected from the two end rows in each subplot to avoid edge effects, nor the central area where final harvest was taking place. Leaves and pods were counted at each growth analysis. Leaf, stem and pod dry weight was obtained after oven-drying at 80^{o}C for 48h. Green leaf area and stem area were measured by using Delta-T leaf area meter.

For the yield measurement, the plants from the two central rows were collected (3.4m^2) and the number of plants was recorded, pods were air-dried on a greenhouse floor for at least one week and weighed. The seeds were shelled and weighed to get the shelling percentage from the equation:

Shelling percentage = (Seed weight / pod weight) x 100

Stomatal conductance

Stomatal conductance measurements started at 56 DAS. Five plants were tagged and the measurements were made weekly on the middle fully expanded leaflet on each plant. All the measured leaves were at the top of the canopy and fully exposed to sunlight. All the measurements were carried out between 1200-1400h.

Climatic factors

Air temperature, relative humidity, rainfall, wind speed and solar radiation were recorded hourly by an automatic weather station installed at the experimental site.

Data Analysis

All the results were analysed statistically using the software package Genstat 12th edition (Lawes Agriculture Trust, Rothamsted Experimental Station, UK) by analysis of variance, the difference was considered significant when probability was equal or less than 0.05.

3.4.2 Experiment 2. The interaction of temperature, early season drought and photoperiod on growth and development of bambara groundnut landraces.

The same protocol of the previous field experiment was repeated in 2008-2009 with more Neutron Probe access tubes installed in date 1, date 3 and date 5 plots. Sowing dates; December 9, December 24, January 5, January 18 and February 1. The experiment was

designed as split-split plot (sowing Irrigation was terminated from the rainfed treatment at 30 DAS (Table 3.5).

The growth analysis of the first sowing was omitted because a hail storm caused severe damage to the leaves of the crop (Plate 3.4). The first growth analysis of date 5 was also omitted because the plants were too small for measurement.

Stomatal conductance was measured fortnightly using technique described in 3.4.1.5

Table 3.5 Amounts of irrigation (mm) applied to each sowing date during the 2008-2009 bambara groundnut field experiment

Date of sowing		1	2	3	4	5
	0					
	1		36	15	15	
	2	18	18			10
	8	18				
	7		18			
	9	18				
	14	36	15			
DAS	15	18				
	21	18				
	28	15				
	32					15
	38				15	
	47				15	
	51			15		
	59					10
	60			15		
	65		15			
	74		15		10	
	78					10
	79	15				
	86					10
	87			10		
	99					6
	101					10
	106			10		
	TOTAL	156	117	55	55	71

Plate 3.4 The effect of the hailstorm on bambara groundnut (first date of sowing) 2008-2009 experiment (6/1/2008).

4 Results

4.1 Glasshouses experiments

The results from the glasshouses experiments will be presented in this section. The results show the data collected from the three growing seasons; 2006, 2007, and 2008, except for some measurements that were taken only in 2007 and 2008, or the data from 2006 were not provided.

4.1.1 Temperature and saturation deficit

Figure 4.1 shows the maximum and the minimum temperatures during the three growing seasons. At the high temperature treatment (HT), temperature ranged between 25 and 41^{o}C, and between 18 to 35^{o}C at the low temperature. Saturation deficit (SD) ranged between 1.2 and 2.9 k pa at the high temperature and between 0.5 to 1 k pa at the low temperature (LT) throughout the three growing seasons (Figure 4.2).

4.1.2 Soil moisture

Figure 4.3 shows the seasonal trends of the total soil moisture in each treatment in the 2007 and the 2008 experiments (no soil moisture measurements were taken in 2006). All the treatments in both seasons showed a steady decrease in soil moisture content. In the 2007 experiment, soil moisture of S19-3 at low temperature had the highest moisture content, with soil moisture decreasing from 282mm at 62 DAS to 249mm at 168 DAS. In 2008, Uniswa Red at the low temperature had the highest soil moisture content throughout the season, while S19-3 at the high temperature had the lowest.

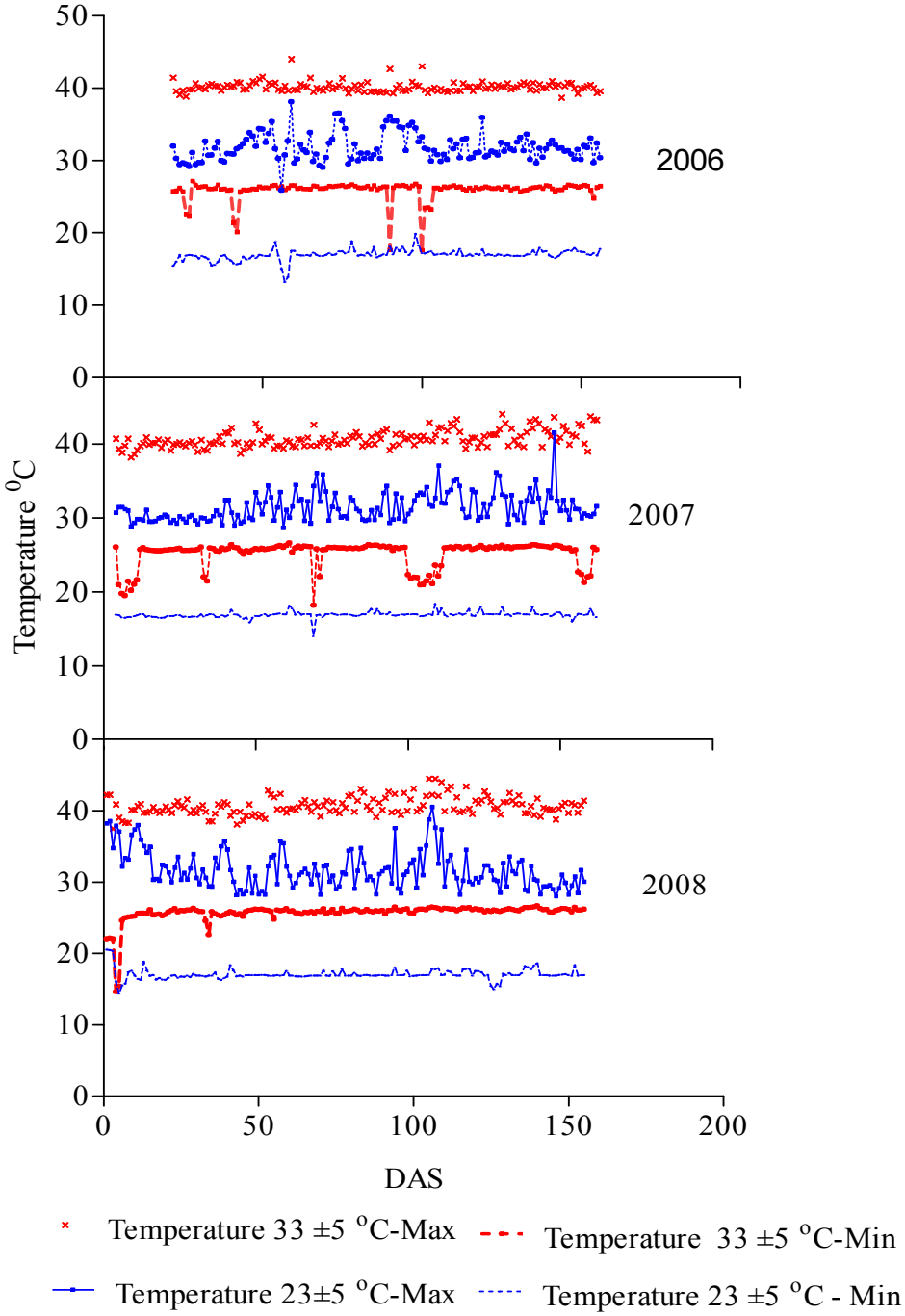

Figure 4.1 Maximum and minimum temperature in the Tropical Crops Research Unit (TCRU) glasshouses, during the experiment of two bambara groundnut landraces (Uniswa Red and S19-3) grown in 2006, 2007 and 2008.

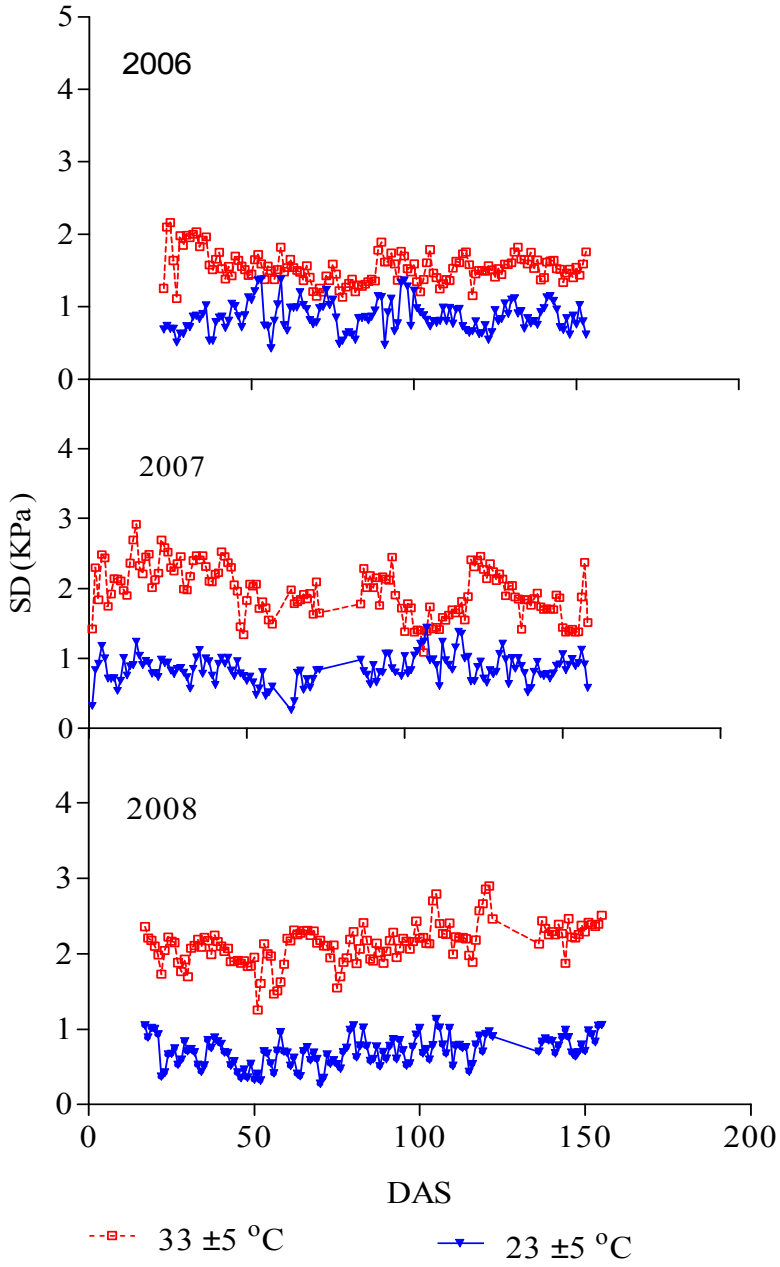

Figure 4.2 Saturation deficit (SD) in the Tropical Crops Research Unit (TCRU) glasshouses, during the experiment of two bambara groundnut landraces (Uniswa Red and S19-3) grown in 2006, 2007 and 2008.

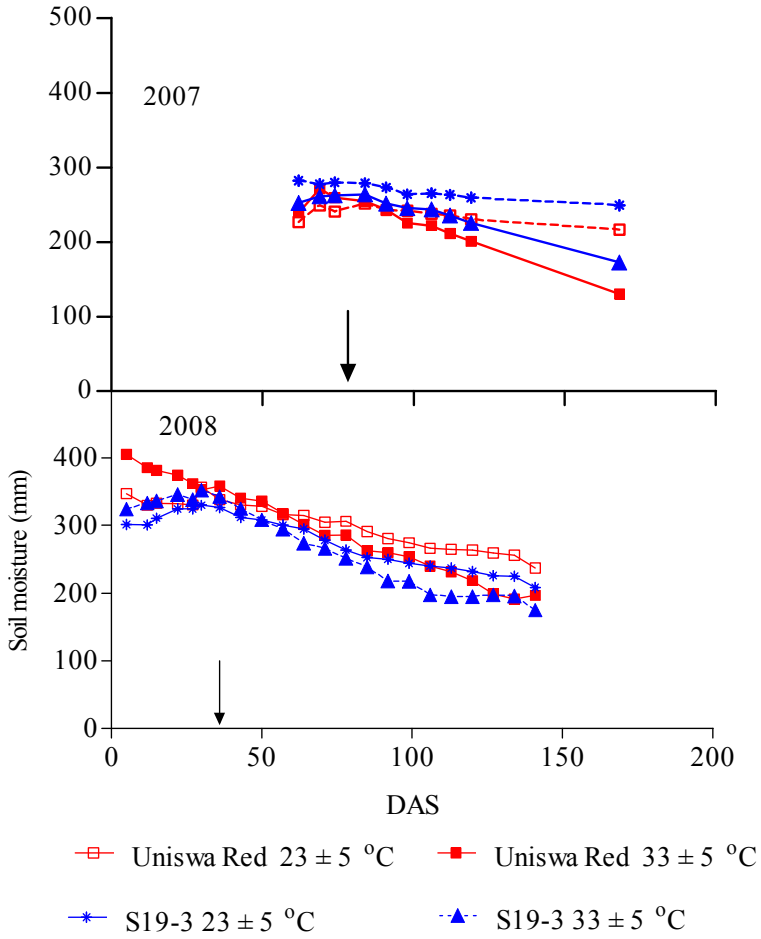

Figure 4.3 Changes in the mean soil moisture content (mm) per treatment throughout the soil profile in the TCRU glasshouses during the experiment of two bambara groundnut landraces (Uniswa Red and S19-3) grown in 2007 and 2008. The arrows indicate the time when drought was imposed.

4.1.3 Growth and development

4.1.3.1 Emergence

In 2007, Uniswa Red at the high and low temperature emerged at similar times, between 10-11 DAS, while S19-3 at the high temperature emerged sooner (9 DAS), but only started emergence at 12 DAS at the low temperature. In 2008, both landraces emerged earlier at the high temperature (9 DAS) than the low temperature (12 DAS) (Table 4.1).

The highest establishment (88.8%) was reached by S19-3 at the high temperature in 2007. In 2008, at the high temperature, Uniswa Red and S19-3 had the same establishment (87%), while S19-3 at the low temperature had a lower establishment than Uniswa Red. (Table 4.1). The statistical analysis showed no significant difference in crop establishment in either growth season.

Table 4.1 Emergence and establishment of two landraces of bambara groundnut landraces grown in the TCRU glasshouses in 2007 and 2008

Treatment	Landrace	Days to emergence		Establishment %	
		2007	**2008**	**2007**	**2008**
33^{o}C	Uniswa Red	10	9	73.2	97.7
33^{o}C	S19-3	9	9	88.8	92.6
23^{o}C	Uniswa Red	11	12	71.7	73.1
23^{o}C	S19-3	12	12	85.3	63.4

Establishment

2007

	df	*SED*
*Temperature*Landrace*	3.97	14.5 ^{ns}

Except when comparing means with the same level(s) of temperature
SED= 15.15, df= 2

2008

	df	*SED*
*Temperature*Landrace*	2.89	12.86

Except when comparing means with the same level(s) of temperature
SED= 16.36, df=2

4.1.3.2 Leaf appearance

Figure 4.4 shows the number of leaves per plant (every three leaflets were counted as one leaf) plotted against days after sowing for the three seasons. Uniswa Red at the high temperature produced the most leaves in all three glasshouse experiments. Both landraces produced fewer leaves at the low temperature than the high temperature. Throughout the three seasons, and at both temperatures, leaf number of S19-3 started to decrease before Uniswa Red. The statistical analysis of 2007 results showed no significant difference between the landraces in terms of landraces and temperature interaction ($P > 0.05$) (Appendix 1). In 2008, the only significant interaction effect on leaf number ($P < 0.05$) was at 28 and 103 DAS (Table 1.4).

Relations between leaf number per plant and cumulative thermal time are shown in Figure 4.5. The landraces showed different responses to temperature in the two different temperature treatments. At the high temperature, the accumulated thermal time exceeded 3000°C^d , while at the low temperature was less than 2500 °C^d. However, the high cumulative thermal time at the high temperature was correlated to higher leaf number. The linear regression of leaf number against cumulative thermal time is presented in Figure 4.6. Throughout the three growing seasons, there were significant differences between the treatments ($p<0.01$). The landraces at LT had always slower leaf appearance rate (LAR) (Slopes) than the landraces at HT, which means the phyllochron of the landraces at the LT was higher than the phyllochron of the landraces at HT (Table 4.2).

4.1.3.3 Flower number

Figure 4.7 shows the relationship between flower number per plant and cumulative thermal time. Plants at the high temperature accumulated more thermal time than the plants at the low temperature before the start of flower production.

4.1.3.4 Pod number

Throughout the three growing seasons, Uniswa Red gave the fewest pods at the high temperature. The highest pod number (57.7) was produced by S19-3 at the high temperature in 2007 (Figure 4.8). In 2007 experiment; S19-3 at the low temperature initially had the most pods, but from 103 DAS S19-3 at the high temperature had the most pods, and difference increased with time until the end of the season (Figure 4.8). Statistical analysis of the three growing seasons showed no significant interaction effect of temperature and landraces on number of pods. (Appendix 1).

Figure 4.9 shows the thermal time accumulated against pod number. Throughout the three growing seasons, the landraces at the low temperature needed less thermal time to start producing pods.

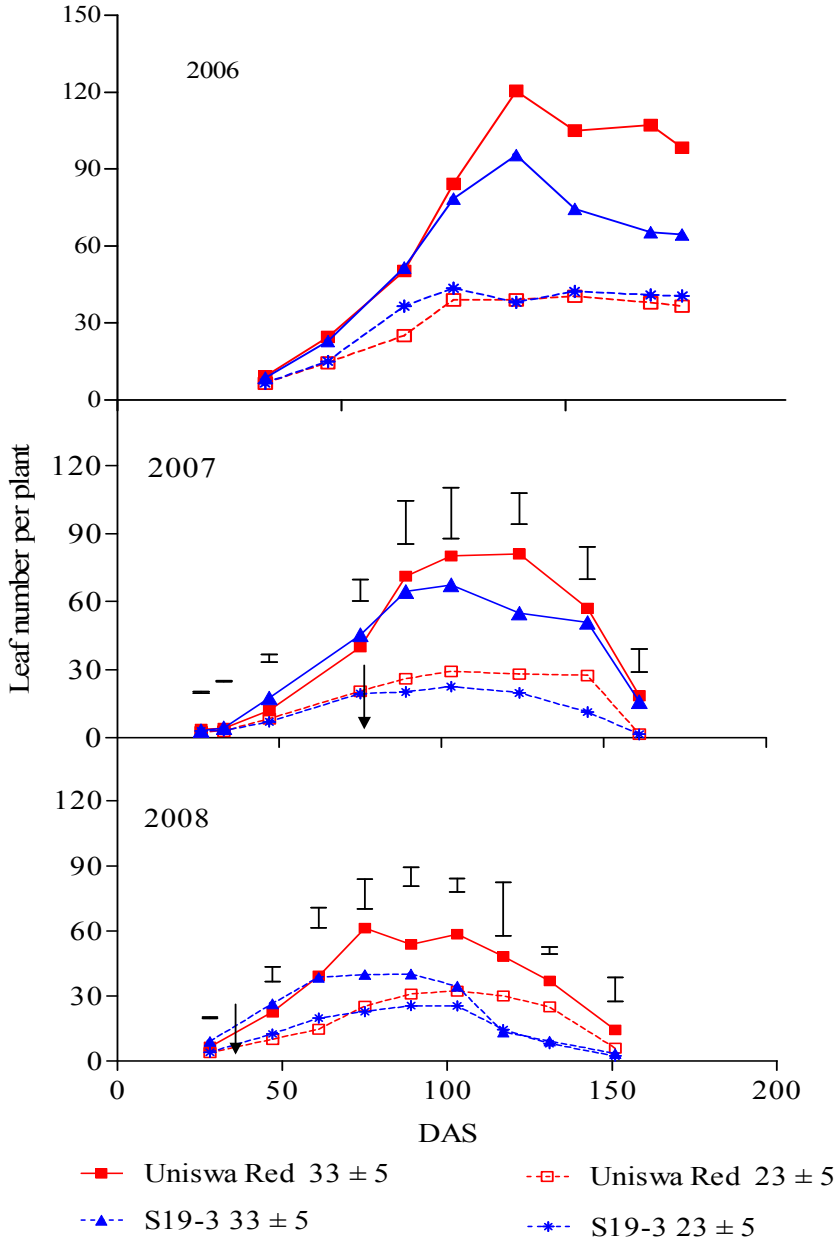

Figure 4.4 The effect of soil moisture and temperature on the leaf number of two landraces (Uniswa Red and S19-3) grown at low temperature (23±5ºC) and high temperature (33±5ºC) in the Tropical Crops Research Unit (TCRU) glasshouses in 2006, 2007 and 2008. The arrows indicate the time when drought was imposed and the vertical bars represent SED.

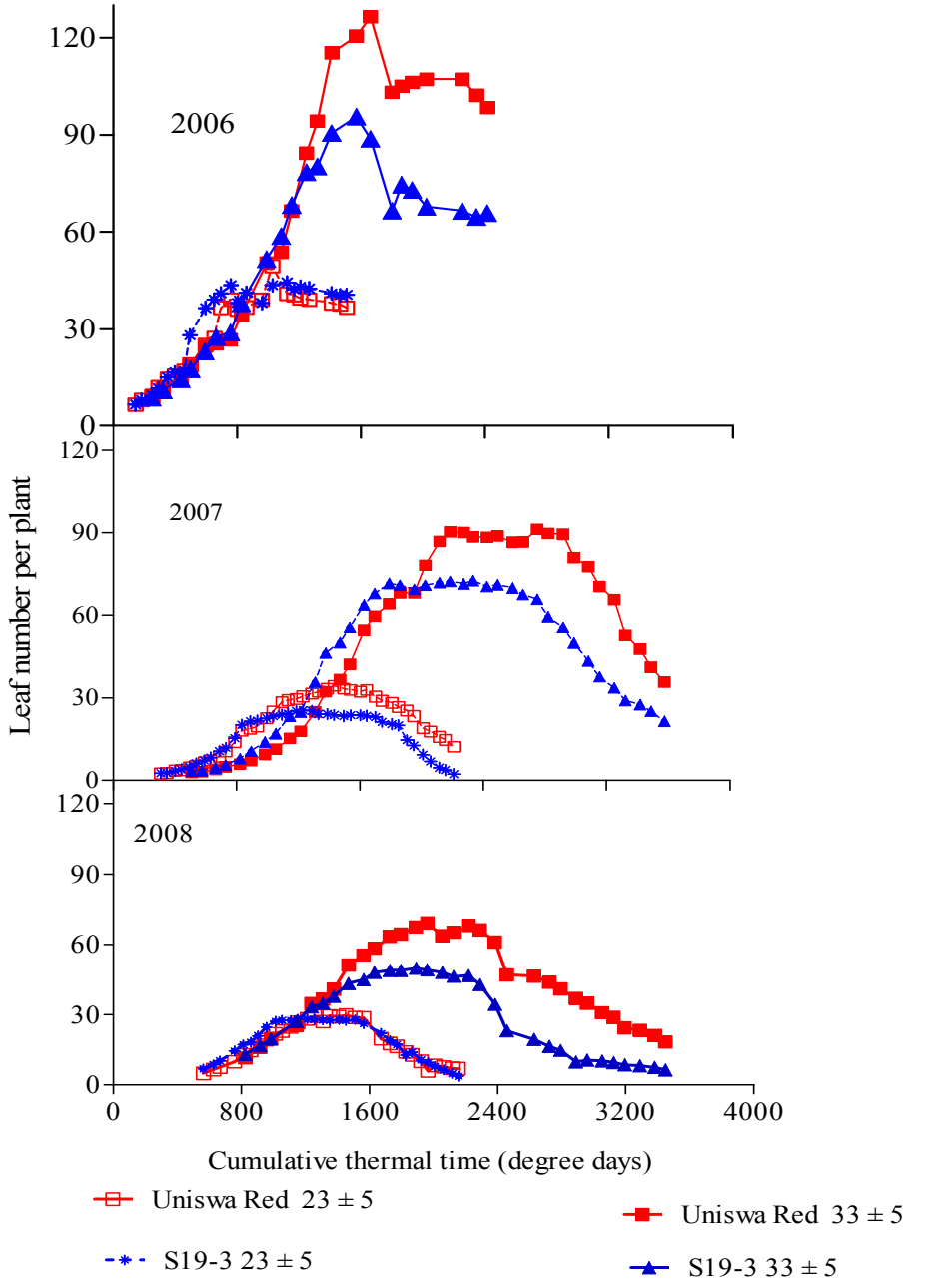

Figure 4.5 Leaf production against cumulative thermal time in two bambara groundnut landraces (Uniswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33±5 °C) in the Tropical Crops Research Unit (TCRU) glasshouses during the experiments in 2006, 2007 and 2008.

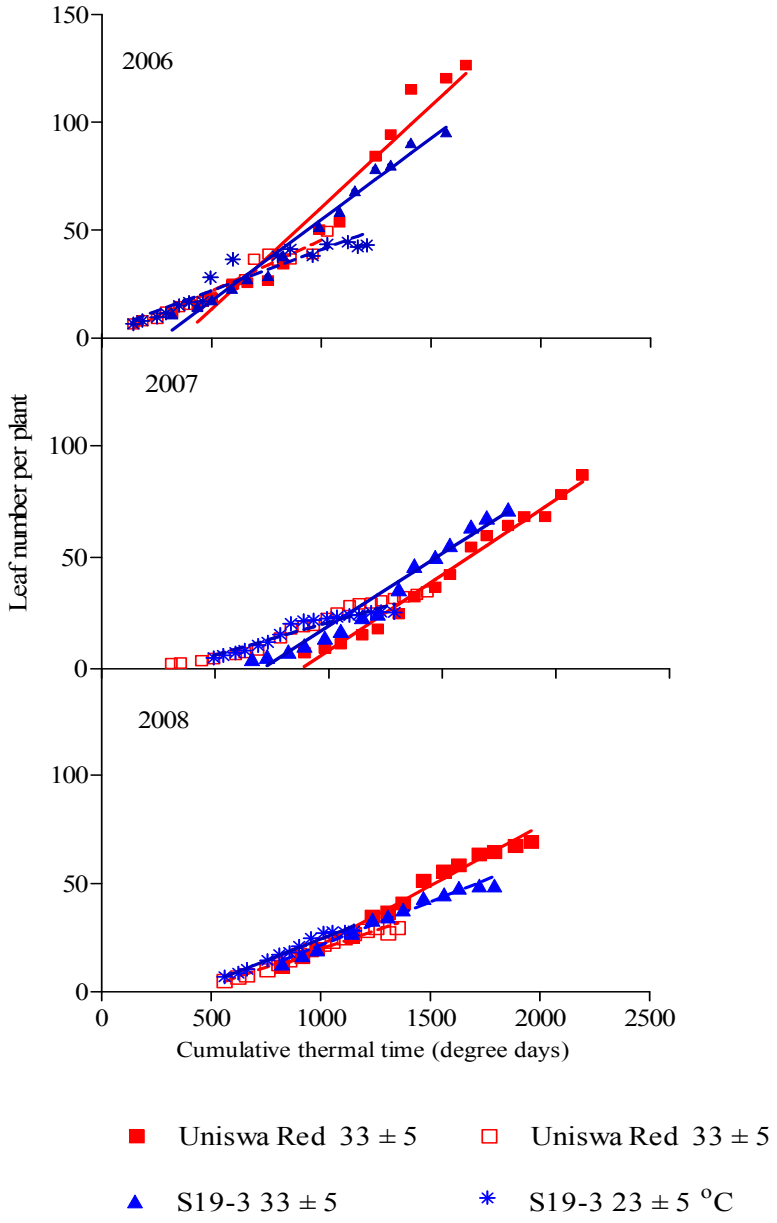

Figure 4.6 Regression of leaf number against cumulative thermal time (degree days) for two bambara groundnut landraces grown at low temperature (23 ±5°C) and high temperature (33 ±5°C) in the Tropical Crops Research Unit (TCRU) during the experiments in 2006, 2007 and 2008. For 2006, r^2=87.1, for 2007, r^2=90.1, for 2008, r^2= 94.2. Slopes and constants are presented in Table 4.2.

Table 4.2 Slopes, constants and phyllochron (ºC^{d} leaf^{-1}) obtained from the regression of leaf number per plant against cumulative thermal time (degree days) for two bambara groundnut landraces grown at low temperature (23 ±5 ºC) and high temperature (33 ±5 ºC) in the Tropical Crops Research Unit (TCRU) during the experiments in 2006, 2007 and 2008.

	Treatment	UNI 33±5 ˚C	UNI 23±5 ˚C	s19-3 33±5 ˚C	s19-3 23±5 ˚C
2006	Slope	0.094	0.045	0.075	0.034
	se	0.00555	0.00684	0.00585	0.00409
	Constant	-33.78	-2.13	-20.36	3.08
	se	4.95	4.54	5.14	3.02
	Phyllochron	10.63	22.22	13.33	29.41
2007	Slope	0.068	0.033	0.065	0.030
	se	0.00361	0.00374	0.0038	0.00314
	Constant	-59.52	-10.55	-45.86	-8.30
	se	4.10	3.50	4.03	2.89
	Phyllochron	14.70	30.30	15.38	33.33
2008	Slope	0.055	0.034	0.040	0.040
	se	0.00349	0.00377	0.00367	0.00314
	Constant	-33.57	-14.31	-18.60	-15.64
	se	3.58	3.50	3.81	2.80
	Phyllochron	18.18	29.41	25.00	25.00

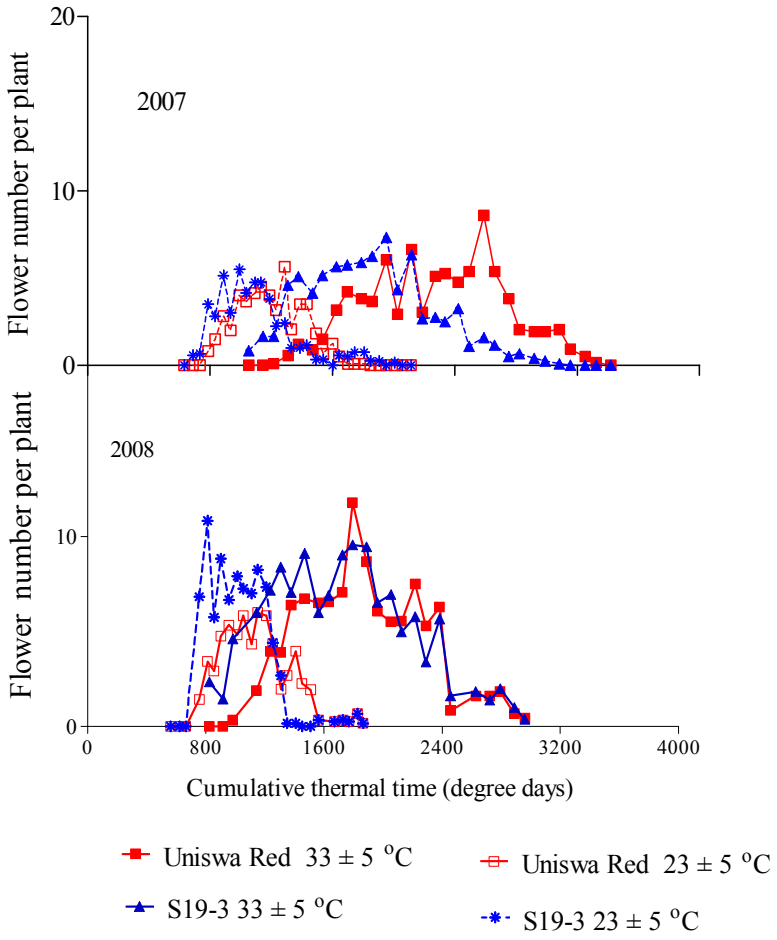

Figure 4.7 Flower number against cumulative thermal time in two bambara groundnut landraces (Uniswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33±5 °C) in the Tropical Crops Research Unit (TCRU) glasshouses during the experiments in 2007 and 2008.

4.1.3.5 Leaf area index

Development of leaf area index (LAI) in the bambara groundnut landraces in three growing seasons is presented in Figure 4.10. The highest peak of leaf area index (6.04) was reached in 2006 by Uniswa Red at the high temperature, while the maximum was 2.9 in 2008 (Figure 4.10). Throughout the three seasons, both landraces gave higher LAI at the high temperature than the low temperature. The statistical analysis showed no significant difference at most of the growth analyses occasions ($P > 0.05$). The absence of significant interaction effect means that the effect of the high temperature stress and the low temperature stress was not enough to show a significant difference between the four treatments, the other reason of not finding significant interaction effect might be because the very similar performance of the landraces at the same temperature. Furthermore, the landraces responded to temperature differently, but they responded to drought in a similar way. In 2006 at HT, both landraces had the same rate of increase in LAI until 89 DAS when the increase in LAI between 89DAS and 103 was higher for Uniswa Red. Both landraces reduced LAI with drought. Although both landraces accumulated the same amount of thermal time at the same temperature, Uniswa Red had higher leaf area index throughout the seasons. That was related to the high leaf number Uniswa Red had at HT since LAI is correlated with leaf number. (Figure 4.11)

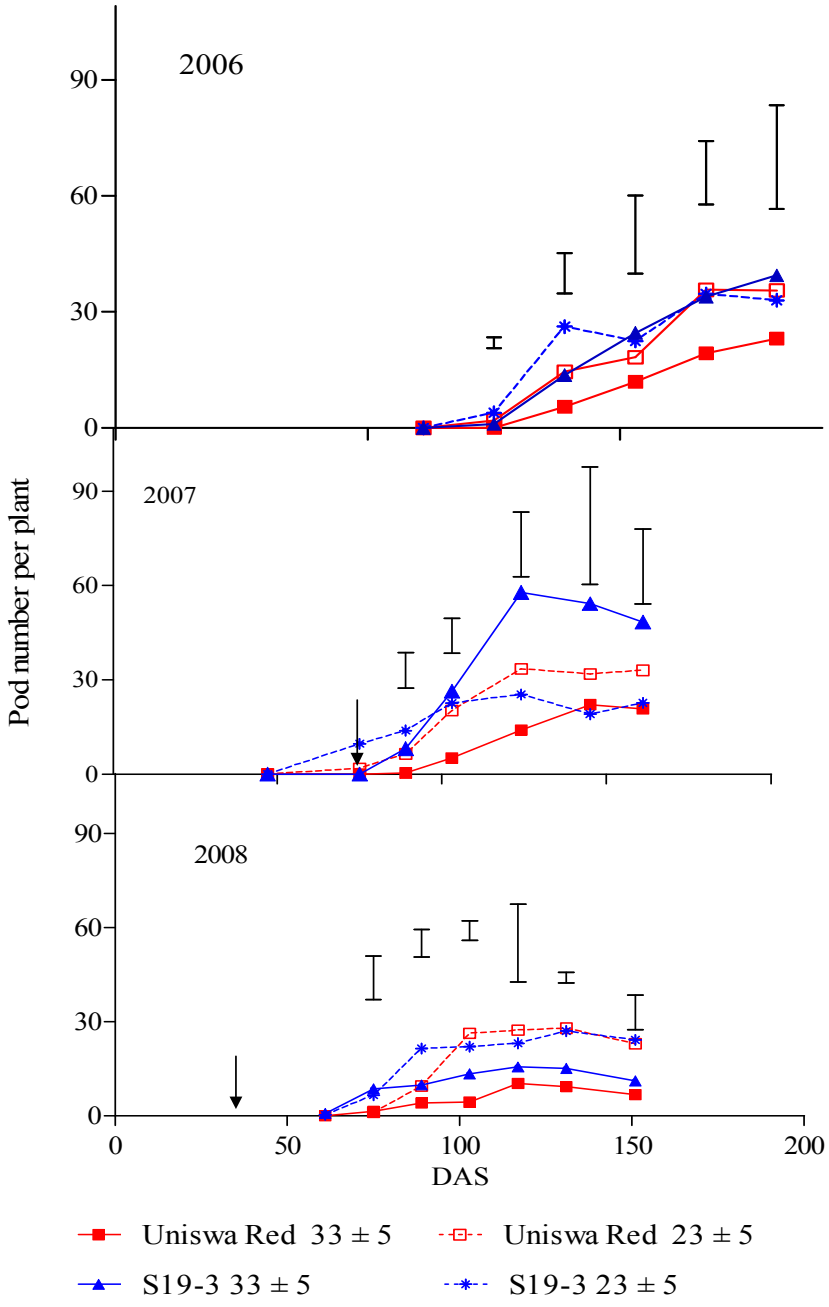

Figure 4.8 The effect of soil moisture and temperature on pod number of two bambara groundnut landraces (Uniswa Red and S19-3) grown in the Tropical Crops Research Unit (TCRU) glasshouses in 2006, 2007 and 2008. The arrows indicate the time when drought was imposed and the vertical bars represent SED.

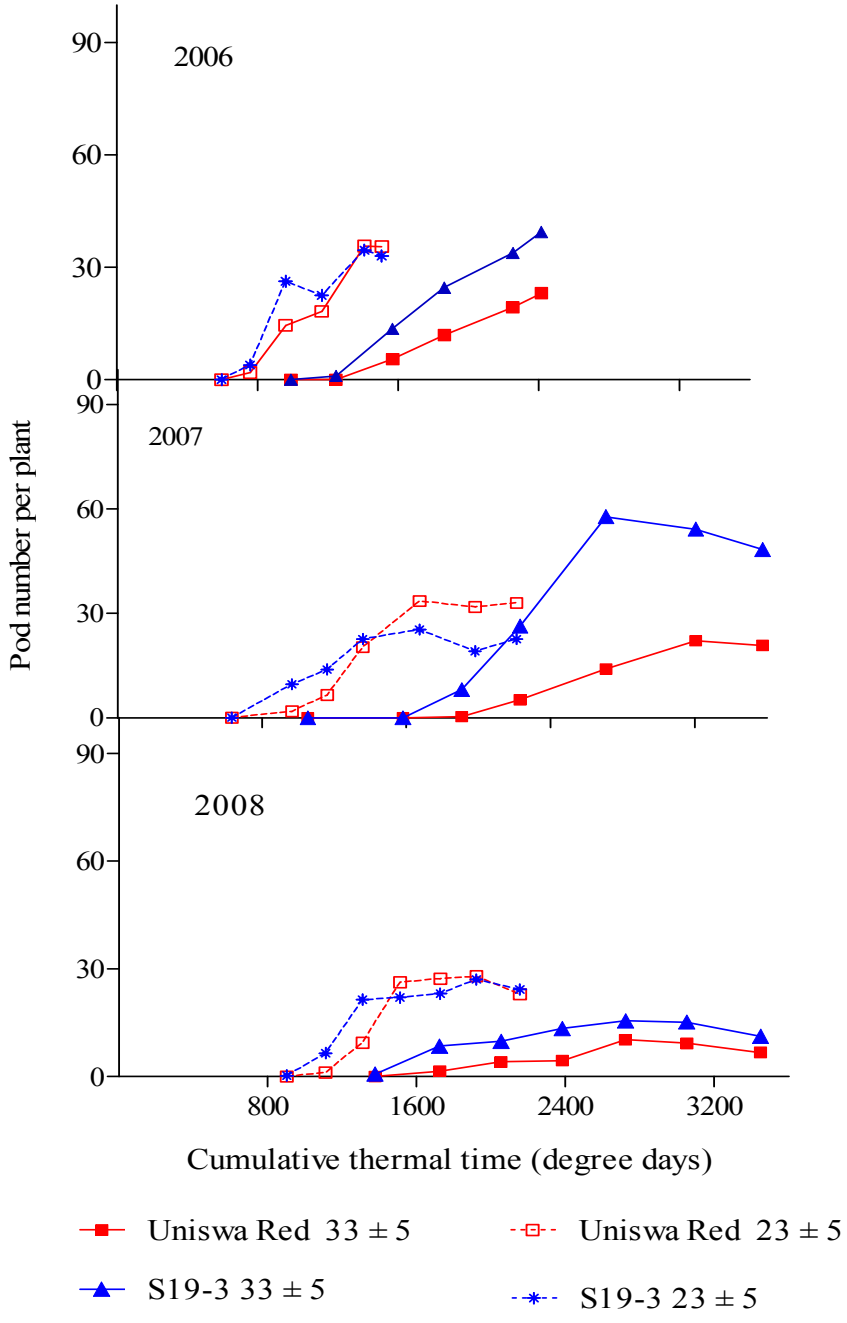

Figure 4.9 Pod number against cumulative thermal time in two bambara groundnut landraces (Uniswa Red and S19-3) grown at low temperature (23± 5oC) and high temperature (33±5 ^{o}C) in the TCRU glasshouses experiments in 2006, 2007 and 2008.

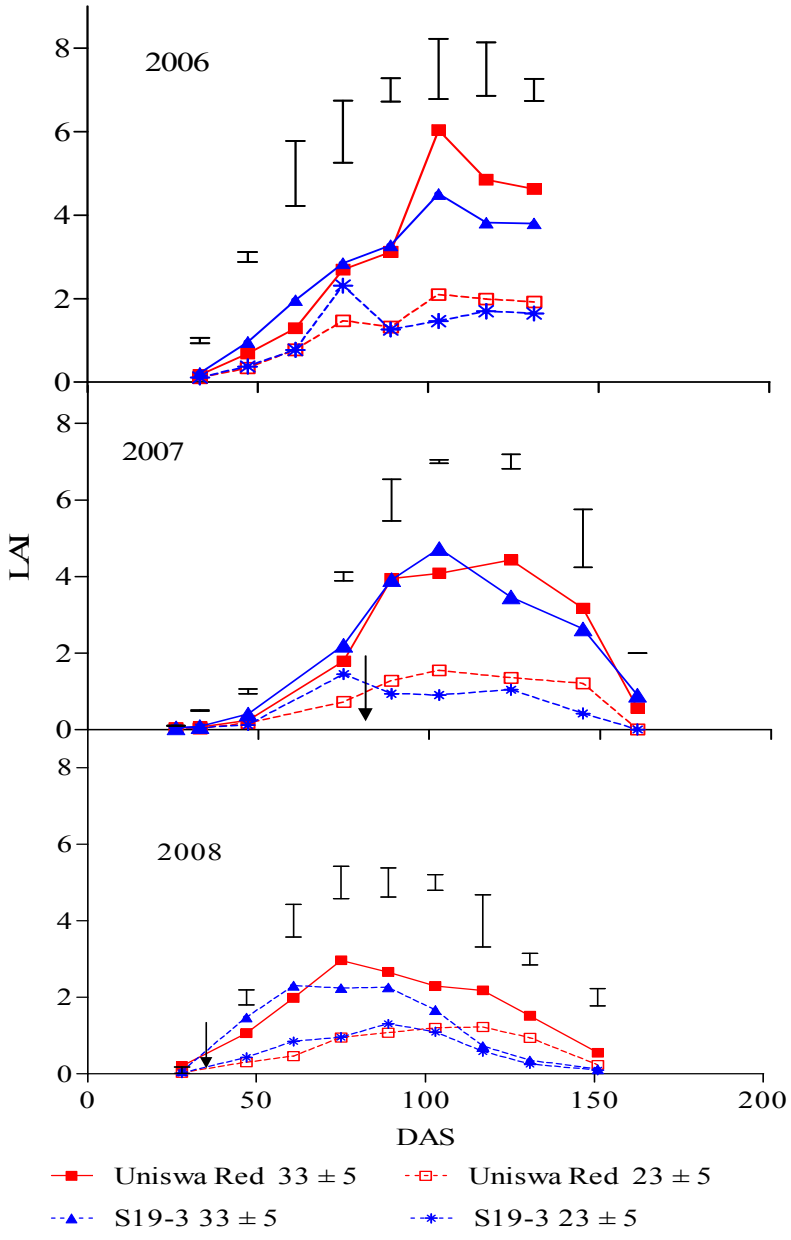

Figure 4.10 The effect of soil moisture and temperature on leaf area index of two landraces (Uiswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33±5 °C) in the TCRU glasshouses in 2006, 2007 and 2008. The arrows indicate the time when drought was imposed and the vertical bars represent SED.

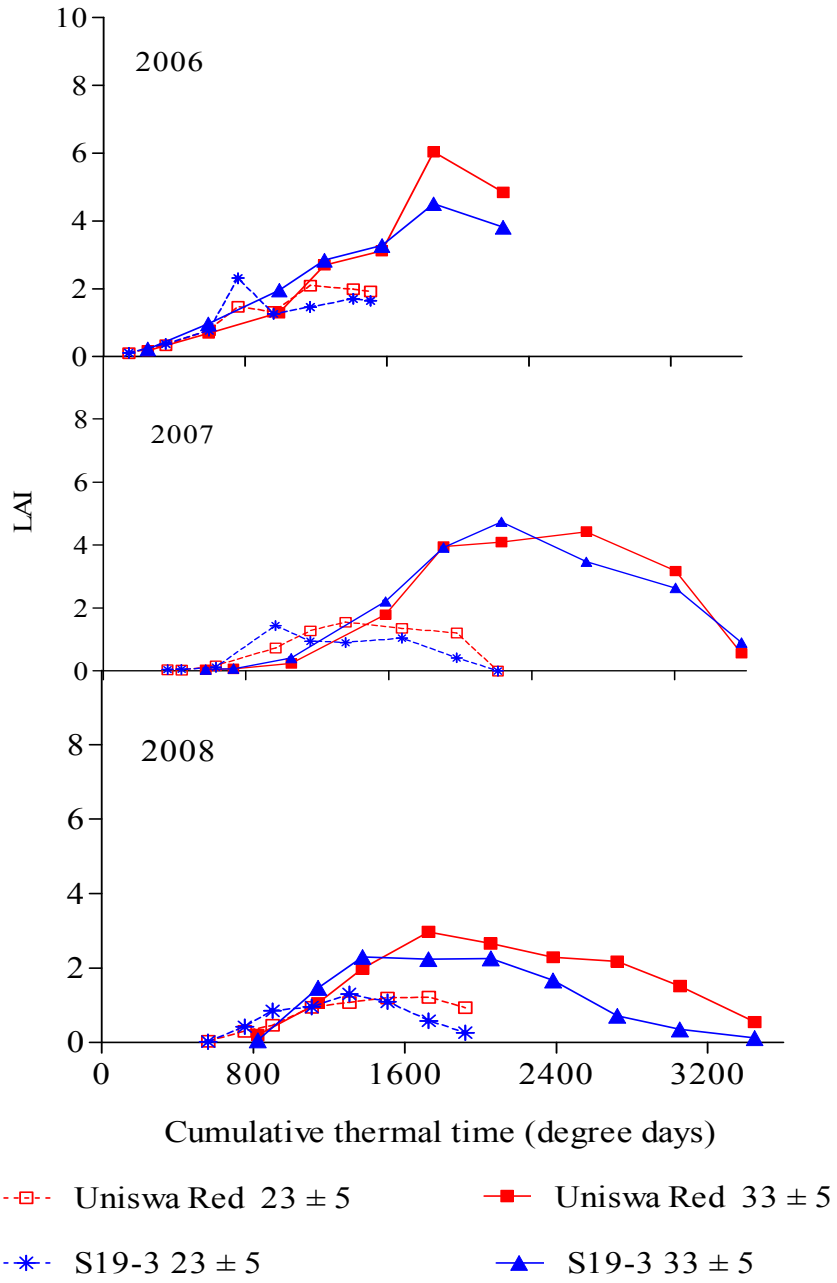

Figure 4.11 Leaf area index (LAI) against cumulative thermal time in two bambara groundnut landraces (Uniswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33±5 °C) in the Tropical Crops Research Unit (TCRU) glasshouses during the experiments in 2006, 2007 and 2008.

4.1.3.6 Specific leaf area

Changes in specific leaf area (SLA) for three growing seasons of S19-3 and Uniswa Red are represented in Figure 4.12. In 2007, SLA started to decline at both high and low temperature from 89 DAS. There was no clear pattern of SLA in 2006 and 2008.

The interaction effect of temperature and landrace was significant ($P<0.05$) in one occasion in 2007 at 26 DAS, and at 75 and 89 DAS in 2008. There was no significant interaction effect of temperature and landraces on SLA in 2006, while the temperature had a significant effect ($p<0.05$) at 89, 117 and 113 DAS. The absence of the interaction effect in 2006, when water was not a limiting factor, and the presence of the interaction effect in 2007 and 2008, can explain how the drought interacts with temperature stress and effect the development of the crops. Both landraces had higher SLA at the high temperature treatment, and this is clearer in 2007, but does not exist in 2008 growing season. Figure 4.13 shows SLA against cumulative thermal time for the three growing season. High SLA was always associated with more accumulated thermal units at HT.

4.1.3.7 Total dry matter

Total dry matter (TDM) accumulation throughout the three growing seasons for each landrace and each treatment is shown in Figure 4.14. In the first and second growing seasons, both landraces had a similar pattern of TDM production. The amount of TDM accumulated in the low temperature was always lower than the accumulation at the high temperature. In the third growing season, both landraces produced more at the high temperature, until 117 DAS where the amount of TDM started to decline (Figure 4.14). The statistical analysis showed no significant interaction effect in the three growing

seasons ($P<0.05$). Figure 4.15 shows that the landraces accumulated less thermal time units also accumulated les dry matter.

4.1.3.8 Leaf dry matter

In 2006, the accumulation of leaf dry matter (LDM) at the high temperature was significantly higher than at the low temperature at 75, 117 and 131 DAS ($P<0.05$) (Figure 4.16). No significant interaction effects of temperature and landraces were found. In 2007, Uniswa Red accumulated significantly less LDM than S19-3 ($P<0.05$) at 33 DAS. At 103 DAS, S19-3 had more LDM than Uniswa Red at 33^{o}C, but not at 23^{o}C ($P<0.05$). From 124 DAS, LDM of S19-3 started to decline hence this difference disappeared. (Appendix 1, Table 1.2). In 2008, the interaction significant effect existed only at 131 DAS (Appendix 1). LDM production decreased towards the end of the growth seasons in both temperatures and landraces (Figure 4.16).

4.1.3.9 Pod dry matter

Figure 4.17 presents the pod dry matter (PDM) production during the growing seasons for both landraces and temperatures. In 2006, PDM production at the high temperature was significantly lower than the production at the low temperature treatment at 117 and 131 DAS ($P<0.05$). The total PDM production of S19-3 at both temperatures was higher than the production by Uniswa Red at 75 DAS. In 2007, temperature, landrace and the interaction were significant at 75 DAS ($P<0.05$). No significant difference existed for the rest of the season. The only significant difference in 2008 was due to temperature at 124 DAS ($P<0.05$) (Appendix 1). Figure 4.18 shows the non linear regression of PDM against TDM. At LT and throughout the three years of growing, pod production was always

associated with dry matter production, but for HT, this positive relation was not clear in 2008. That is presented in table 4.3 where the slopes (B values) became negative.

4.1.4 Yield and yield components

Tables 4.4: a, b and c show yield, shelling percentage and harvest index (HI) of the three growing seasons. The highest yield (306 g m^{-2}) was produced by S19-3 in 2007 at the high temperature, while the lowest was given by Uniswa Red in 2008 at the high temperature (31.1 g m^{-2})

In 2006, S19-3 produced similar pod yield at both temperatureS while Uniswa Red yield was reduced fourfold at high temperature compared to low (P=0.02). No significant effects were found in 2007. In 2008, yield was significantly lower at the high temperature than at the low temperature ($P<0.05$) with both landraces responding similarly.
A statistical analysis across 2007 and 2008 showed no significant effect, except for the difference between the total yield of 2007 and 2008 (P = 0.007).

Generally, shelling percentage (shell weight/pod weight x 100) was stable in 2007 and 2008 growing seasons, especially for Uniswa Red, while HI was highly reduced by drought in Uniswa Red at the low temperature and S19-3 at the high temperature

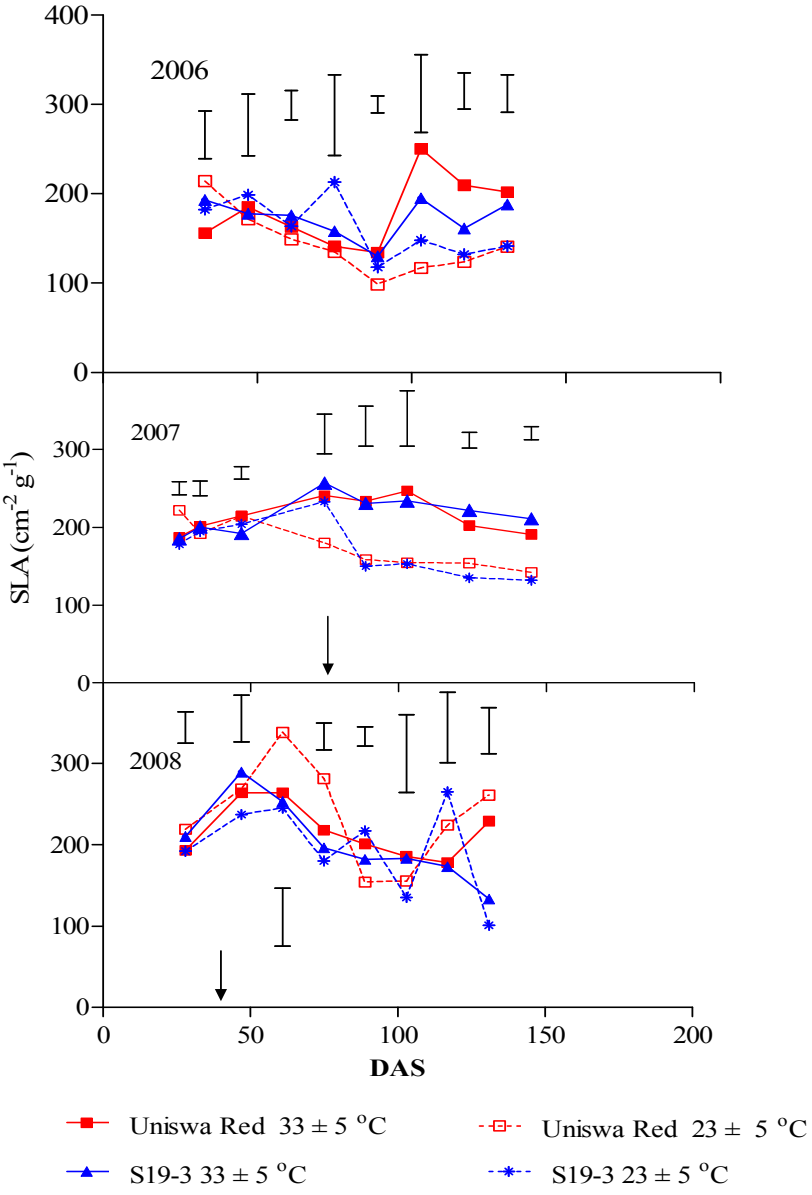

Figure 4.12 The effect of soil moisture and temperature on the specific leaf area of two bambara groundnut landraces (Uniswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33±5 °C) in the Tropical Crops Research Unit (TCRU) glasshouses in 2006, 2007 and 2008. The arrows indicate the time when drought was imposed and the vertical bars represent SED.

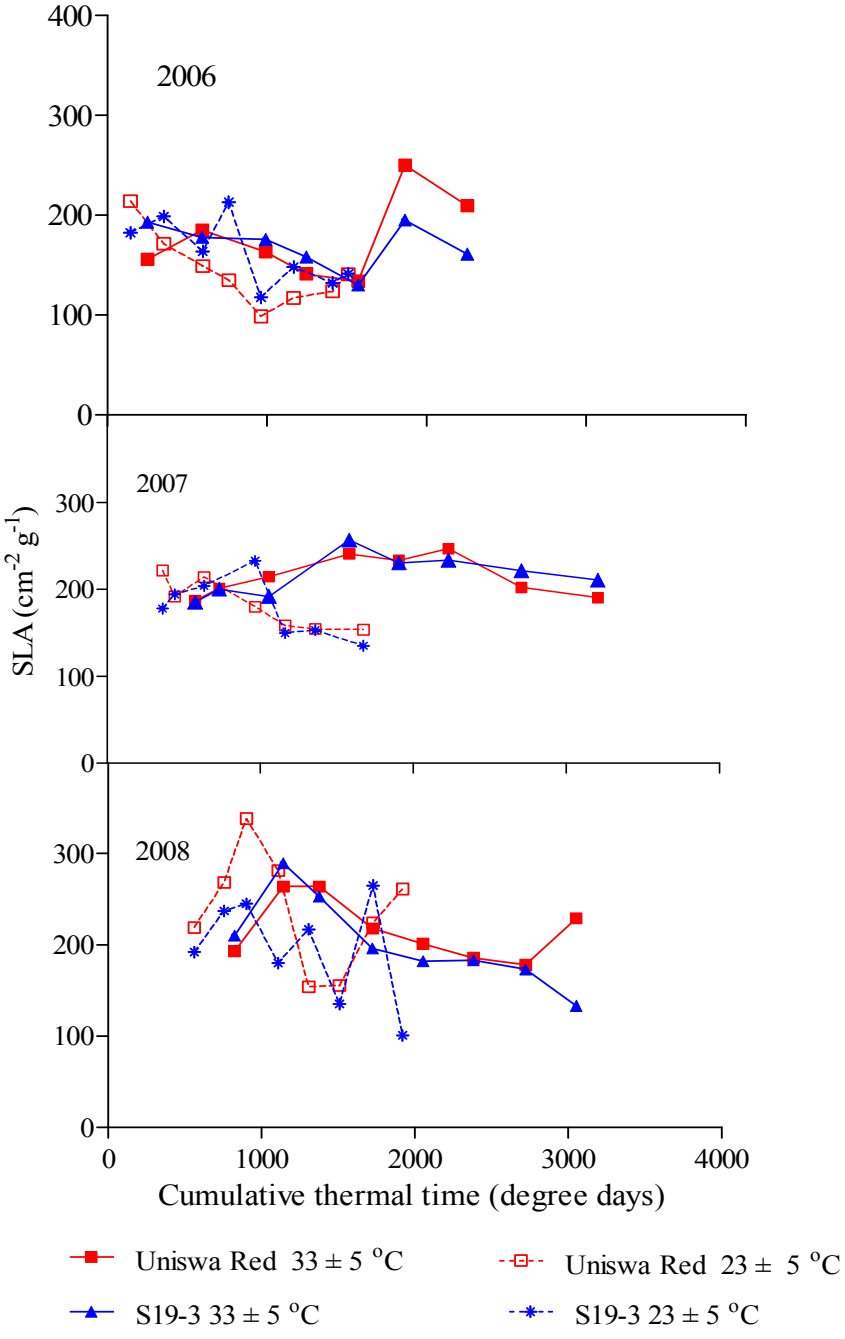

Figure 4.13 Specific leaf area against cumulative thermal time (degree days) in two bambara groundnut landraces (Uniswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33±5 °C) in the Tropical Crops Research Unit (TCRU) glasshouses in 2006, 2007 and 2008.

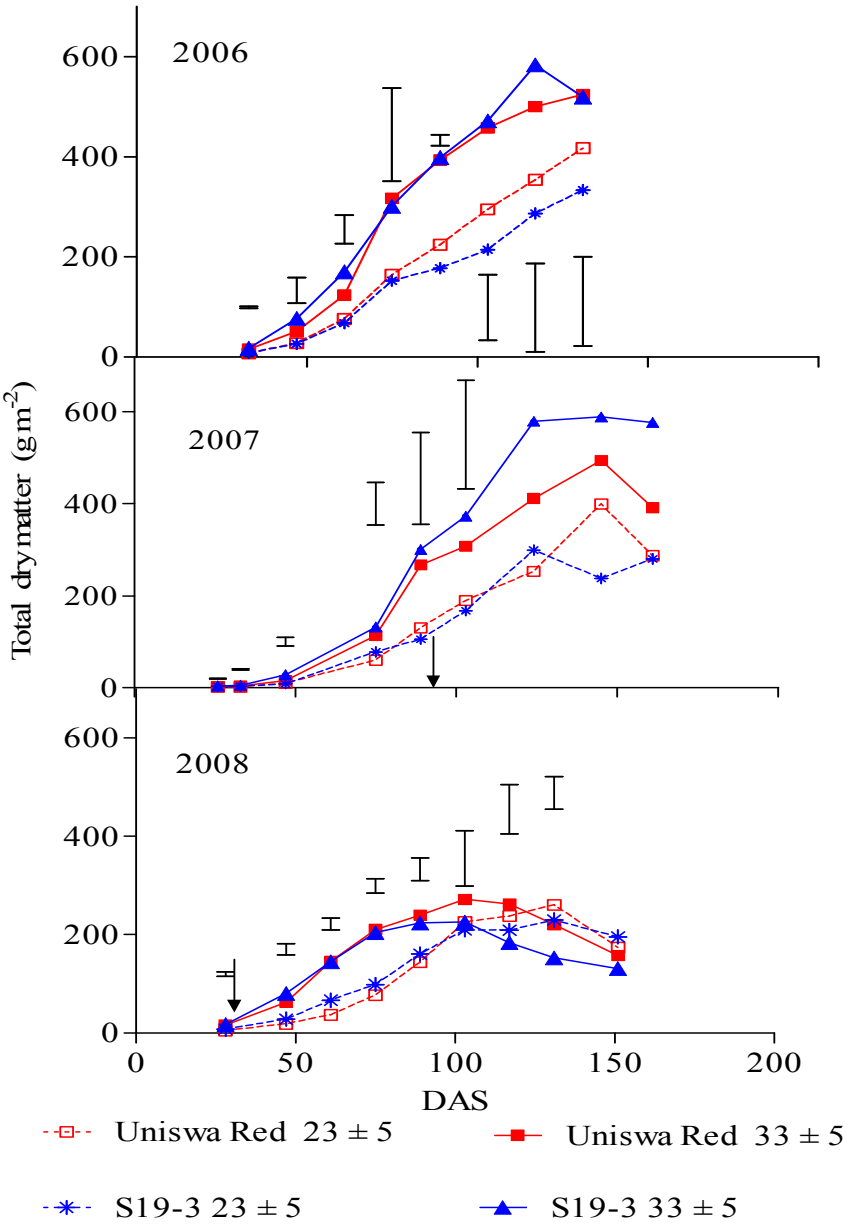

Figure 4.14 The effect of soil moisture and temperature on the total dry weight of two landraces (Uniswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33±5°C) in the Tropical Crops Research Unit (TCRU) glasshouses in 2006, 2007 and 2008. The arrows indicate the time when drought was imposed and the vertical bars represent SED.

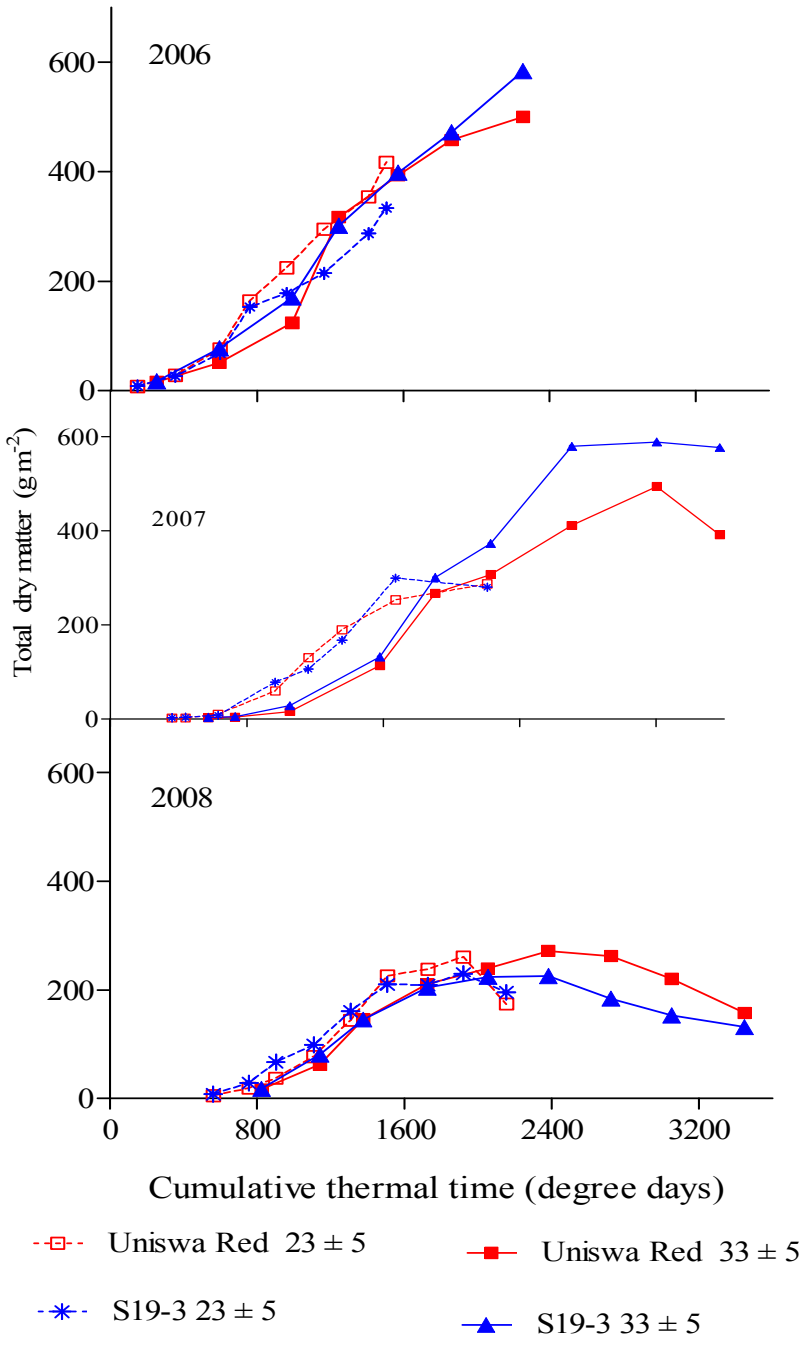

Figure 4.15 Total dry matter (g m^{-2}) against cumulative thermal time (degree days) in two bambara groundnut landraces (Uniswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33±5 °C) in the Tropical Crops Research Unit (TCRU) glasshouses in 2006, 2007 and 2008.

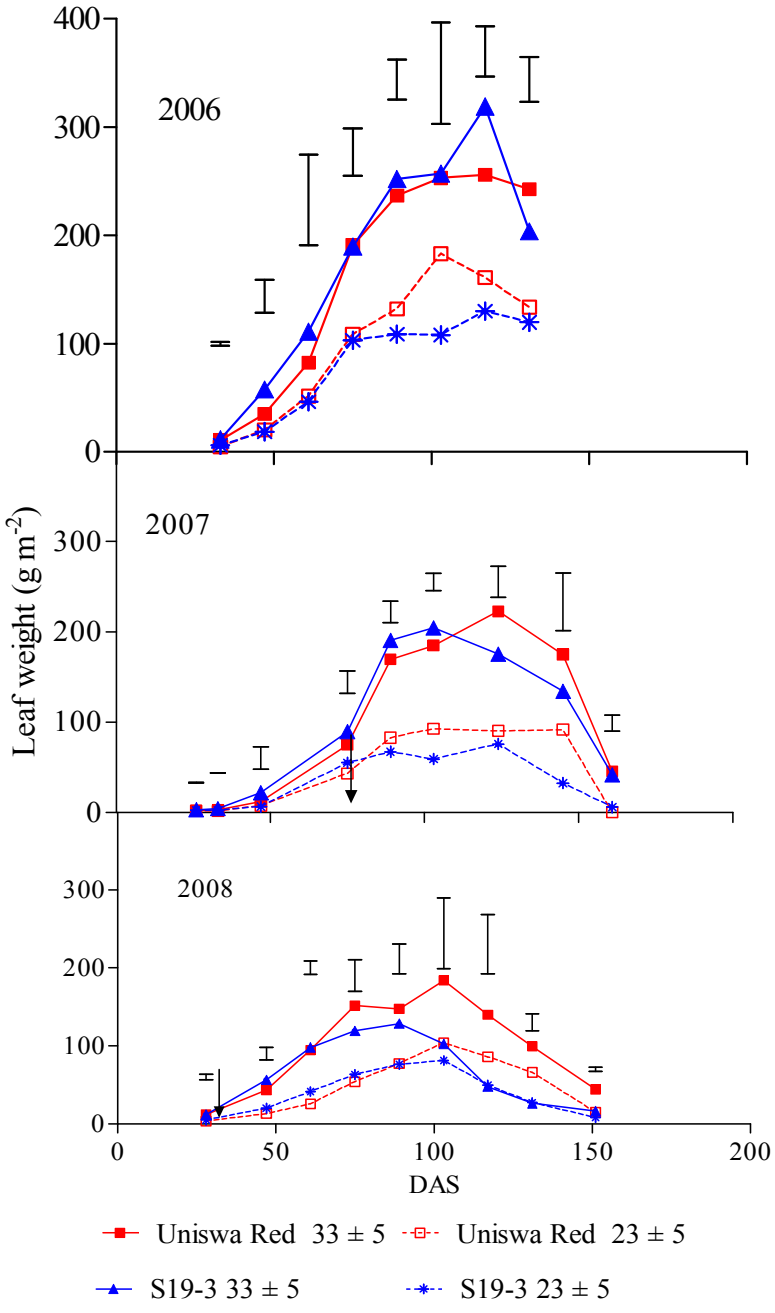

Figure 4.16 The effect of soil moisture and temperature on the leaf dry weight of two landraces (Uniswa Red and S19-3) grown in the Tropical Crops Research Unit (TCRU) glasshouses in 2006, 2007 and 2008. The arrows indicate the time when drought was imposed and the vertical bars represent SED.

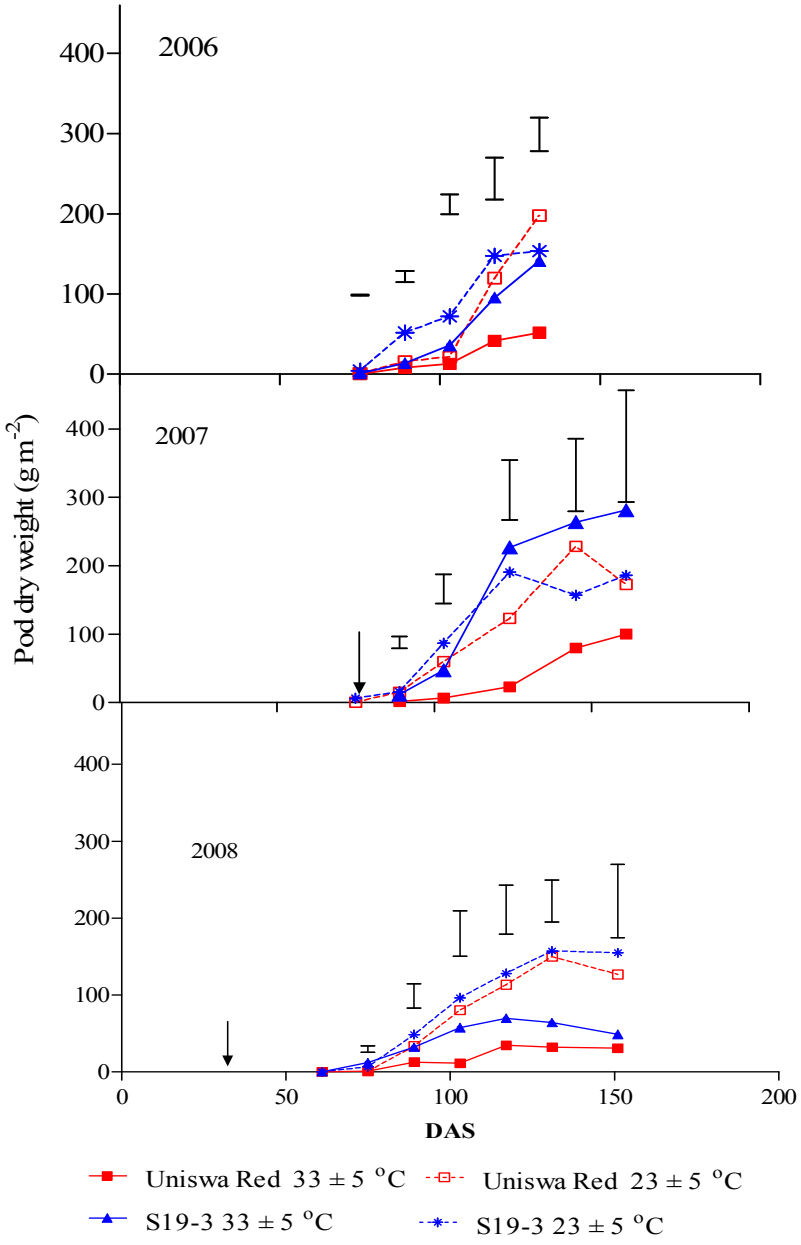

Figure 4.17 The effect of soil moisture and temperature on the pod dry weight of two landraces (Uniswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33±5 °C) in the Tropical Crops Research Unit (TCRU) glasshouses in 2006, 2007 and 2008. The arrows indicate the time when drought was imposed and the vertical bars represent SED.

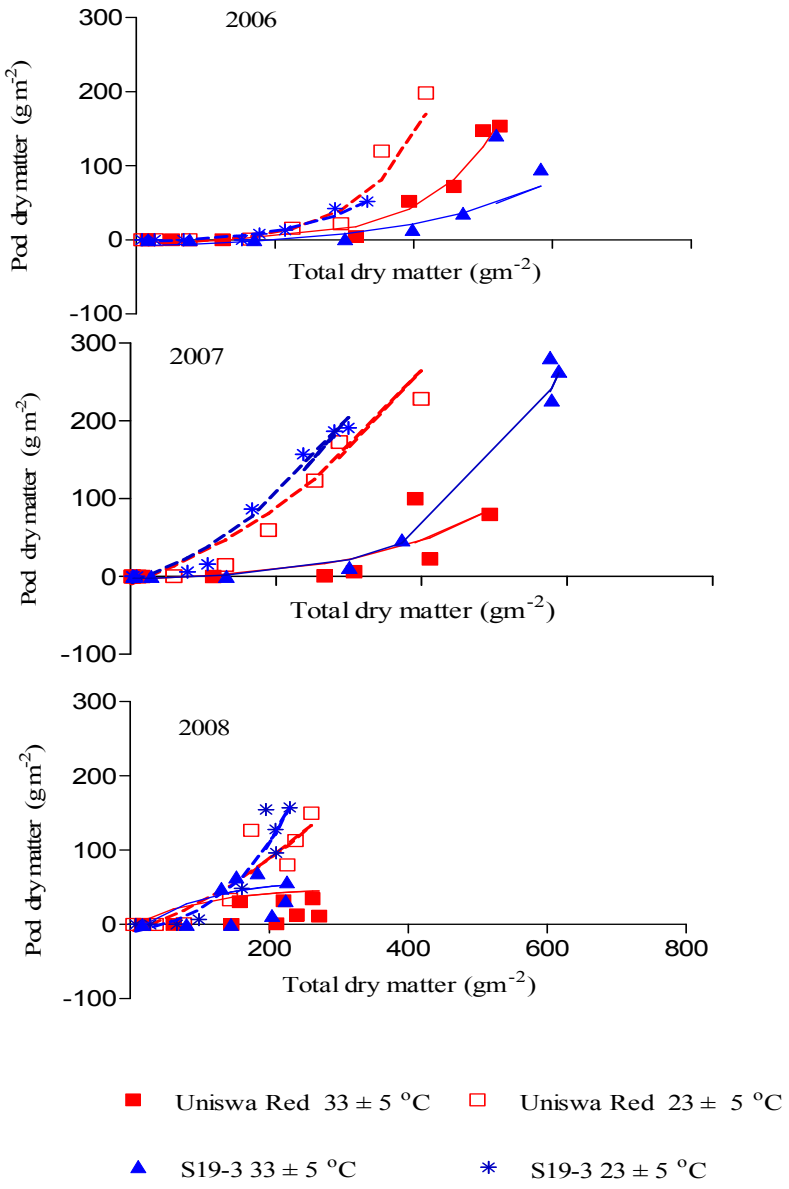

Figure 4.18 Regression of pod dry weight (g m^{-2}) against total dry matter (g m^{-2}) of two landraces (Uniswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33±5 °C) in the Tropical Crops Research Unit (TCRU) glasshouses in 2006, 2007 and 2008. r2= 65.1, 73.4 and 57.2, for 2006, 2007 and 2008 respectively. Slopes, Constants and R values are presented in table 4.3

Table 4.3 Slopes and constants obtained from the exponential regression ($Y = a + br^X$) of pod dry matter (g m^{-2}) against total dry matter (g m^{-2}) for two bambara groundnut landraces grown at low temperature (23 ±5°C) and high temperature (33 ±5°C) in the Tropical Crops Research Unit (TCRU) during the experiments in 2008.

	Treatment	UNI 33±5 ˚C	UNI 23±5 ˚C	s19-3 33±5 ˚C	s19-3 23±5 ˚C
2006	A	-3.9	-6.4	-12.7	-5.5
	se	12.7	12.4	19.2	21.3
	B	0.94	1.83	4.64	2.9
	se	1.52	2.24	7.56	10.3
	R	1.0099	1.0114	1.0057	1.0092
	SE	0.0031	0.0029	0.0027	0.0102
2007	A	-9.2	-129	-5.1	-90.1
	se	20.8	108	13.5	93.2
	B	5.7	119	2.45	81.5
	se	11.8	100	3.34	85.2
	R	1.0056	1.0028	1.0080	1.0043
	SE	0.0040	0.0014	0.0023	0.0025
2008	A	49	-95	61.1	-26.3
	se	479	191	90.4	40
	B	-53	85	-74.2	16
	se	460	179	75.5	25.4
	R	0.9976	1.0038	0.9932	1.0107
	SE	0.0312	0.0051	0.0179	0.0063

Table 4.4 (a, b and c). Yield components and yield (gm^{-2}) among two landraces (Uniswa Red and S19-3) of bambara groundnut grown in the Tropical Crops Research Unit (TCRU) glasshouses under high and low temperature treatment in (a) 2006, (b) 2007 and (c) 2008

a

Treatment	Landrace	Pod yield g m^{-2}
33°C	UNI	55.0
23°C	UNI	209.8
33°C	S19-3	149.9
23°C	S19-3	162.7
SED	***df***	
Landraces 23 °C	3	24.2 ^{ns}
Landraces 33 °C	5.1	29**
*Landraces*temperature*	3	19.7**

b

Treatment	Landrace	Shelling %	HI	seed Yield g m^{-2}	pod yield gm^{-2}	TDM g m^{-2}
33°C	UNI	12	0.4	98.8	112	276
23°C	UNI	7.7	0.87	174	189	216
33°C	S19-3	16.13	0.83	306	365	439
23°C	S19-3	5.4	0.88	184	195	214

	SED	***df***	
HI	*Landraces 23± 5 °C*	2	0.08 ^{ns}
	Landraces 33± 5 °C	2	0.11^{ns}
	*Landraces*temperature*	0.12	4.8 ^{ns}
	Landrace s23± 5 °C	2	125.9 ^{ns}
Yield	*Landraces 33± 5 °C*	2	102.8 ^{ns}
	*Landrace*temperature*	4.4	108 ^{ns}
	Landraces 23± 5 °C	2	136.4 ^{ns}
TDM	*Landraces 33± 5 °C*	2	111.4 ^{ns}
	*Landrace*temperature*	4.2	112.8 ^{ns}

c

Treatment	Landrace	Shelling %	HI	Yield gm^{-2}	Pod yield	TDM g m^{-2}
33°C	UNI	12.4	0.25	31.1	35.50228	141
23°C	UNI	15.7	0.83	127.7	151.4828	182
33°C	S19-3	13.3	0.46	49.1	56.63206	123
23°C	S19-3	16.08	0.87	140.6	165	189

		df	*SED*
HI	*Landraces 23± 5 °C*	3	0.22 ^{ns}
	Landraces 33± 5 °C	3	0.18 ^{ns}
	*Landrace*temperature*	4.2	*0.16* ^{ns}
Yield	*Landraces 23± 5 °C*	3	52.3^{ns}
	Landraces 33± 5 °C	3	42.7^{ns}
	*Landrace*temperature*	4.3	37.6^{ns}
TDM	*Landraces 23± 5 °C*	3	74.7 ^{ns}
	Landraces 33± 5 °C	3	61 ^{ns}
	*Landrace*temperature*	5	57 ^{ns}

4.1.5 Water capture

4.1.51. Soil surface evaporation

Figure 4.19 shows the cumulative surface evaporation (E_s). In 2007 in both landraces stands, E_s was higher at the low temperature. In 2008 E_s was higher at the high temperature.

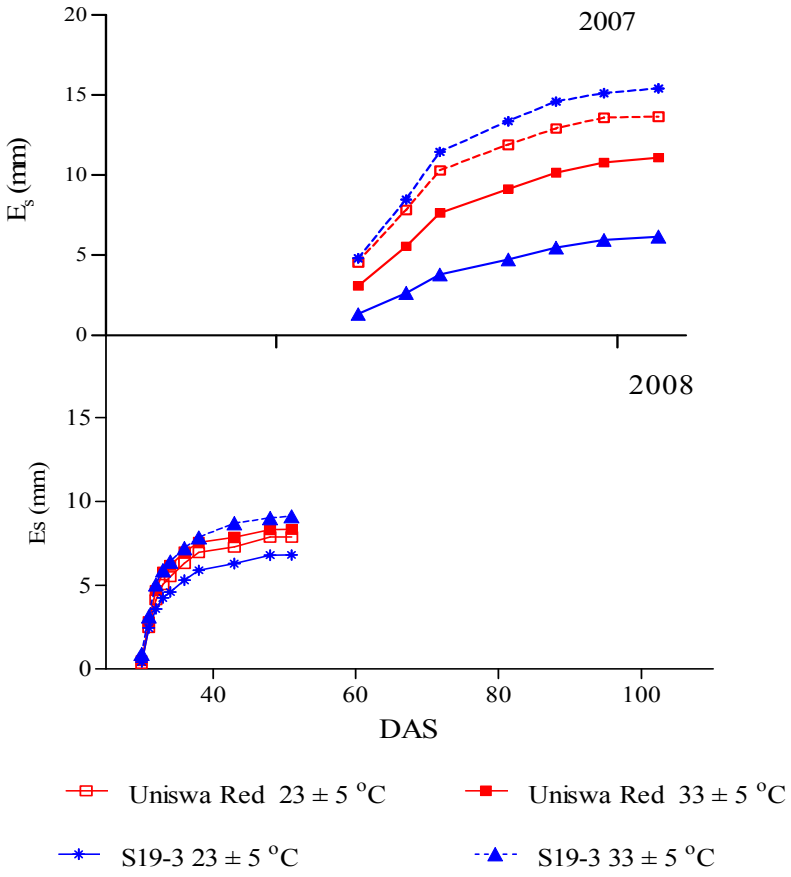

Figure 4.19 Cumulative soil surface evaporation (mm) from stands of two bambara groundnut landraces (Uniswa Red and S19-3) grown in the TCRU glasshouses at low temperature (23± 5 °C) and high temperature (33± 5 °C) in 2007 and 2008.

4.1.5.2 Evapotranspiration (E_t)

Figure 4.20 shows the total amount of water used by the two landraces at low and high temperature in 2007 and 2008. The rate of E_t started to rise at the beginning of the seasons, after that it started to get slower as the drought become more severe towards the end of the season. In 2007, there was a clear difference between low and high temperature of the amount of the water used. For example, in 2007, for S19-3 at the high temperature, the amount of E_t at 168 DAS was 267 mm which is three times the amount of E_t at the low temperature (89mm). This difference was less in 2008 (Figure 4.20).

4.1.5.3 Water distribution and extraction from the soil profile

The distribution of water in each layer of the soil profile and the pattern of water extraction for each landrace and treatment in 2007 and 2008 growing seasons is presented in Figure 4.21 and 4.22.

In 2007, large differences existed between the two landraces and the treatments. The soil moisture content decreased towards the end of the season especially at 100 and 60 cm depths. For Uniswa Red soil moisture profile, at 100 cm depth at the high temperature treatment, soil moisture decreased from 170 mm at 55 DAS to 104mm at 168 DAS which represents a reduction of 61%. S19-3 at the high temperature extracted less water from depth 40, 60 and 100cm than S19-3 at the low temperature, while Uniswa Red showed similar pattern of soil water extraction in both temperatures. Soil moisture content at 60cm depth was always less than the water content at 100cm except for S19-3 at the high temperature (Figure 4.21). Soil water distribution was similar in 2008 except for S19-3 at HT (Figure 4.22).

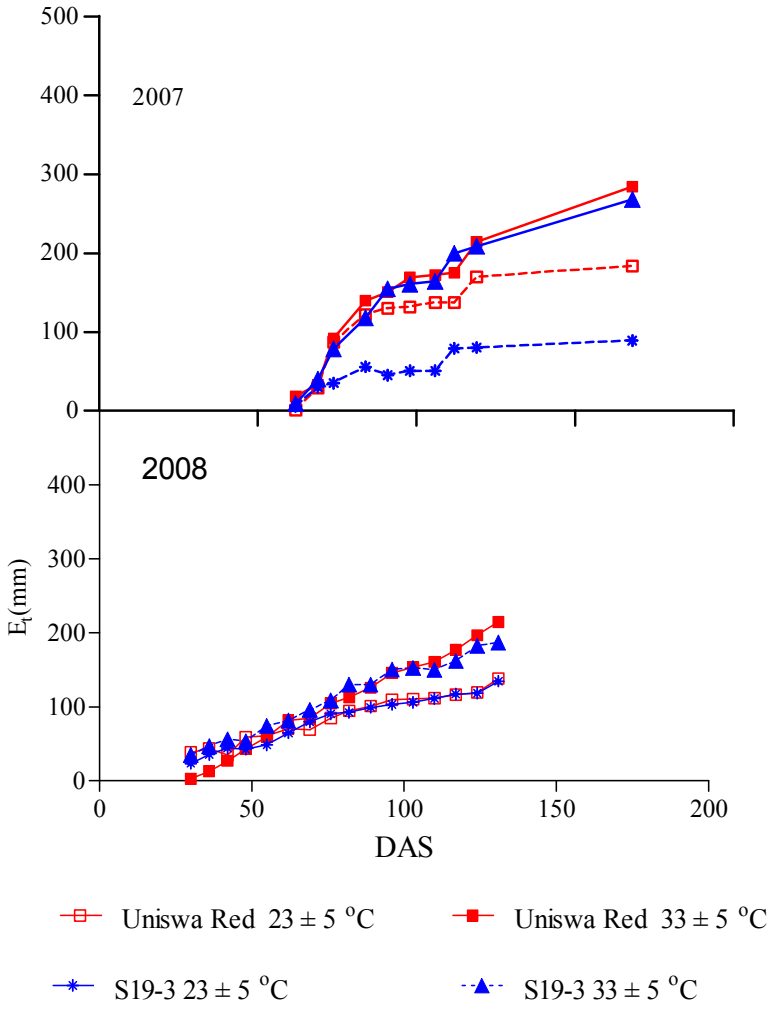

Figure 4.20 Cumulative evapotranspiration (mm) from stands of two bambara groundnut landraces (Uniswa Red and S19-3) grown in the TCRU glasshouses at low temperature (23± 5 °C) and high temperature (33± 5 °C) in 2007 and 2008.

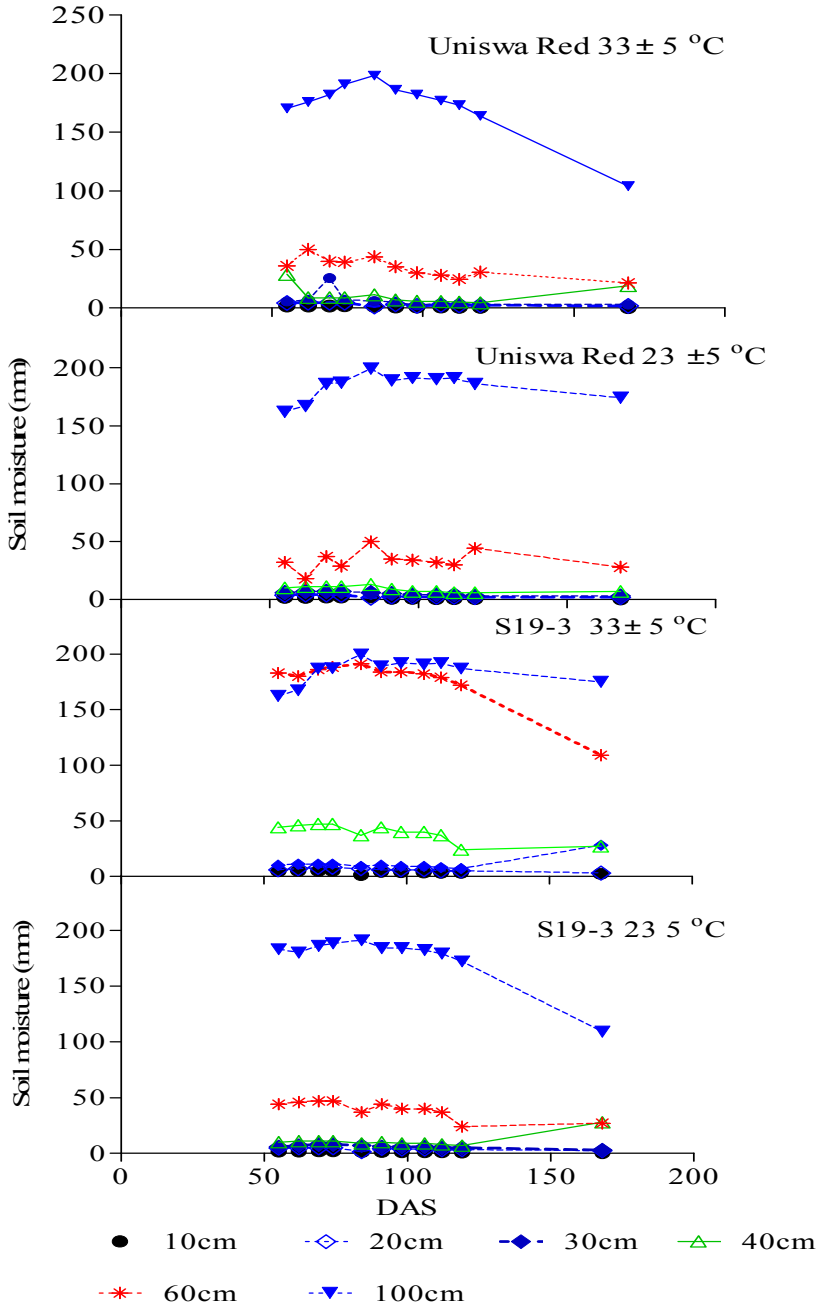

Figure 4.21 Profile soil moisture content (mm) at low temperature treatment (23 ±5°C) and high temperature treatment (33 ±5°C) of two bambara groundnut landraces (Uniswa Red and S19-3) grown in the Tropical Crops Research Unit (TCRU) glasshouses in 2007.

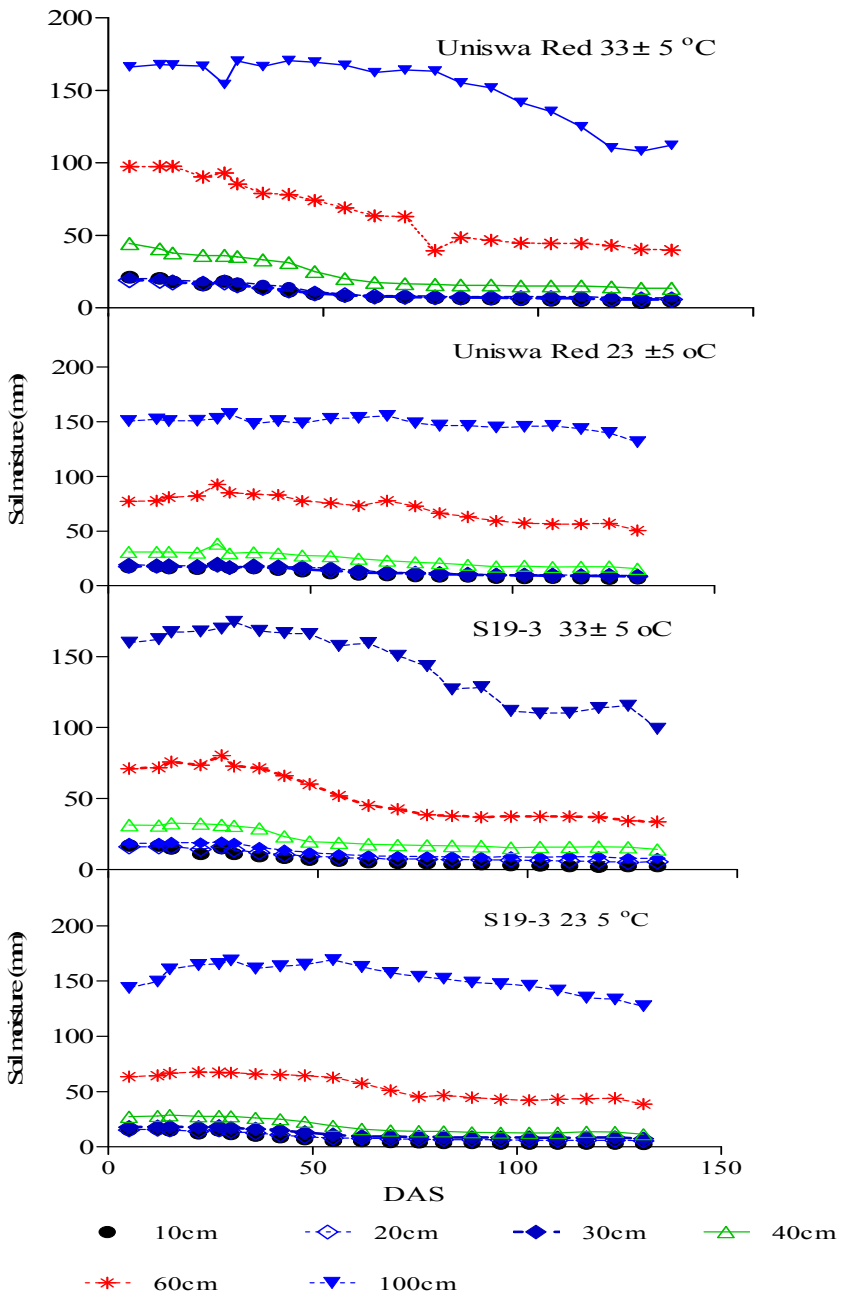

Figure 4.22 Profile soil moisture content (mm) at low temperature treatment (23 ±5°C) and high temperature treatment (33 ±5°C) of two bambara groundnut landraces (Uniswa Red and S19-3) grown in the Tropical Crops Research Unit (TCRU) glasshouses in 2008.

4.1.5.4 Water use efficiency (WUE)

Regression results of total dry matter (TDM) against transpired water are presented in Figure 4.23. There was a significant linear regression ($P<0.01$) between Transpiration (T) and TDM at both temperatures in 2007 and 2008 growing seasons. A comparison of the regression of TDM against T showed no significant difference between treatments in 2007. However, there was a significant difference between the treatments of 2008 ($P<0.05$) (Figure 4.23). When pod yield was regressed against transpiration, there were significant differences between temperature and landrace in both years ($P<0.01$). In 2007, S19-3 produced 2.25 g of pods per mm transpiration at both temperatures while Uniswa-Red produced 1.55g at 23^{o}C and 0.73g at 33^{o}C. In 2008, when drought was imposed earlier, the amount of pods produced per unit transpiration was reduced at high temperature for both landraces but by a much greater extent for Uniswa Red (Figure 4.24). S19-3 produced 0.72 g of pods per mm transpiration at 33^{o}C and 1.91 g of pods per mm transpiration at 23^{o}C while Uniswa-Red produced 1.20 g at 23^{o}C and 0.15g at 33^{o}C.

Mean daylight saturation deficit (SD) values were used as a normalising factor in calculating the transpiration equivalent (Ω_w) for the two landraces (Azam-Ali and Squire, 2002). Figure 4.25 shows the relationships between TDM corrected for SD and T. The values of Ω_w were obtained from the fitted regression lines. When the TDM values were corrected for SD, significant differences in WUE were found in both years ($P<0.05$).

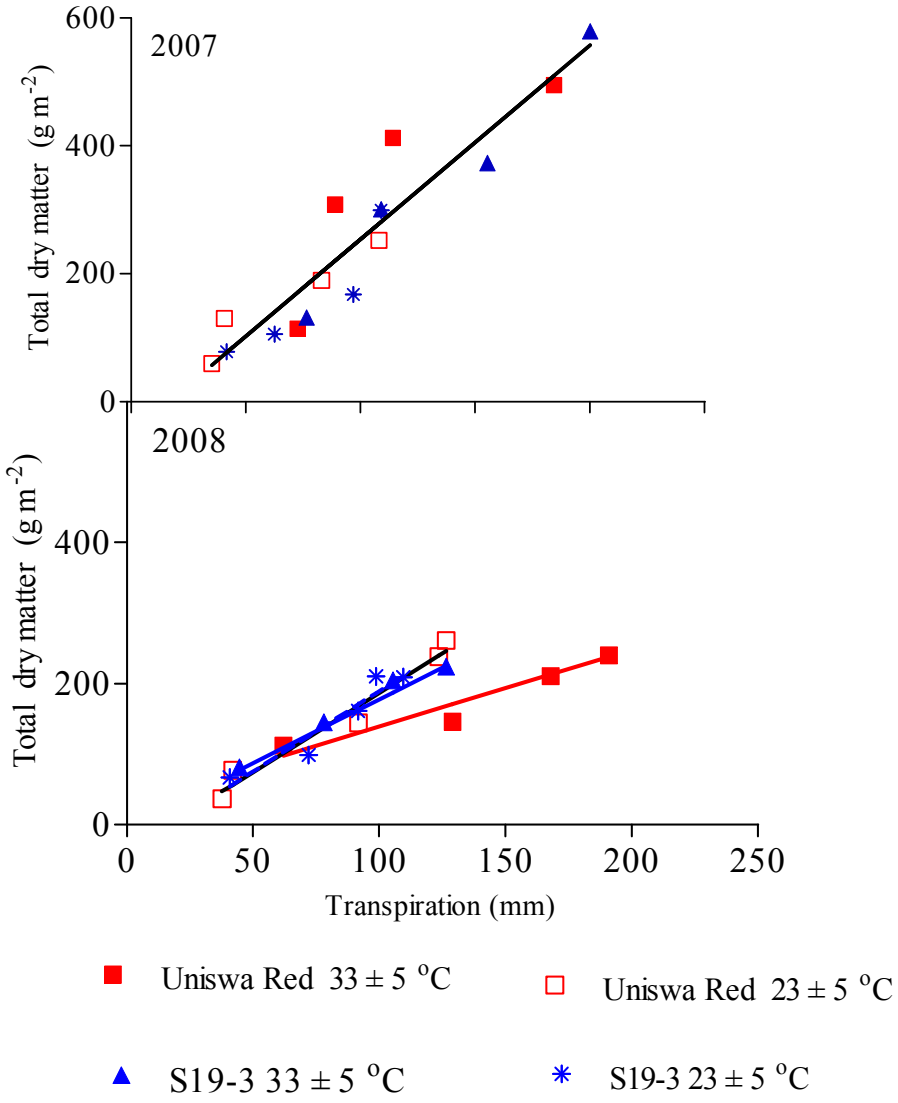

Figure 4.23 Regression of total dry matter (g m^{-2}) against transpiration (mm) for two bambara groundnut landraces grown at low temperature (23 ±5°C) and high temperature (33 ±5°C) in the Tropical Crops Research Unit (TCRU) during the experiments in 2007 and 2008. For 2007, the regression equation is: y=3.028x -48.7, (Slope se=0.29, Constant se=31.9) r^2= 88.5, For 2008. r^2=92.9 .Slopes and constants are presented in Table 4.5

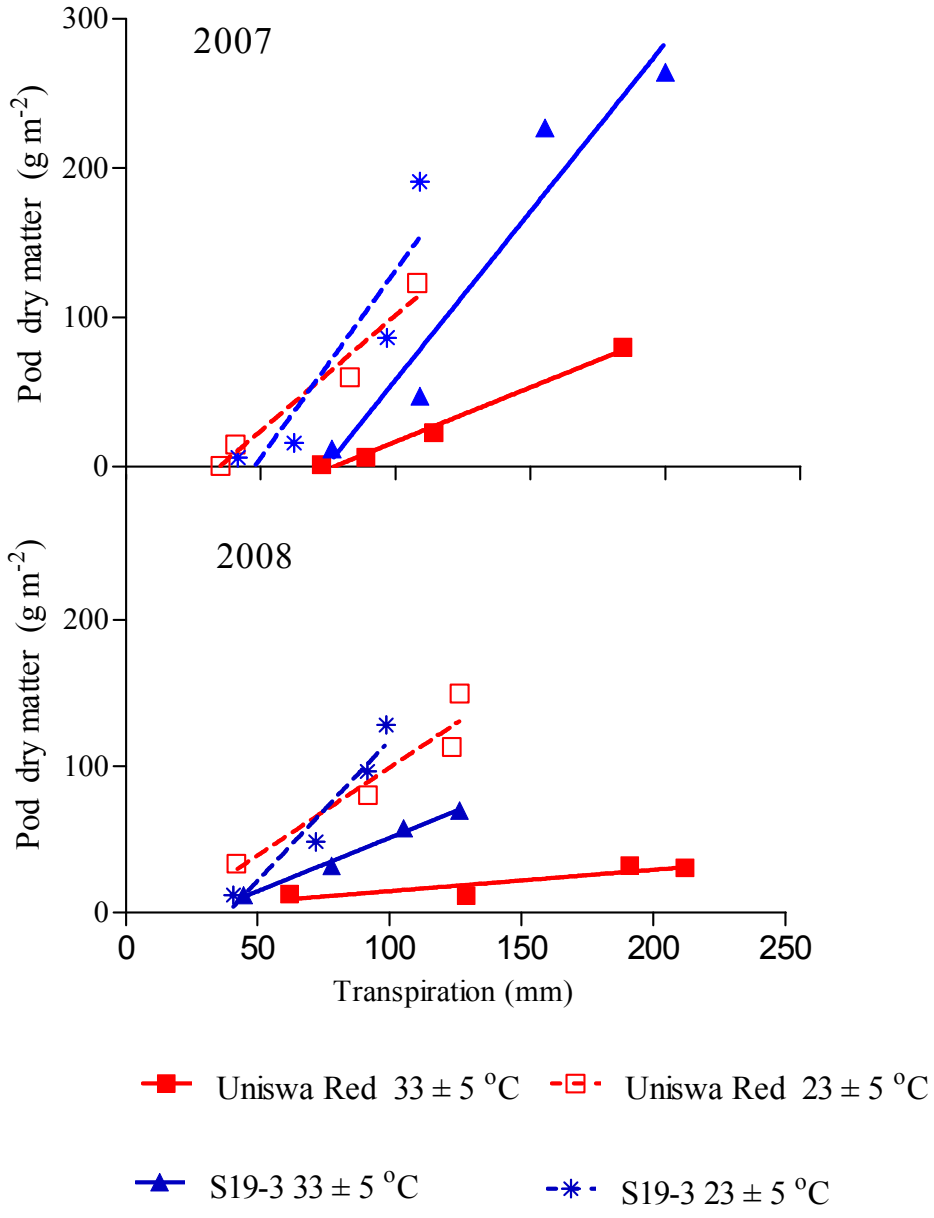

Figure 4.24 Regression of pod dry matter (g m^{-2}) against transpiration (mm) for two bambara groundnut landraces grown at low temperature (23 ±5°C) and high temperature (33 ±5°C) in the Tropical Crops Research Unit (TCRU) during the experiments in 2007 and 2008. r^2= 76.5 and 57.3 for 2007 and 2008, respectively. Slopes and constants are presented in Table 4.6

Table 4.5 Slopes and constants obtained from the regression of total dry matter (g m^{-2}) against transpiration (mm) for two bambara groundnut landraces grown at low temperature (23 ±5°C) and high temperature (33 ±5°C) in the Tropical Crops Research Unit (TCRU) during the experiments in 2008.

Treatment	Slope	se	Constant	se
UNI 33±5°C	1.09	0.16	30.5	26
UNI 23±5°C	2.23	0.22	-37.4	20.6
S19-3 33±5°C	1.8	0.31	3.4	29.1
S19-23±5°C	2.28	0.35	-39.2	30.3

Table 4.6 Slopes and constants obtained from the regression of pod dry matter (g m^{-2}) against transpiration (mm) for two bambara groundnut landraces grown at 23 ±5°C and 33 ±5°C) in 2007 and 2008.

	Treatment	Slope	se	Constant	se
2007	UNI 33±5°C	0.73	0.66	-56.0	63.6
	UNI 23±5°C	1.55	0.75	-53.5	59.1
	S19-3 33±5°C	2.26	0.65	-167.5	65.6
	S19-3 23±5°C	2.25	0.56	-119.5	46.3
2008	UNI 33±5°C	0.15	0.3	0.3	27.9
	UNI 23±5°C	1.2	0.4	-20.7	28.9
	S19-3 33±5°C	0.72	0.35	-21.6	29.2
	S19-3 23±5°C	1.91	0.27	-73.9	22.1

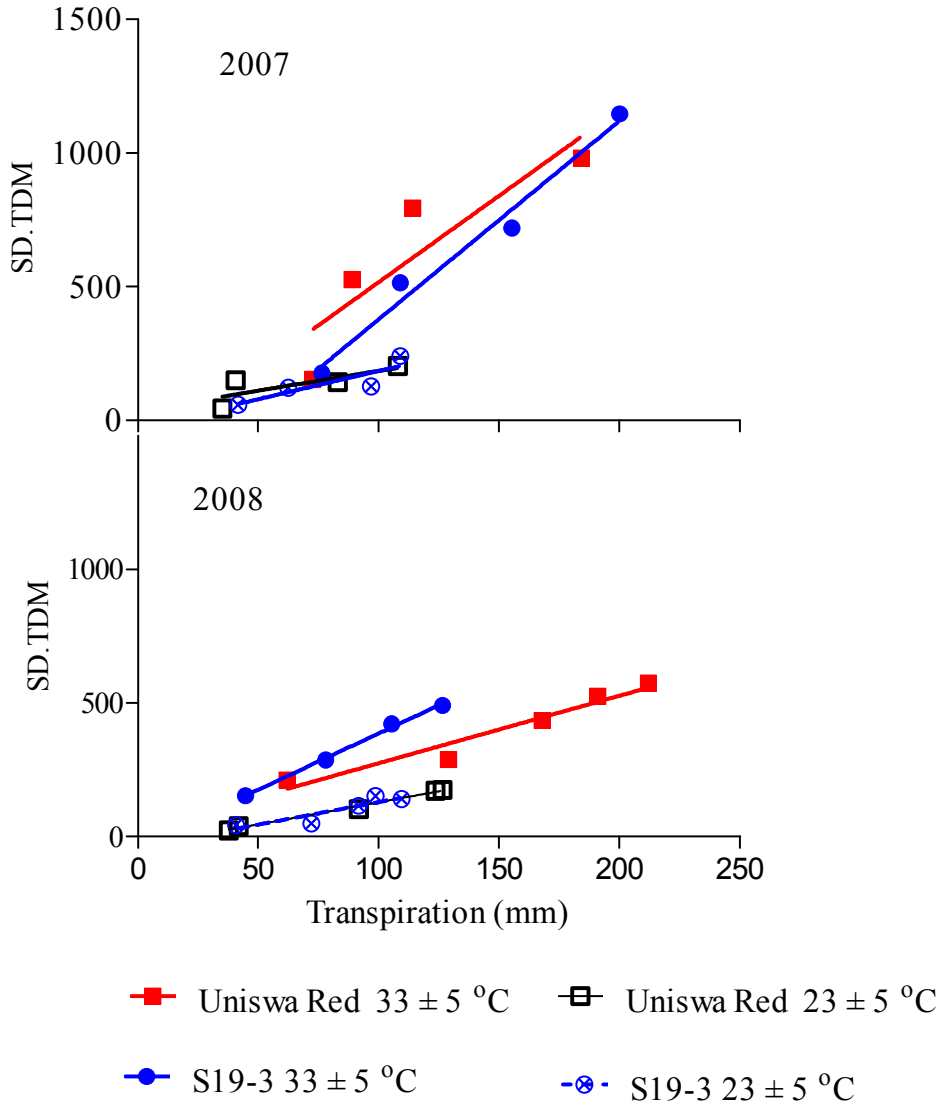

Figure 4.25 Regression of total dry matter (g m^{-2}) corrected for saturation deficit (SD) against transpiration (mm) for two bambara groundnut landraces grown at low temperature (23 ±5°C) and high temperature (33 ±5°C) in the Tropical Crops Research Unit (TCRU) during the experiments in 2007 and 2008. For 2007, r^2=97.7. For 2008, r^2=94.1. Slopes and constants are presented in Table 4.7.

Table 4.7 Slopes and constants obtained from the regression of total dry matter (g m^{-2}) corrected for saturation deficit (SD) against transpiration (mm) for two bambara groundnut landraces grown at low temperature (23 ±5°C) and high temperature (33 ±5°C) in the Tropical Crops Research Unit (TCRU) during the experiments in 2007 and 2008.

		UNI	UNI	S19-3	S19-3
	Treatment	**33±5°C**	**23±5°C**	**33±5°C**	**23±5°C**
2007	**Slope**	6.46	1.47	7.42	2.12
	se	1.33	1.88	1.22	2.12
	Constant	-130	37	-365	-27
	se	164	138	174	174
2008	**Slope**	2.52	1.65	4.2	1.69
	se	0.225	0.31	0.433	0.491
	Constant	21.9	-36.8	-35.2	-39.9
	se	36.2	28.7	40.6	42.3

4.1.6 Leaf relative water content (LRWC)

The 2007 results showed that both landraces managed to keep LRWC higher than 85 % throughout the season. S19-3 always had the highest LRWC at the all measurements, while Uniswa Red at low temperature had the lowest. (Figure 4.26). In 2008, LRWC was maintained higher than 84% throughout the season. Both landraces at the two temperatures had almost similar LRWC until 77 DAS where S19-3 LRWC at the high temperature started to decrease.

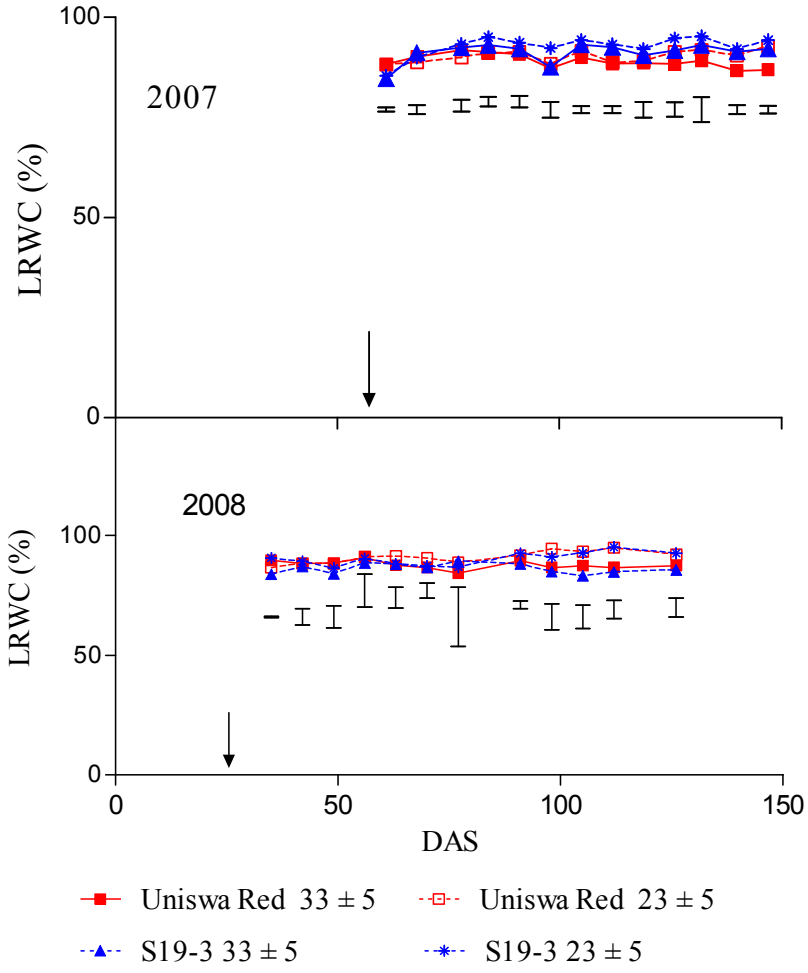

Figure 4.26 The effect of soil moisture and temperature on the leaf relative water content of two landraces (Uniswa Red and S19-3 grown at low temperature (23 ±5^{o}C) and high temperature (33 ±5^{o}C) in the Tropical Crops Research Unit (TCRU) during the experiments in 2007 and 2008. The arrows show the time when drought was imposed and the vertical bars represent SED.

4.1.7 Gas exchange

In 2006, there were no clear differences between landraces and temperatures. Photosynthesis (A) decreased towards the end of the season in both landraces and temperatures. eg. Photosynthesis in S19-3 at 33^{o}C decreased from 13.2 µmol m^{-2} s^{-1} at 36 DAS to 3.0 µmol m^{-2} s^{-1} at 113 DAS.

2007 results showed that S19-3 had the highest rate of photosynthesis throughout the period of measurements. Generally the rate of photosynthesis decreased towards the end of the season. The first landrace to start decreasing the rate of photosynthesis was Uniswa Red at low temperature (Figure 4.27). The statistical analysis of A and g in 2007 and 2008 showed no significant interaction of temperature and landrace throughout the seasons. The only significant effect of landrace on photosynthesis in 2007 ($P<0.05$) existed at 56 DAS (Appendix) where S19-3 at 33 ^{o}C and 23^{o}C had higher photosynthesis (27.0 and 26.4 µmol m^{-2} s^{-1} respectively). 2008 results showed steady decrease of photosynthesis towards the end of the season. The statistical analysis of 2008 results showed no significant interaction difference between the treatments ($P>0.05$). At 83, 97 and 125 DAS, temperature significantly affected the rate of A, where A for the two landraces was higher at 23°C than at 33°C. For 23°C, averages of A were 9.7, 11.5 and 9.9 µmol m^{-2} s^{-1} and 8.4, 5.9 and 2.4 µmol m^{-2} s^{-1} for 33°C, respectively Generally, photosynthesis rate had a similar pattern throughout the three growing seasons.

Stomatal conductance (g) was considerably lower in 2008 than in 2006 and 2007. The stomatal conductance in the first growing season was always higher at the high temperature than the lower temperature. This difference was not consistent in the second growing season. In the third growing season, stomatal conductance was higher at the high

temperature until 70 DAS when this difference started to decrease (Figure 4.28). Temperature affected significantly g at 42 and 125 DAS (Appendix 1). The statistical analysis across 2007 and 2008 of A and g at 56 and 138 DAS showed no significant difference ($P>0.05$).

Figure 4.29 does not show a clear difference between internal CO_2 (C_i) in the landraces in 2007, but Uniswa Red had the lowest concentration of C_i. However, generally, C_i in 2007 was higher than C_i in 2008.

In 2007, the pattern of transpiration was not stable, but it can be noticed that the rate of transpiration started decreasing from 98 DAS. S19-3 at the high temperature had the highest rate of transpiration during the all days of the measurements (Figure 4.30). Transpiration results were not statistically analysed, but results show that the two crops maintain transpiration higher at the high temperature than the low temperature until 76 DAS when the transpiration started to decrease to the same level of the transpiration at the low temperature.

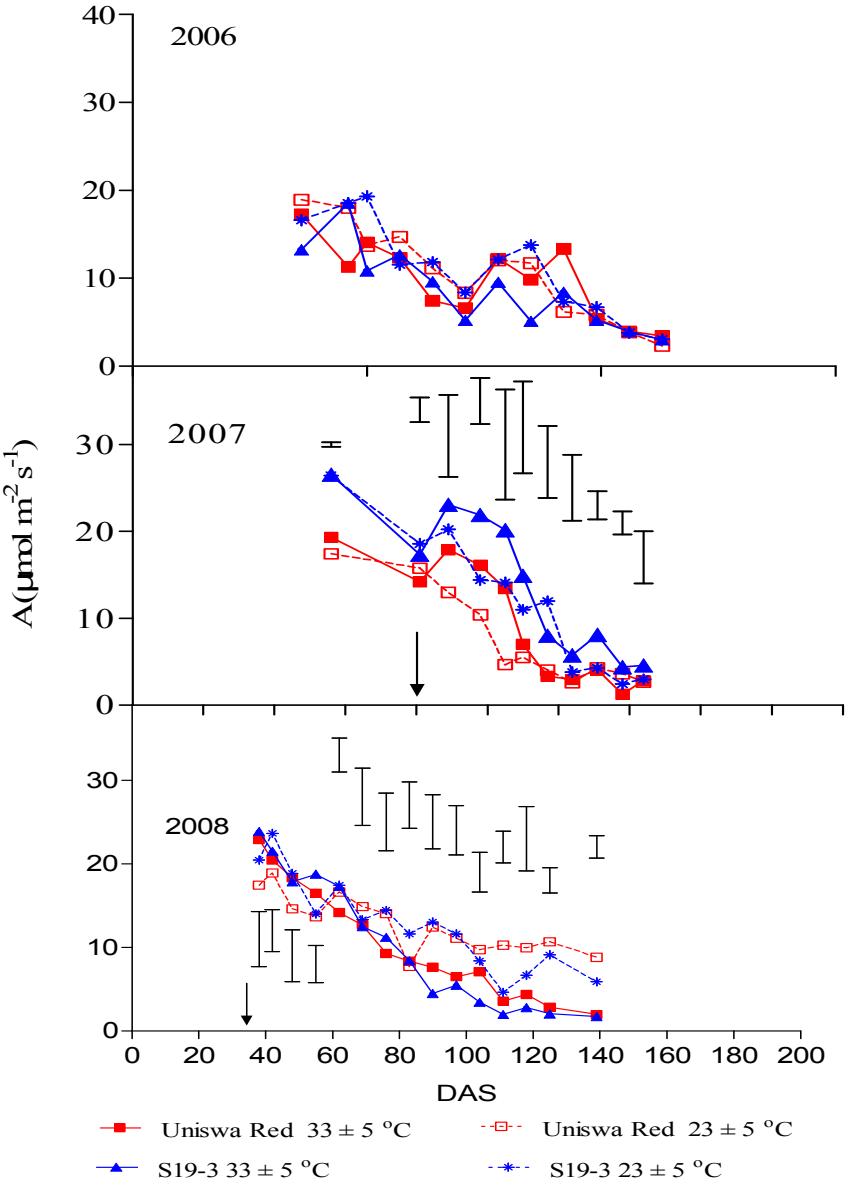

Figure 4.27 The effect of soil moisture and temperature on the photosynthesis of two landraces (Uniswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33±5 °C) in the Tropical Crops Research Unit (TCRU) glasshouses in 2007 and 2008. The arrows show the time when drought was imposed and the vertical bars represent SED.

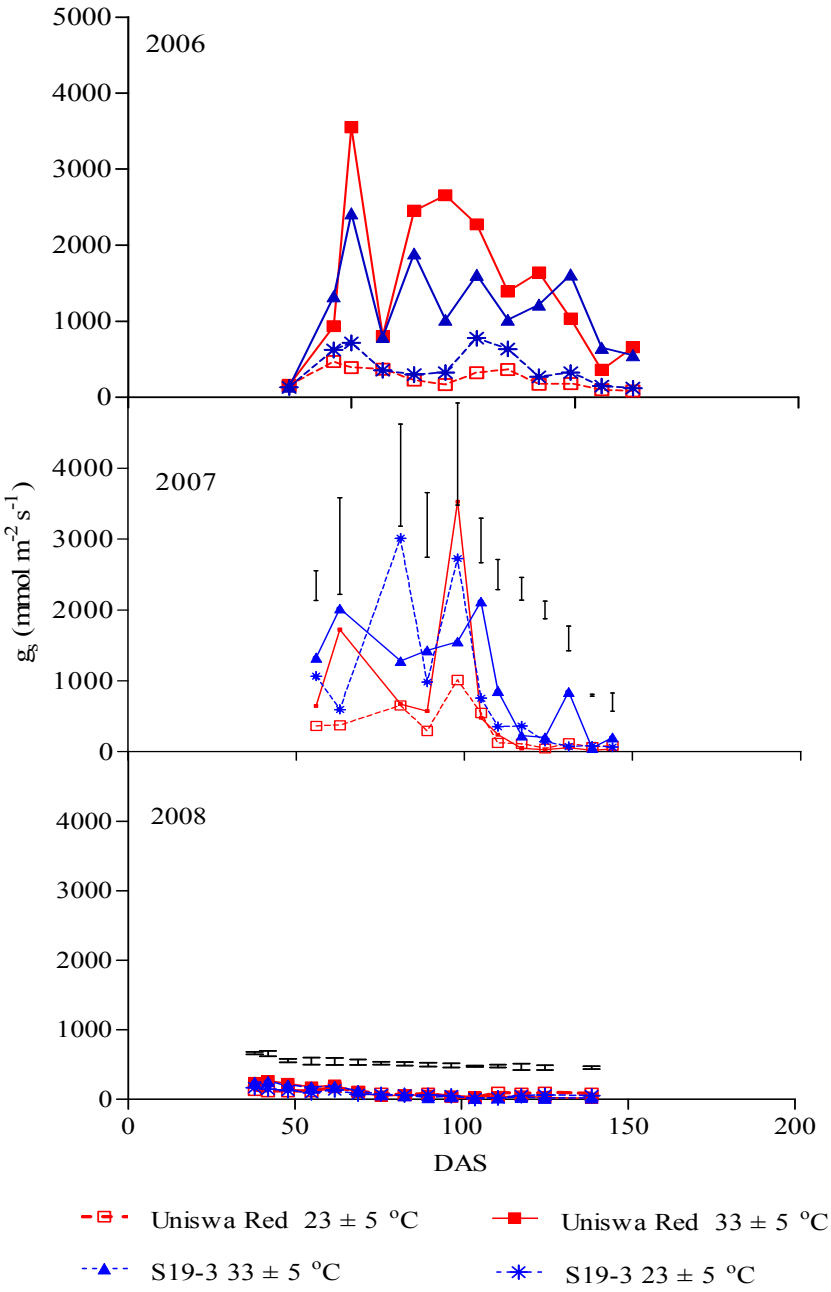

Figure 4.28 The effect of soil moisture and temperature on the stomatal conductance of two landraces (Uniswa Red and S19-3) grown in the Tropical Crops Research Unit (TCRU) glasshouses at low temperature (23± 5°C) and high temperature (33±5 °C) in 2007 and 2008. The vertical bars represent SED.

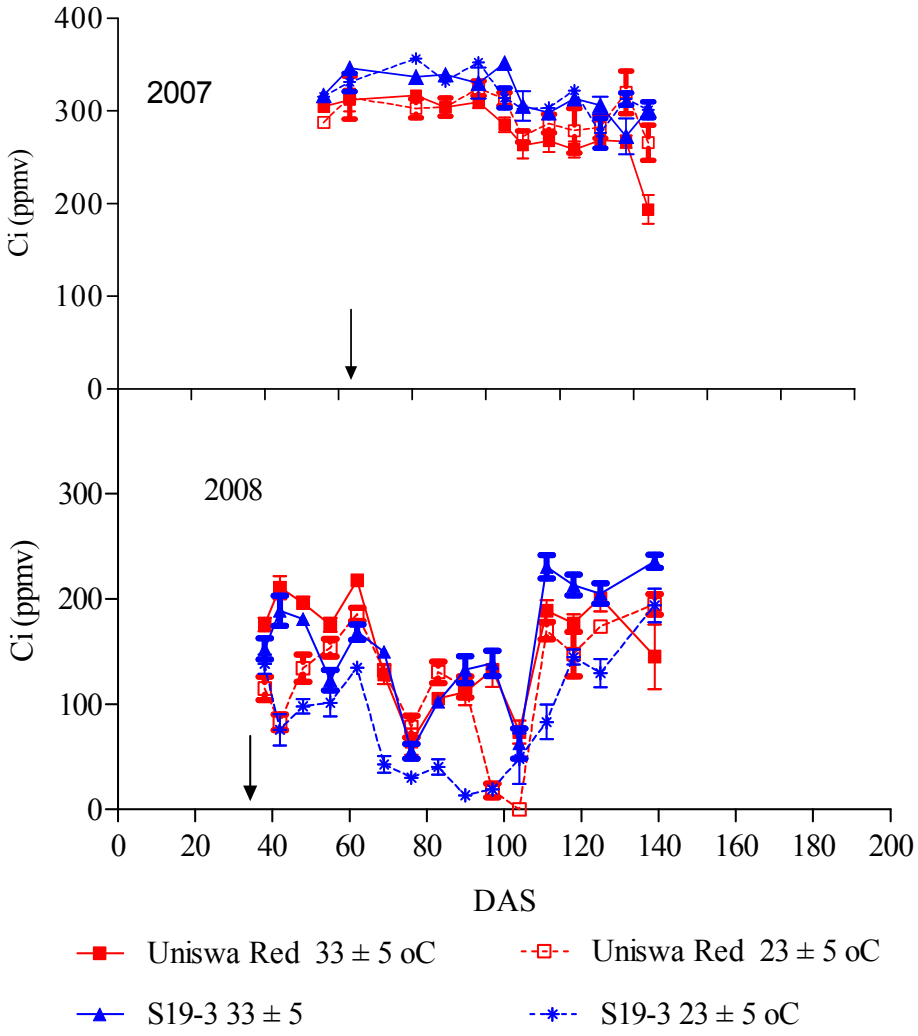

Figure 4.29 The effect of soil moisture and temperature on the internal CO_2 (C_i) of two landraces (Uniswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33± 5°C) in the Tropical Crops Research Unit (TCRU) glasshouses in 2007 and 2008. The arrows show the time when drought was imposed and the vertical bars represent SED.

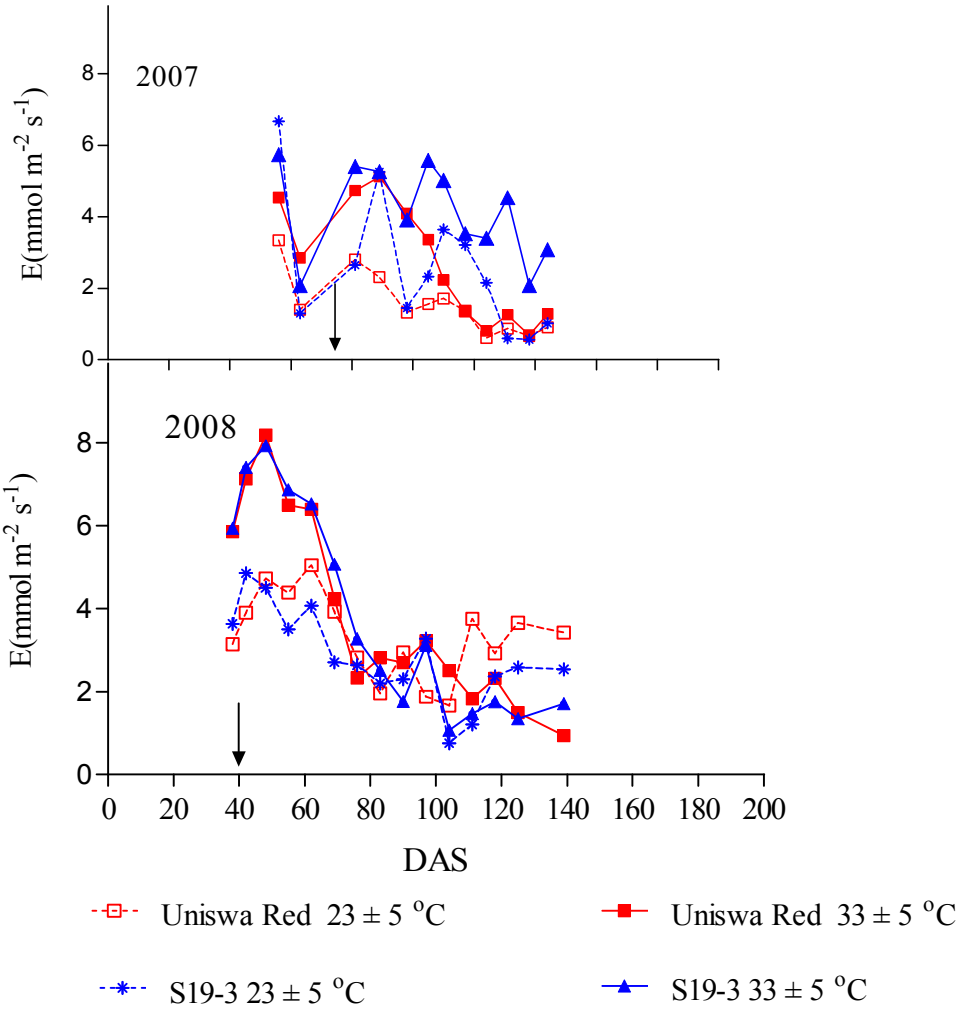

Figure 4.30 The effect of soil moisture and temperature on the leaf transpiration of two bambara groundnut landraces (Uniswa Red and S19-3) grown in the Tropical Crops Research Unit (TCRU) glasshouses in 2007 and 2008. The arrows show the time when drought was imposed.

4.1.8 Radiation capture and radiation use efficiency

4.1.8.1 Intercepted radiation

Cumulative intercepted radiation throughout the 2007 and 2008 growing seasons is presented in Figure 4.31. In 2007 and 2008, Uniswa Red at the high temperature intercepted more radiation than Uniswa Red at low temperature and S19-3 at high and low temperature. In both growing seasons, Uniswa Red at the low temperature had the lowest intercepted radiation. The statistical analysis of the total intercepted radiation showed no significant differences between the four treatments in either growing season ($P<0.05$).

4.1.8.2 Fractional interception of radiation and light extinction coefficient

Figure 4.32 shows the fractional interception of radiation (*f*) for the two landraces and the two treatments in 2007 and 2008 growing seasons. The pattern of f was similar for the two landraces at the high temperature in both seasons, while at the low temperature they were different. For Uniswa Red, *f* at the low temperature was lower than *f* for S19-3, but it was the opposite in 2008. In both growing seasons, *f* was higher at the high temperature than *f* at the low temperature

The maximum *f* values for the landraces at the high temperature were close to 1, while at the low temperature it was less than 0.8. *f at* 42, 100 and 145 DAS in 2007 and 2008 was statistically analysed, no significant differences were found in either growing seasons.

Figure 4.33 shows the light extinction in 2007 and 2008. No significant difference was found between the treatments in 2007, nor in 2008.

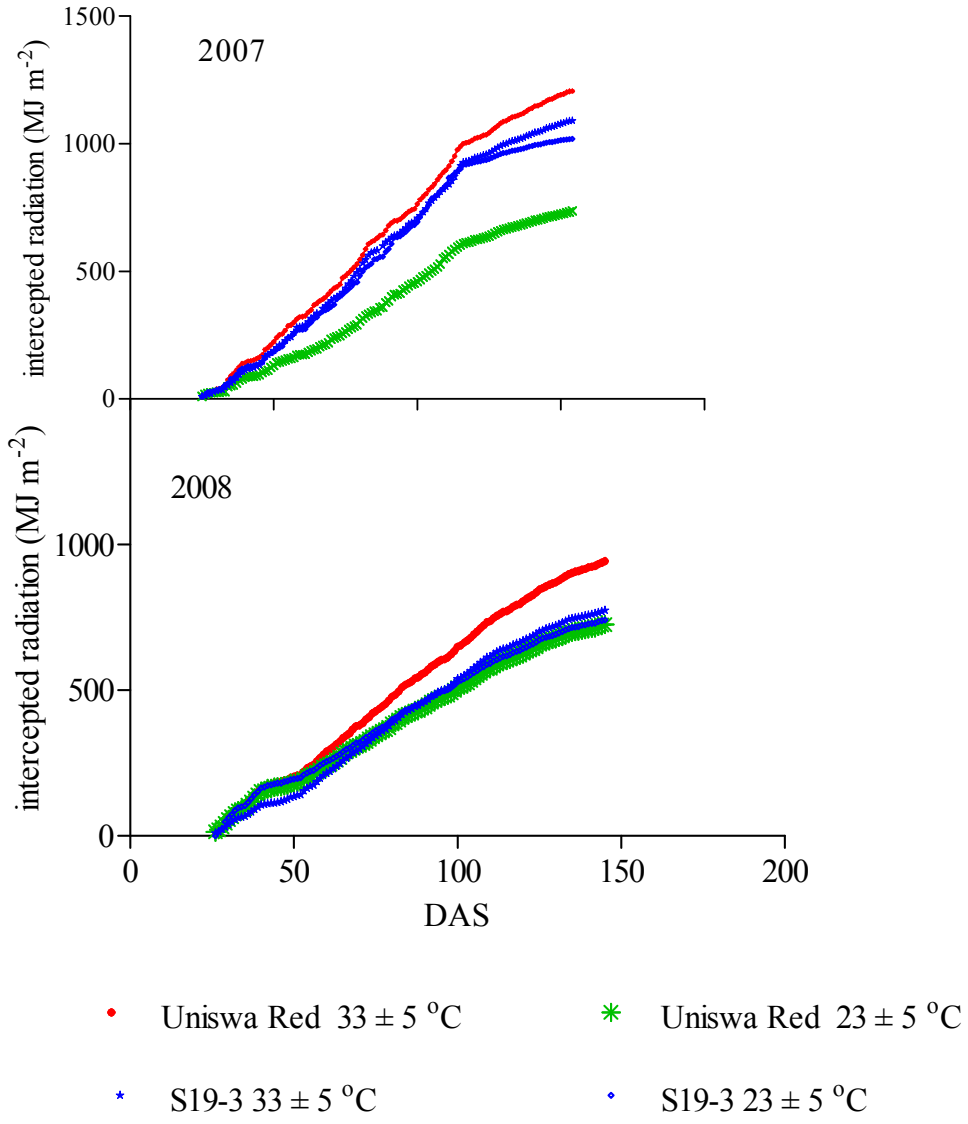

Figure 4.31 Cumulative intercepted radiation (MJ m^{-2}) of two bambara groundnut landraces (Uniswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33±5 °C) in the TCRU glasshouses during the experiments of 2007 and 2008.

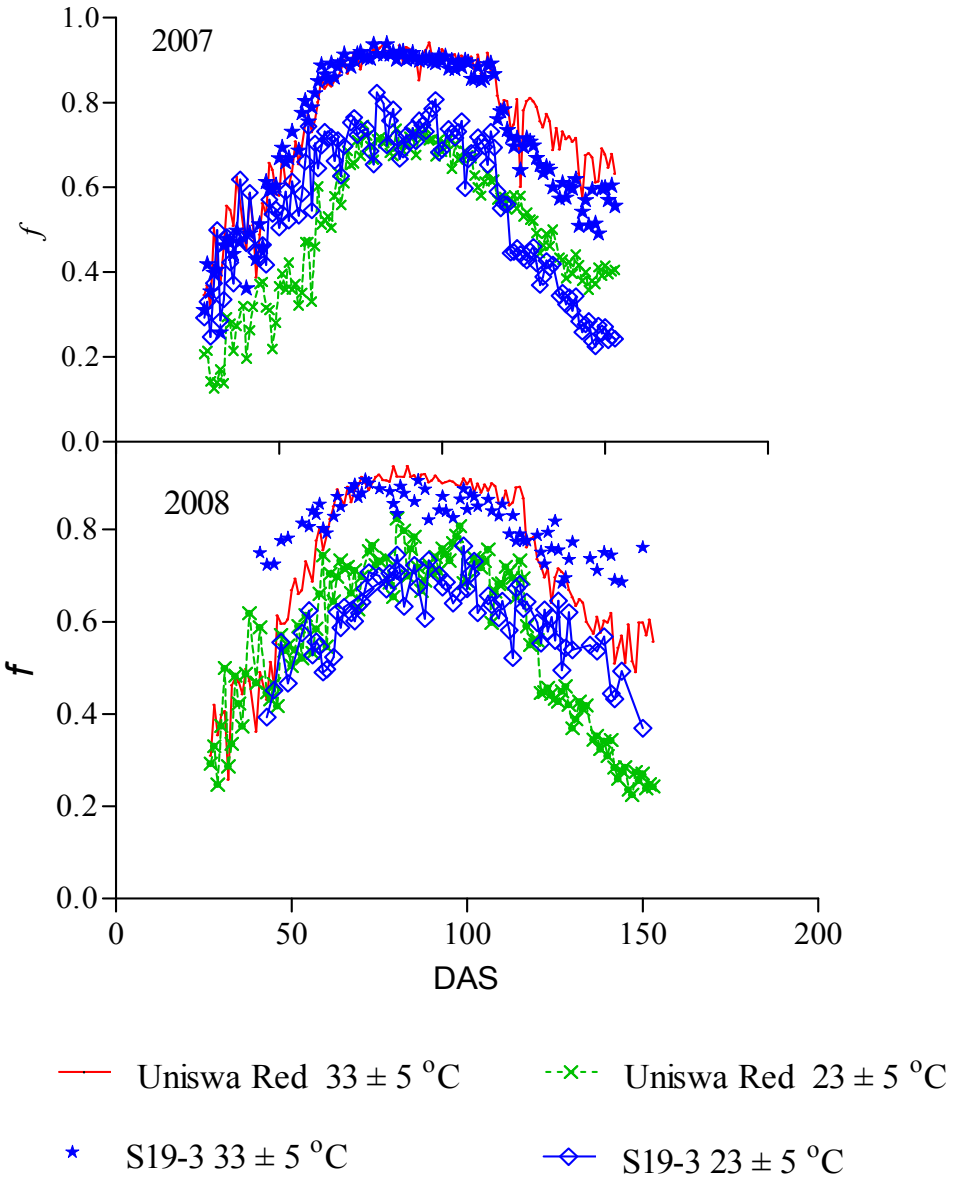

Figure 4.32 Fractional intercepted radiation of two bambara groundnut landraces (Uniswa Red and S19-3) grown at low temperature (23± 5°C) and high temperature (33±5 °C) in the TCRU glasshouses during the experiments of 2007and 2008.

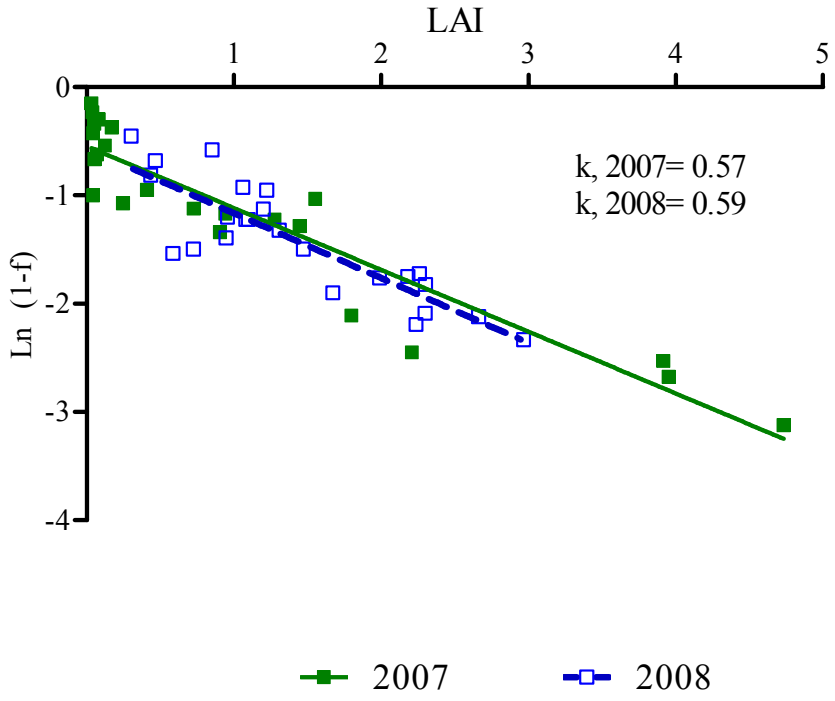

Figure 4.33 Regression of ln (1-f) against leaf area index (LAI) for two bambara groundnut landraces grown under high temperature and low temperature) conditions in glasshouses (2007&2008). The slope of the regression line represents the light extinction coefficient (K). Regression equations are: For 2007, y = -0.57x - 0.5453; r^2 = 0.87 and for 2008, y = -0.59x - 0.56; r^2 = 0.7523.

4.1.8.3 Radiation use efficiency (RUE)

RUE of the two landraces varied in the respect to temperature in 2007 (*P*=0.001) and in 2008 (*P*=0.047) (Figure 4.34). In both years, S19-3 at 33^{o}C had the highest RUE and S19-3 at 23^{o}C the lowest. In 2007, RUE of Uniswa Red was similar at both temperatures, while in 2008 RUE was higher at 33^{o}C.

Mean day light SD values were used as normalising factor in calculating radiation equivalent for the two landraces (Azam-Ali *et.al*, 1994) (Figure 4.35) . Differences between treatments are greater when normalised for SD, but the ranking remains consistent.

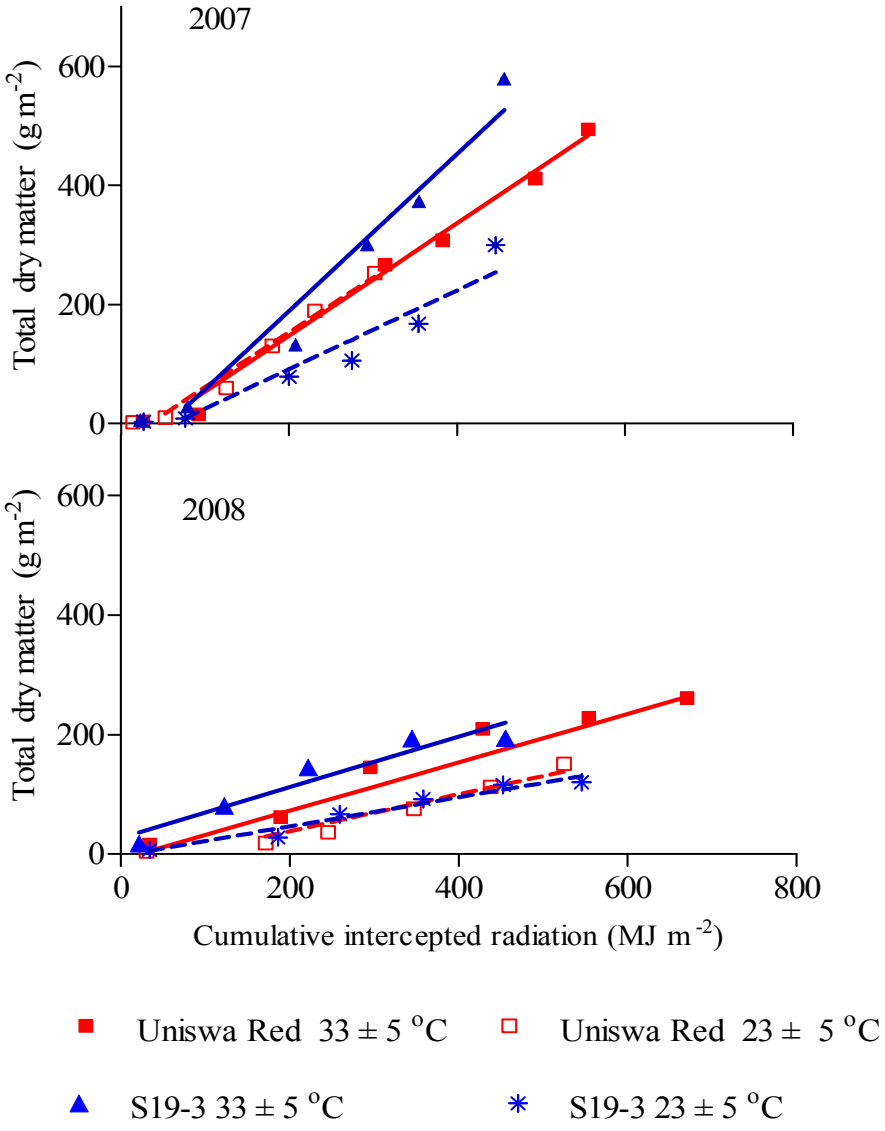

Figure 4.34 Regression of total dry matter (g m^{-2}) cumulative intercepted radiation for two bambara groundnut landraces grown at low temperature (23 ±5°C) and high temperature (33 ±5°C) in the Tropical Crops Research Unit (TCRU) during the experiments in 2007 and 2008. For 2007, r^2=96.1. For 2008. r^2=93.9 Slopes and constants are presented in Table 4.8

Table 4.8 Slopes and constants obtained from the regression of total dry matter (g m^{-2}) against cumulative intercepted radiation for two bambara groundnut landraces grown at low temperature (23 ±5°C) and high temperature (33 ±5°C) in the Tropical Crops Research Unit (TCRU) during the experiments in 2007 and 2008.

		UNI	**UNI**	**S19-3**	**S19-3**
	Treatment	**33±5°C**	**23±5°C**	**33±5°C**	**23±5°C**
2007	**Slope**	0.94	0.92	1.31	0.66
	se	0.07	0.13	0.09	0.09
	Constant	-43.6	-31.3	-74.2	-41.8
	se	25.9	25	25.5	25.5
2008	**Slope**	0.40	0.31	0.42	0.24
	se	0.03	0.04	0.05	0.04
	Constant	7.90	-23.30	27.43	-2.90
	se	15.1	15.7	15.3	16.0

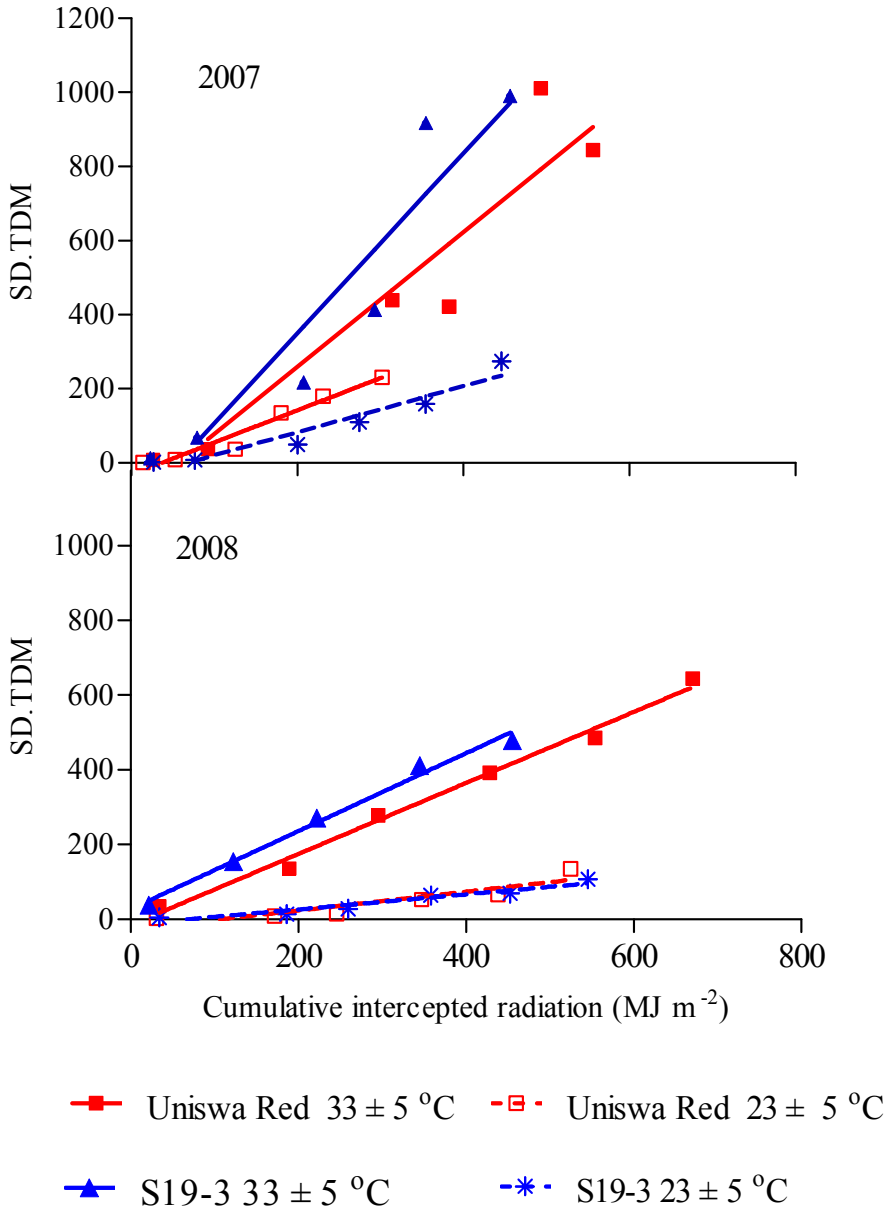

Figure 4.35 Regression of total dry matter (g m^{-2}) corrected for saturation deficit (SD) against cumulative intercepted radiation for two bambara groundnut landraces grown at low temperature (23 ±5°C) and high temperature (33 ±5°C) in the Tropical Crops Research Unit (TCRU) during the experiments in 2007 and 2008. For 2007, r^2=89.5. For 2008. r^2=97.7 Slopes and constants are presented in table 4.9.

Table 4.9 Slopes and constants obtained from the regression of total dry matter (g m^{-2}) corrected for saturation deficit against cumulative intercepted radiation for two bambara groundnut landraces grown at low temperature (23 ±5°C) and high temperature (33 ±5°C) in the Tropical Crops Research Unit (TCRU) during the experiments in 2007 and 2008.

		UNI	**UNI**	**S19-3**	**S19-3**
	Treatment	**33±5°C**	**23±5°C**	**33±5°C**	**23±5°C**
2007	**Slope**	1.81	0.86	2.42	0.62
	se	0.22	0.44	0.29	0.30
	Constant	-103.4	-31.3	-136.2	-42.4
	se	83.3	80.5	82	82.1
2008	**Slope**	0.94	0.25	1.04	0.2
	se	0.03	0.05	0.06	0.05
	Constant	-14.5	-26.2	28.1	-13.3
	se	16.7	17.4	17.0	17.6

4.2 Field experiments

4.2.1 Results of the first growing season 2007-2008

4.2.1.1 Temperature and rainfall

Figure 4.36 shows the maximum, the minimum and the daily mean of temperature at Notwane Farm, for the first sowing date (D1), the third (D3) and the fifth date of sowing (D5). (The difference between D1 and D3, and between D1 and D5 was added to x axis. For example, there was a 28 days difference between D1 and D3, which means, 25 DAS in date three equals (25+28) that means 25 DAS in D3 presented on 53 at x axis. The same is followed for D5 in all the graphs). In D1, maximum temperature ranged between 22^{o}C and 36^{o}C and the minimum between 9^{o}C and 21 ^{o}C. The daily mean ranged between 14 ^{o}C and 26^{o}C. The maximum temperature ranged between 14^{o}C and 33^{o}C, and the minimum between 3^{o}C and 20^{o}C during D3. The daily mean ranged between 14^{o}C and 25^{o}C. For D5, the maximum temperature ranged between 14 and 33^{o}C, and the minimum between 2 and 20^{o}C , and the daily mean between 15^{o}C and 26^{o}C.

The total amount of rain was 410, 326 and 247 mm, for D1, D3 and D5, respectively. Figure 4.37 shows the distribution of rainfall during the three dates of sowing.

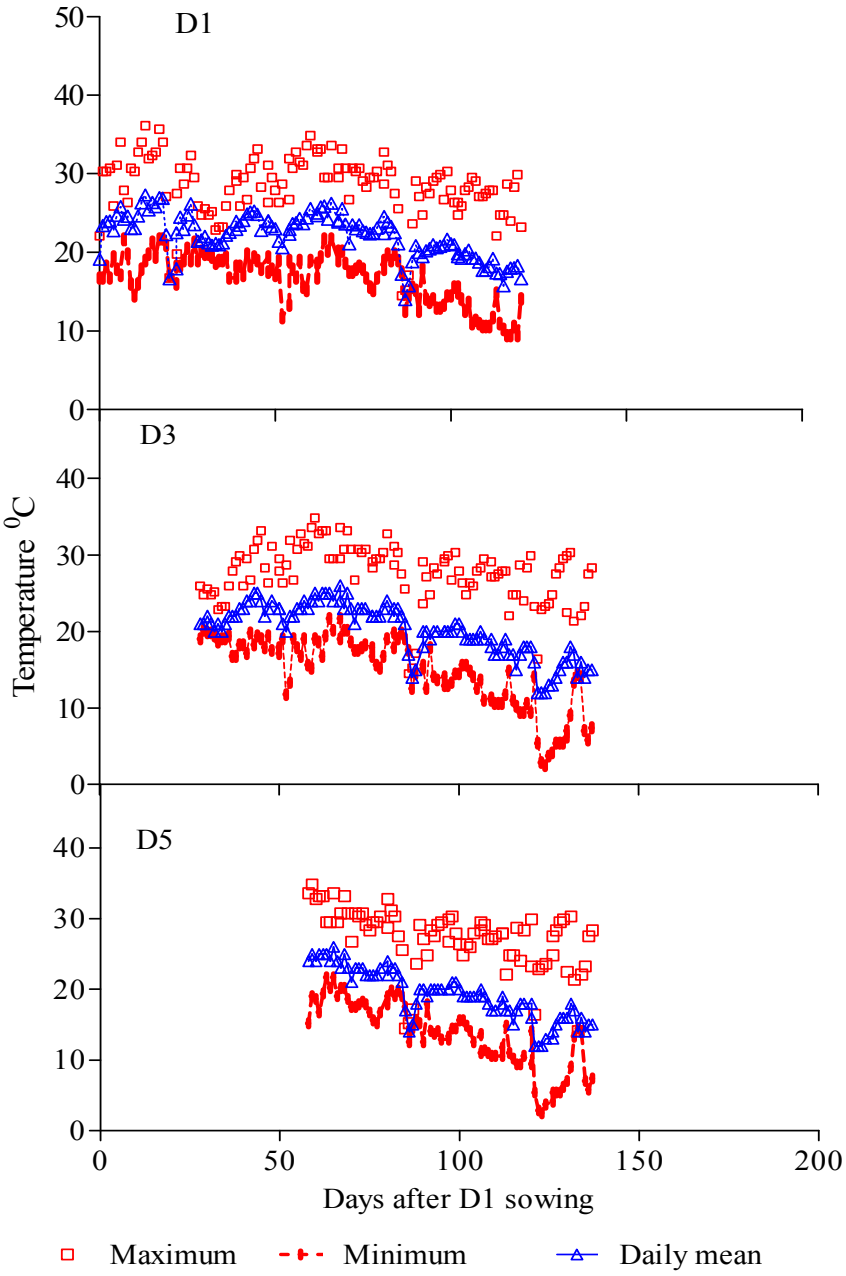

Figure 4.36 Air temperature for three dates of sowing at Notwane, Farm, Botswana College of Agriculture during the experiment of two bambara groundnut landraces (Dip C and Uniswa Red) grown in 2007-2008.

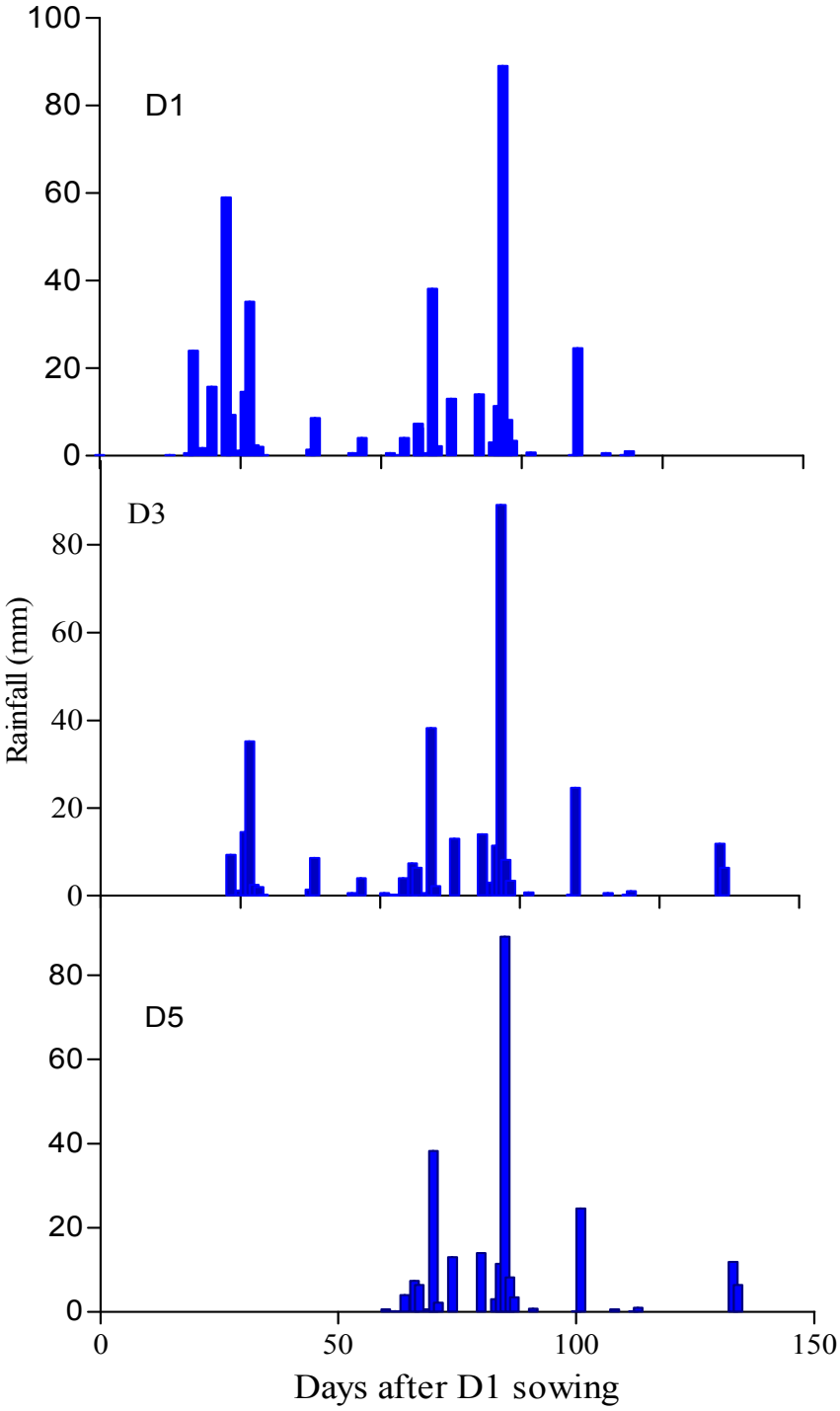

Figure 4.37 Amounts of rain for three dates of sowing in Notwane Farm , Botswana College of Agriculture during the experiment of two bambara groundnut landraces (Dip C and Uniswa Red) grown in 2007- 2008.

4.2.1.2 Soil moisture

Soil moisture was measured for D1 only. Figure 4.38 shows the trend of total soil moisture in each treatment. There was no clear trend in the soil moisture content. The highest soil moisture content was in Dip C plot (269 mm) at 90 DAS in the rain fed treatment following 89 mm rainfall on 86 DAS, and the lowest was 129 mm in Uniswa Red soil, irrigation treatment at 81 DAS. There was a fluctuation in the moisture content, but the difference between the treatments was very small.

4.2.1.3 Growth and development

Emergence (first date of sowing)

Both landraces and treatments started emergence at the same time (7 DAS). The results are presented as mean of each landrace in the irrigation and rain fed treatments, because at the time of emergence all the treatments were irrigated until 63 DAS where the irrigation was terminated in the rain fed treatment. Dip C had a lower mean establishment (75.8%) than Uniswa Red (81.32%) but no significant difference was found between them $P>0.05$.

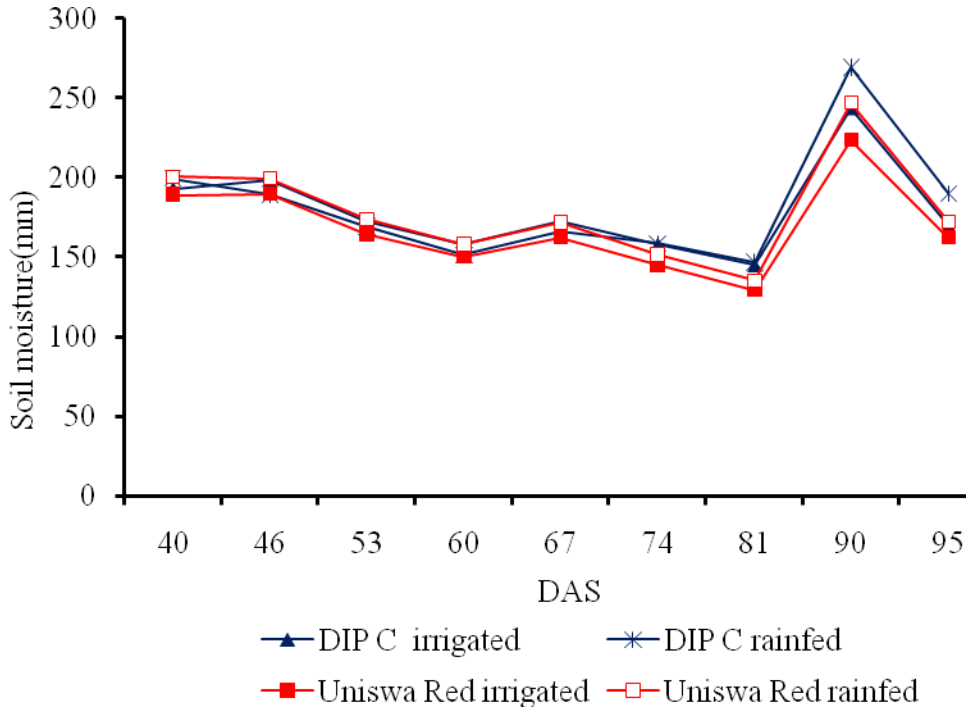

Figure 4.38 Changes in the mean soil moisture content (mm) per treatment throughout the soil profile with time during the experiment of two bambara groundnut landraces (Dip C and Uniswa Red) grown in Notwane Farm, Botswana College of Agriculture. 2007-2008 (First date of sowing).

Leaf appearance

Figure 4.39 shows the number of leaves of Uniswa Red and Dip C plotted against days after sowing for three dates of sowing. At D1 and D3, Dip C gave high number of leaves in both irrigated and rain fed treatment, but it produced fewer leaves in the rain fed treatment at D5. The two landraces showed a decrease in leaf number with delay in sowing.

Figure 4.40 shows the leaf number plotted against cumulative thermal time. Thermal time units needed for leaf production decreased with delay in sowing. In D1, the cumulative thermal time reached 1500, while in D5, the maximum was 750. A regression of leaf number against cumulative thermal time showed significant difference between the three dates of sowing ($P<0.001$) (Figure 4.41).

Pod number

The pod number produced by Dip C and Uniswa Red throughout the three dates of sowing is presented in Figure 4.42. The effect of sowing date was significant ($P< 0.05$) (Appendix2), with pod number reaching 20 pods per plant in D1, while in D5 , but only 2 pods per plant in D5.

Figure 4.43 shows the thermal time accumulated against pod number. Crops sown on D5 needed less thermal time to initiate pods. A regression analysis of pod number against cumulative thermal time showed no significant differences between the sowing dates (Figure 4.44).

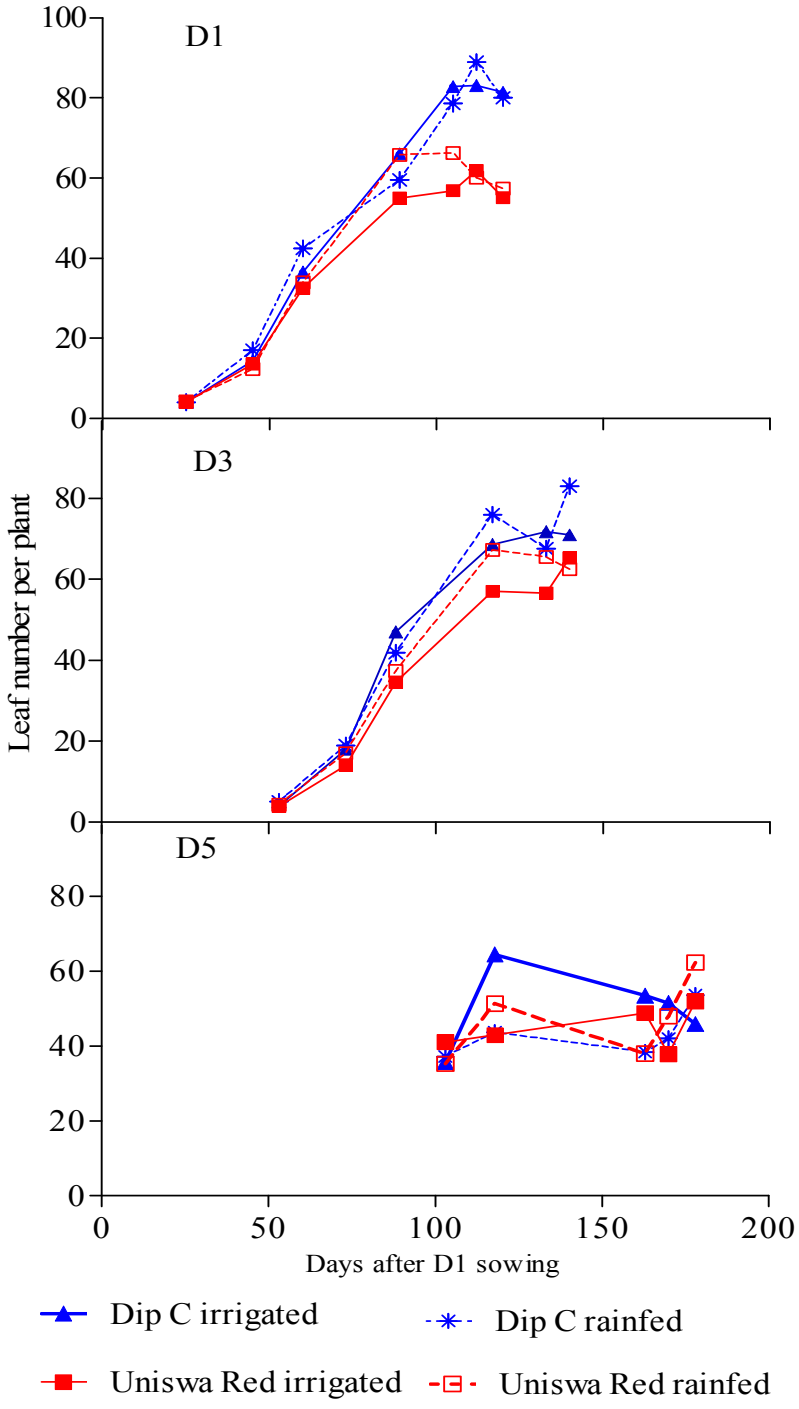

Figure 4.39 The effect of soil moisture and sowing date on the leaf number of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2007-2008.

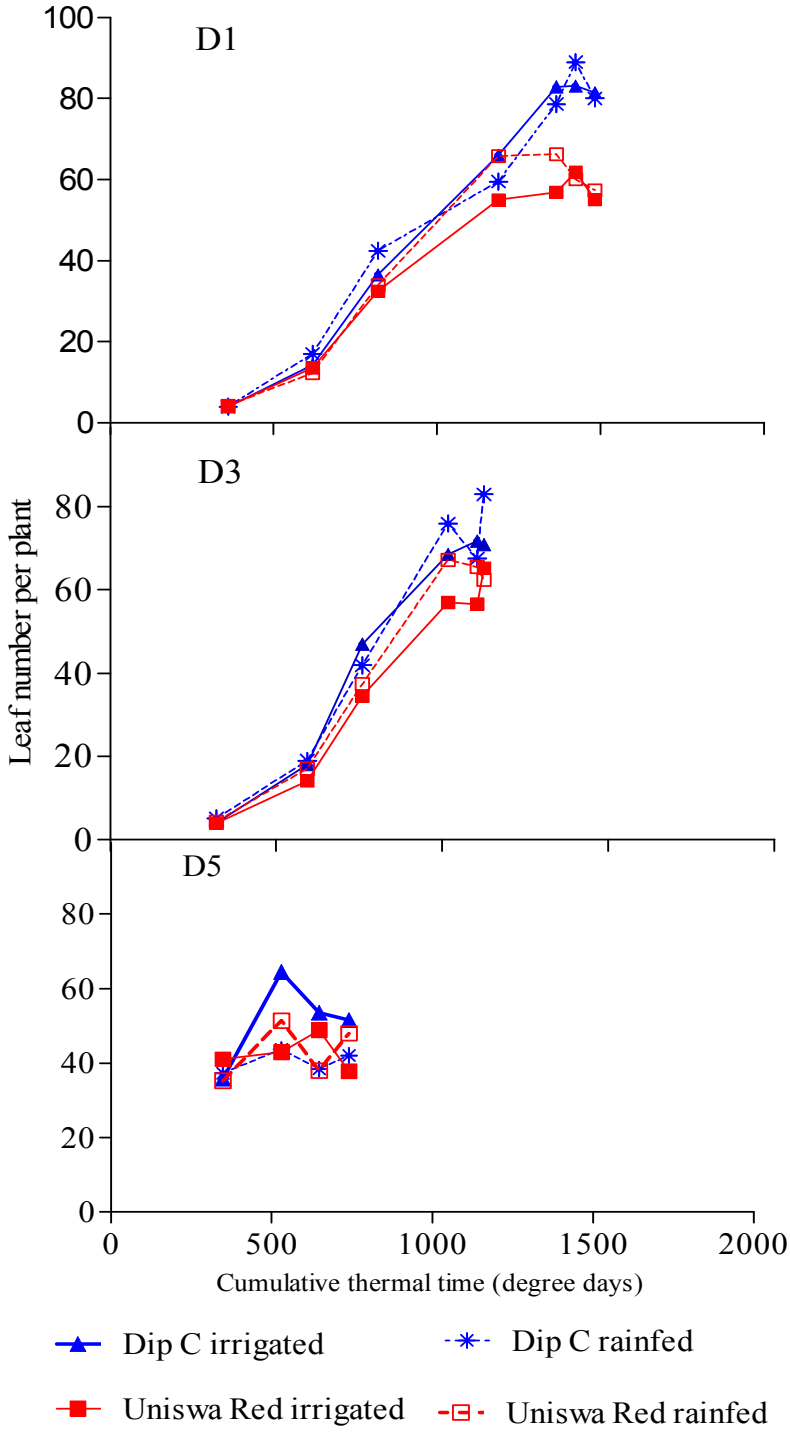

Figure 4.40 Leaf production against cumulative thermal time in two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2007-2008.

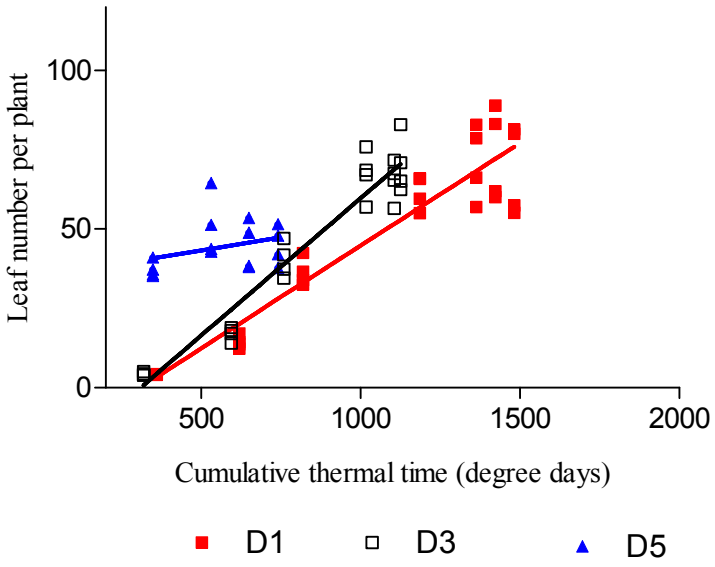

Figure 4.41 Regression of leaf production against cumulative thermal time in two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2007-2008. r^2= 67.1, slopes and constants are presented in Table 4.10.

Table 4.10 Slopes, constants and phyllochron ($^oC^d$ $leaf^{-1}$) obtained from the regression of leaf number per plant against cumulative thermal time (degree days) for two bambara groundnut landraces (Dip C and Uniswa Red) grown in Notwane Farm, Botswana College of Agriculture at three dates of sowing; the first date (D1), the third date (D3) and the fifth date (D5) in 2007-08.

	Treatment	**D1**	**D3**	**D5**
2007-2008	Slope	0.065	0.087	0.017
	se	0.00415	0.00719	0.015
	Constant	-20.03	-26.85	35.03
	se	4.7	6.95	9.1
	Phyllochron	15.38	11.49	58.82

Leaf Area index

Leaf area index development in the bambara groundnut landraces in D1 is presented in Figure 4.45. The highest peak of leaf area index (4.3) was reached by Uniswa Red at the rain fed treatment with no significant differences (P> 0.05).

Specific Leaf area

Changes in specific leaf area (SLA) for D1 are presented in Figure 4.46. There was no evident difference between treatments until the end of the season, but the irrigated Uniswa Red had the highest value until 89 DAS with no significant difference.

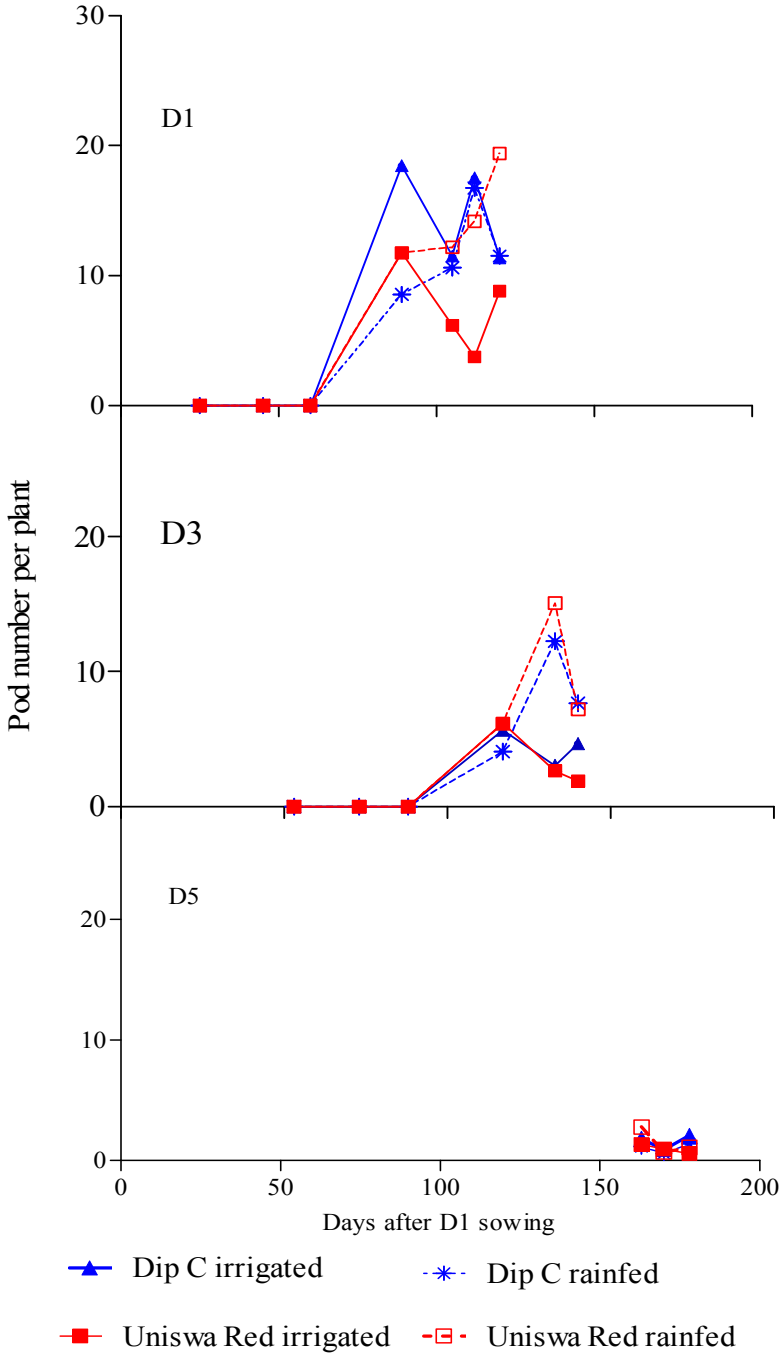

Figure 4.42 The effect of soil moisture and sowing date on the pod number of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2007-2008.

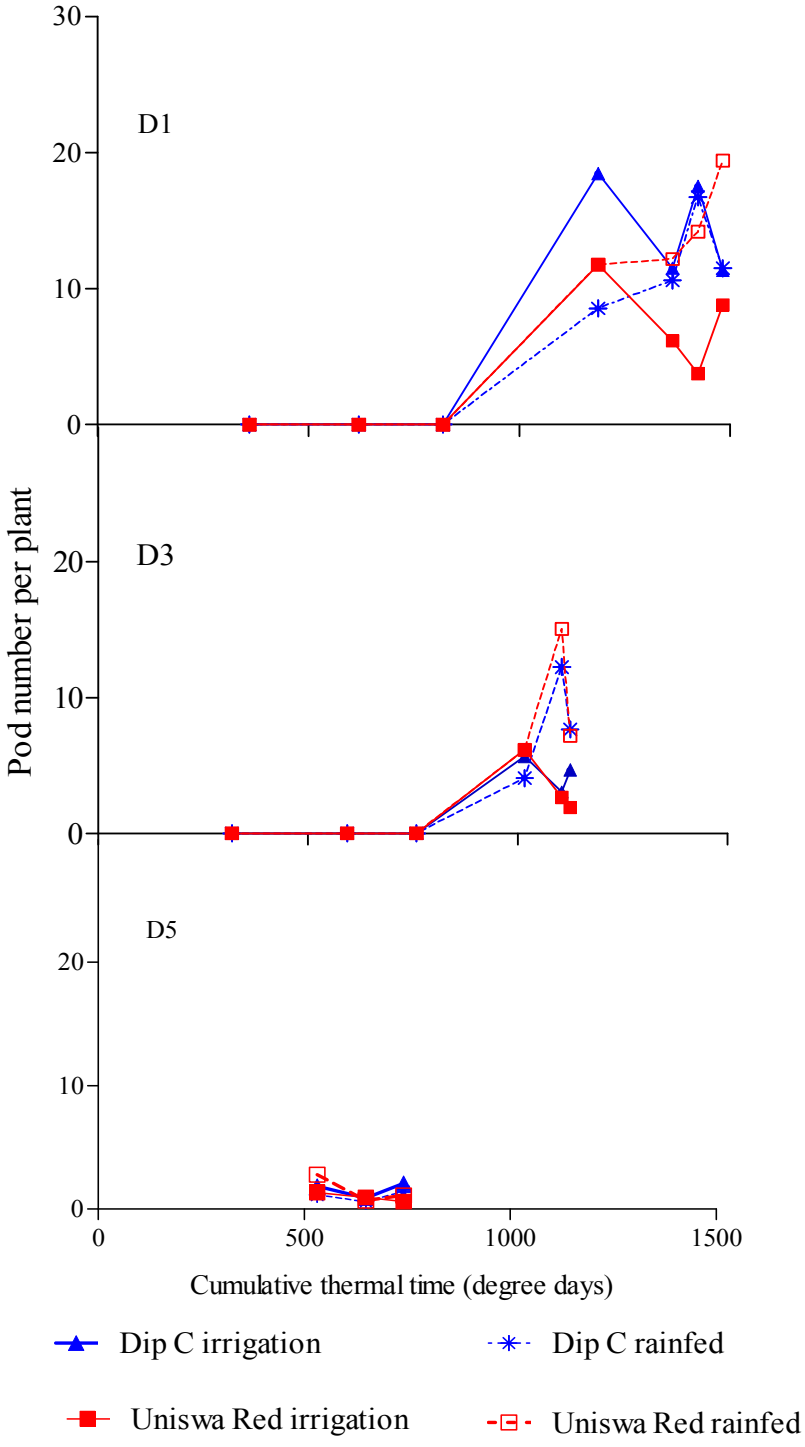

Figure 4.43 Pod production against cumulative thermal time in two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2007-2008.

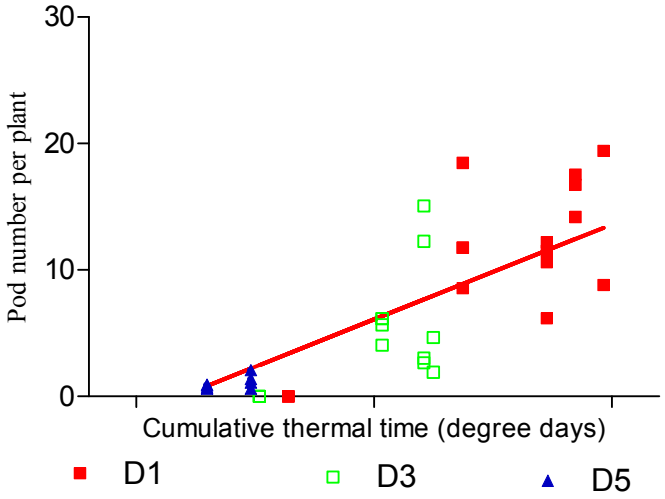

Figure 4.44 Regression of pod number against cumulative thermal time in two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2007-2008. The regression equation is y= 0.016x-10.54, r^2=65.3.

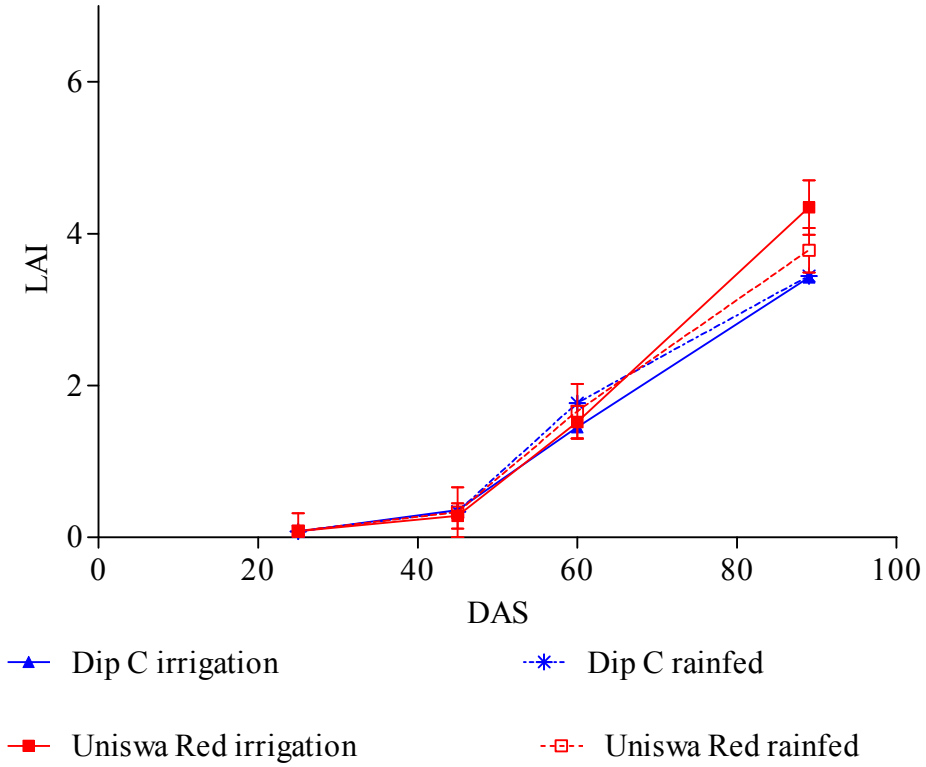

Figure 4.45 The effect of soil moisture and temperature on the leaf area index (LAI) of two bambara groundnut landraces (Dip C and Uniswa Red) grown in Notwane Farm, Botswana College of Agriculture. First date of sowing 2007-2008. The Vertical bars represent SEM values.

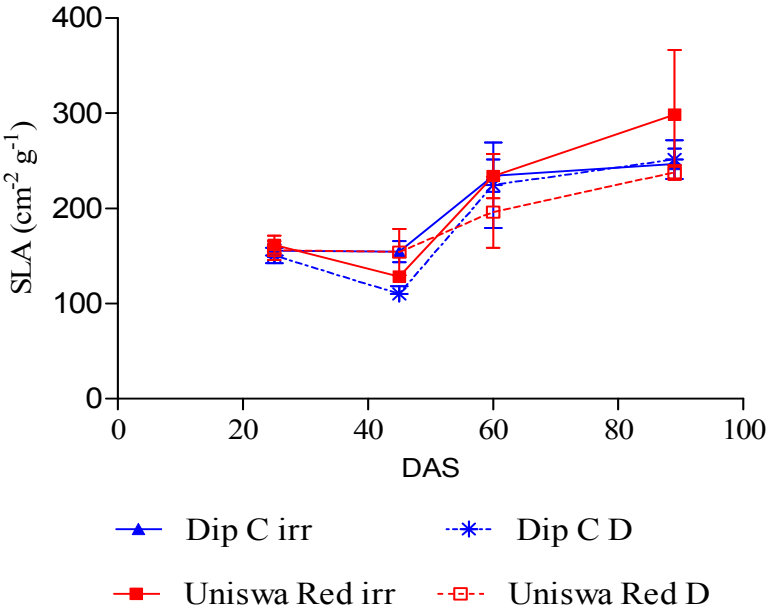

Figure 4.46 The effect of soil moisture and temperature on the specific leaf area of two bambara groundnut landraces (Dip C and Uniswa Red) grown in Notwane Farm, Botswana College of Agriculture. (First date of sowing) 2007-2008. The vertical bars represent SEM values.

Total dry matter

Total dry matter (TDM) accumulation for each landrace and each treatment is shown in Figure 4.47. The statistical analysis showed no significant interaction effect of the landrace, sowing date and temperature ($P>0.05$) (Appendix 2). TDM accumulated in D1, was significantly higher than TDM accumulated in D5. In D1, the amount of accumulated TDM started to decline from 105 DAS.

Leaf dry matter

The leaf dry matter (LDM) accumulation throughout three sowing dates in Dip C and Uniswa Red is presented in Figure 4.48. The statistical analysis showed that sowing date had a high significant effect on the LDM accumulation ($P<0.001$), but no interaction effect was found (Appendix 2). The amount of LDM reached close to 300 gm^{-2} in D1, while in D5, the maximum amount was around 100 gm^{-2}. In D1, towards the end of the season, Dip C accumulated more LDM than Uniswa Red.

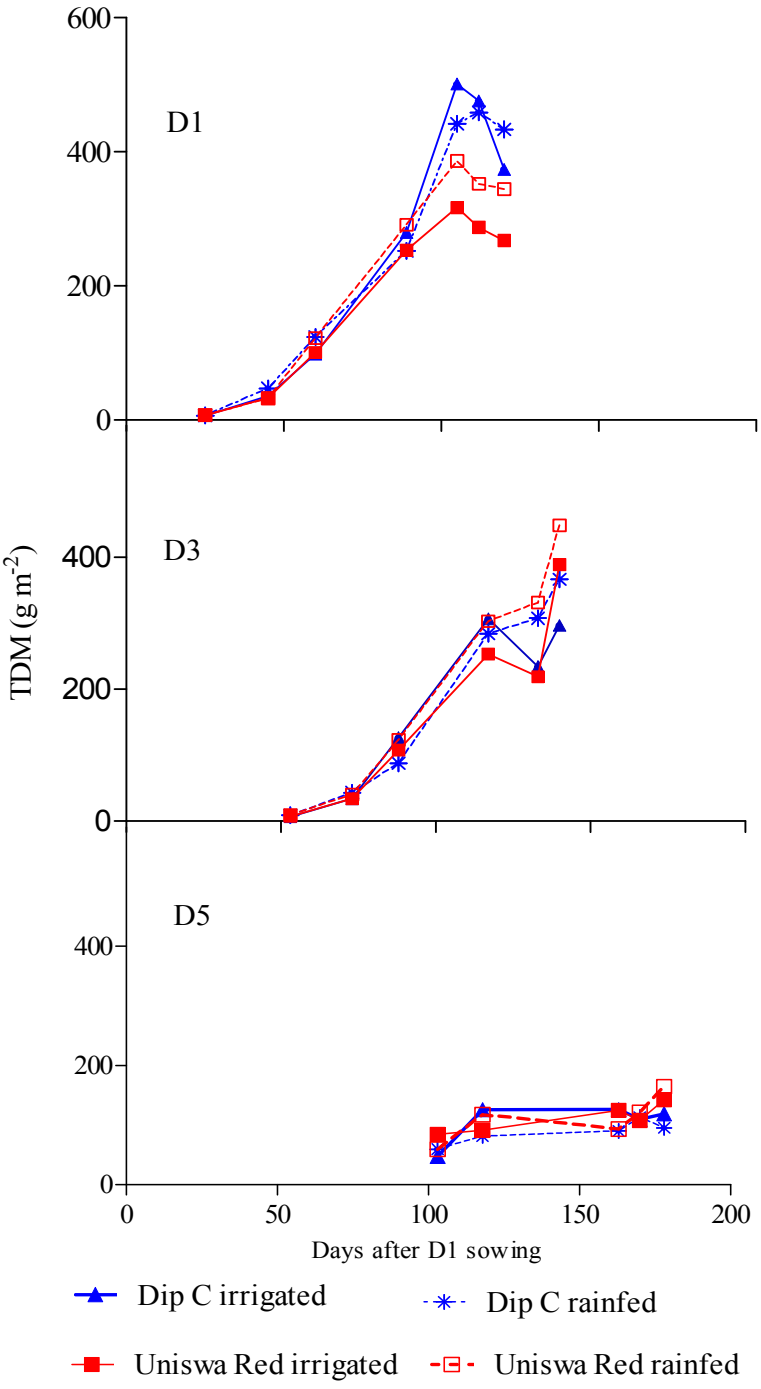

Figure 4.47 The effect of soil moisture and sowing date on the total dry matter production of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2007-2008.

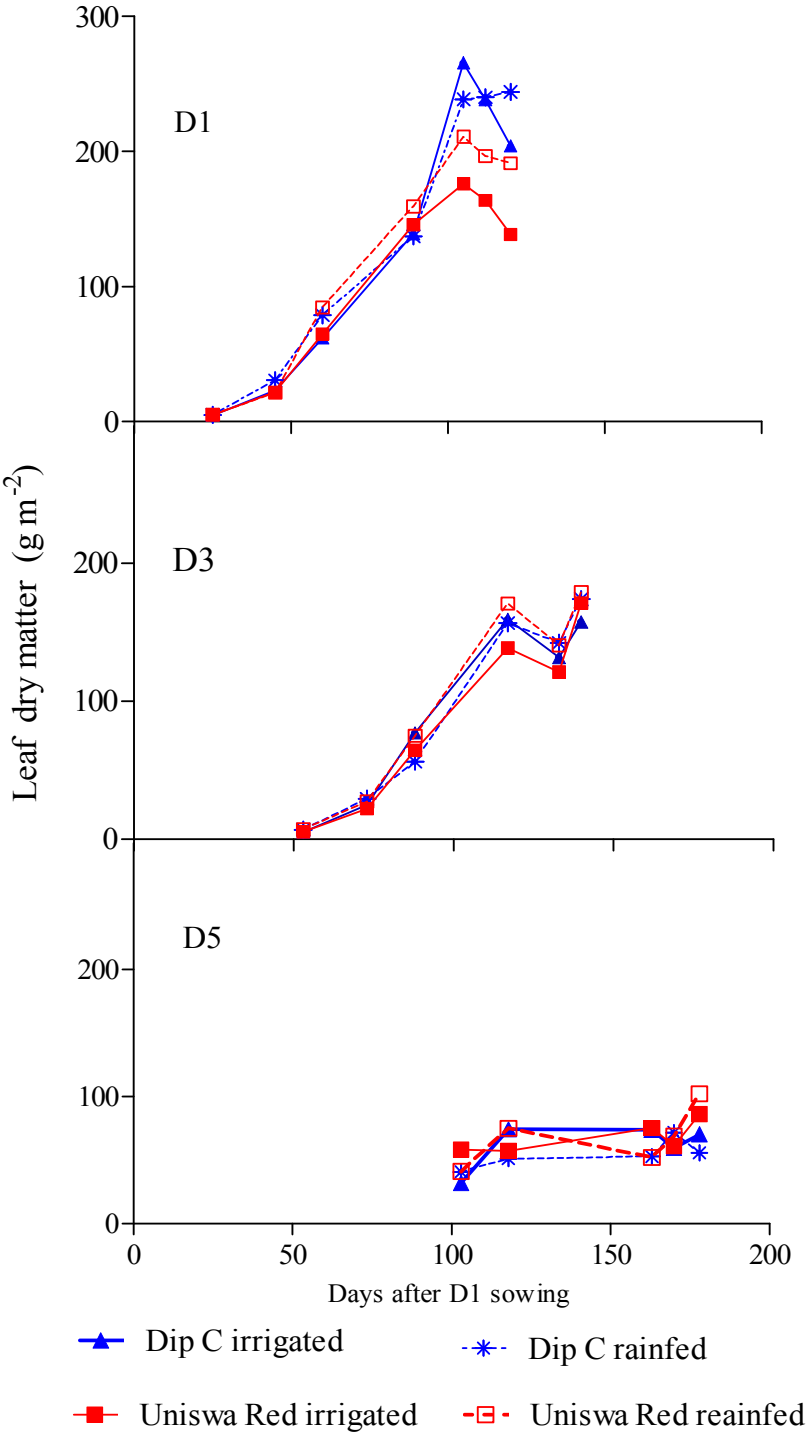

Figure 4.48 The effect of soil moisture and sowing date on the leaf dry matter production of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2007-2008.

Pod dry matter

Figure 4.49 shows the pod dry matter (PDM) accumulation throughout three sowing dates in Dip C and Uniswa Red. The accumulated pod dry matter in the D3 was higher than the accumulated PDM in D1 and D5 ($P<0.001$).

4.2.1.4 Yield and yield component

Table 4.11 shows yield, TDM, shelling percentage and harvest index (HI) of the three dates of sowing. The highest yield (97.6 g m^{-2}) was produced by Uniswa Red in D1, and the lowest was given by Dip C in the rainfed treatment sown on D5. The yield differed significantly between the landraces and the sowing date ($P<0.05$). Although the statistical analysis showed no significant differences, the results a showed decrease in HI with the delay of sowing.

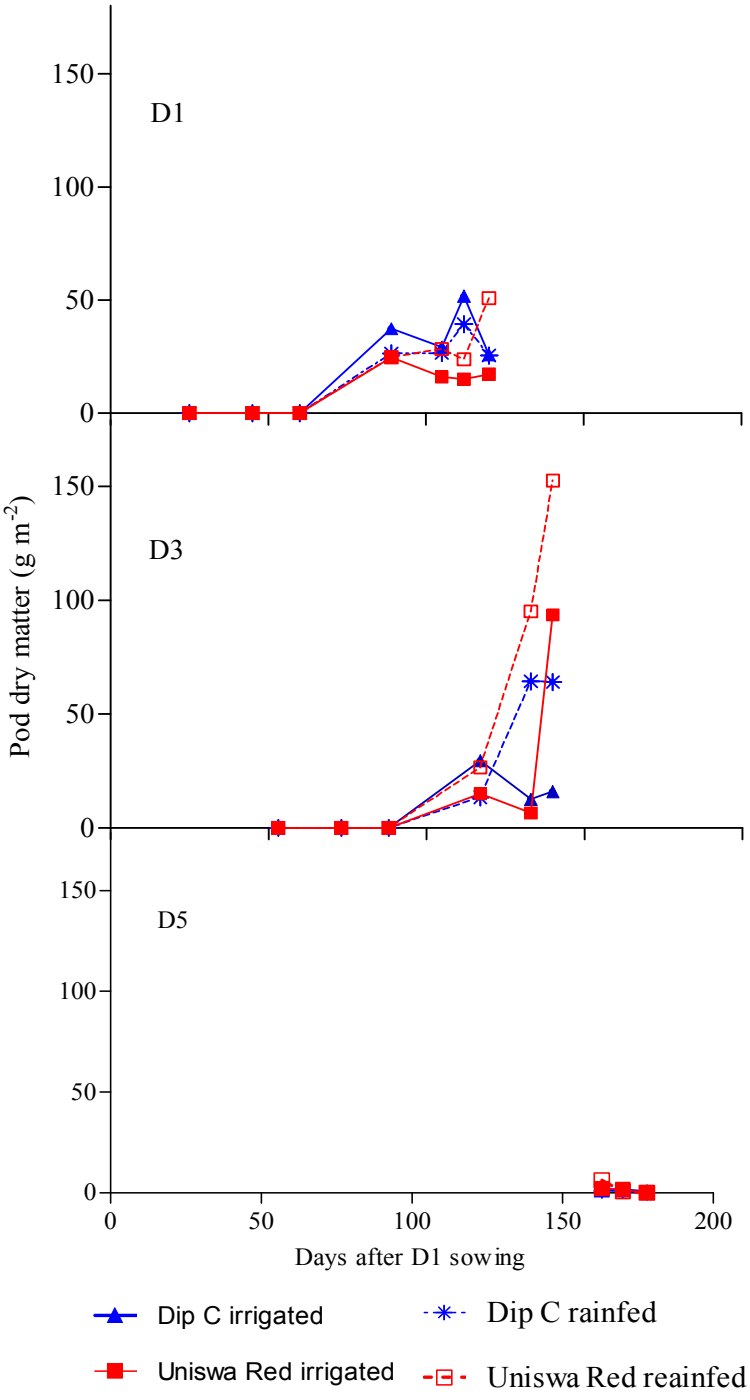

Figure 4.49 The effect of soil moisture and sowing date on the pod dry matter production of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2007-2008.

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Table 4.11 Yield components and yield (gm^{-2}) (from final harvest) among two landraces of bambara groundnut (Dip C and Uniswa Red) grown in Notwane Farm, Botswana College of Agriculture at three dates of sowing; the first date (D1), the third date (D3) and the fifth date (D5) under two water regimes; irrigation (irr) and rainfed (rf) during the experiment of 2007-2008

	Treatment	Seed yield g^{-2}	HI	TDM g^{-2}	Shelling %	Pod yield gm^{-2}
D1	Dip C irr	83.3	0.32	373.7	30.15	119.3
	Dip C rf	53.5	0.17	433.2	28.19	74.5
	UNI irr	94.9	0.5	267.9	29.58	134.9
	UNI rf	97.6	0.37	344.3	23.95	128.6
D3	Dip C irr	13.8	0.06	296.4	31.31	19.8
	Dip C rf	59.8	0.25	366.1	36.54	93.8
	UNI irr	18.4	0.07	388.5	30.69	26.4
	UNI rf	95.1	0.4	331.3	26.28	129.1
D5	Dip C irr	1.3	0.03	119.2	60.59	3.3
	Dip C rf	2.5	0.04	95.3	34.66	4
	UNI irr	3.6	0.04	142.2	39.4	5.6
	UNI rf	5.9	0.07	164.6	50	11.9

	Yield		***HI***		***TDM***	
	df	***SED***	***df***	***SED***	***df***	***SED***
Landrace	3	5.72*	18	0.01^{ns}	18	28.59
Sowing date	19	13.0*	15	0.04^{ns}	15	34.7***
irrigation	19	10.6^{ns}	15	0.03^{ns}	15	28.33
*Landrace*sowing date*irrigation*	21.98	16.1^{ns}	19.4	0.06^{ns}	32.78	69.72

*ns for not significant, * for P≤ 0.05, ** for P≤0.01 and *** for P≤0.001*

4.2.1.5 Water capture

Evaporation (E_s)

Figure 4.50 shows the cumulative Es from the soil surface in D1. The lowest amount of Es was in rain fed Dip C and the highest was in irrigated Dip C.

Evapotranspiration (E_t)

Figure 4.51 shows the cumulative amount of water used by the two landraces in D1 in the irrigation and rain fed treatments between 53 and 95 DAS (no soil moisture measurements were taken for the rest of sowing dates). Uniswa Red in the rain fed treatment had the most evapotranspired water throughout the season.

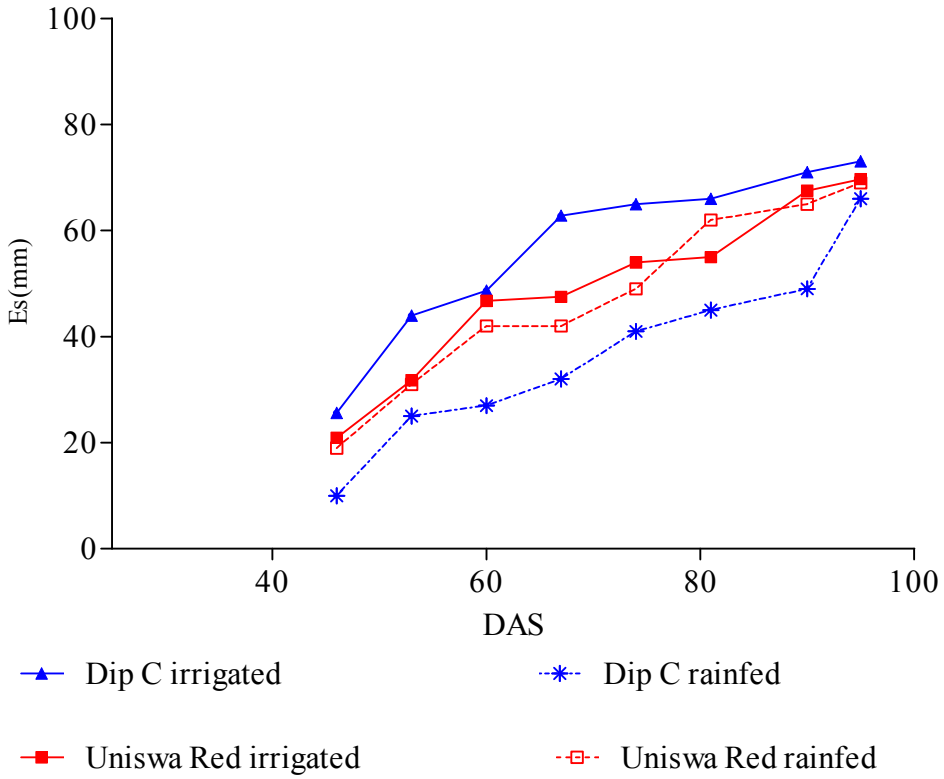

Figure 4.50 Cumulative soil surface evaporation (mm) from stands of two bambara groundnut landraces (Dip C and Uniswa Red) grown in Notwane Farm, Botswana College of Agriculture. (First date of sowing) 2007-2008.

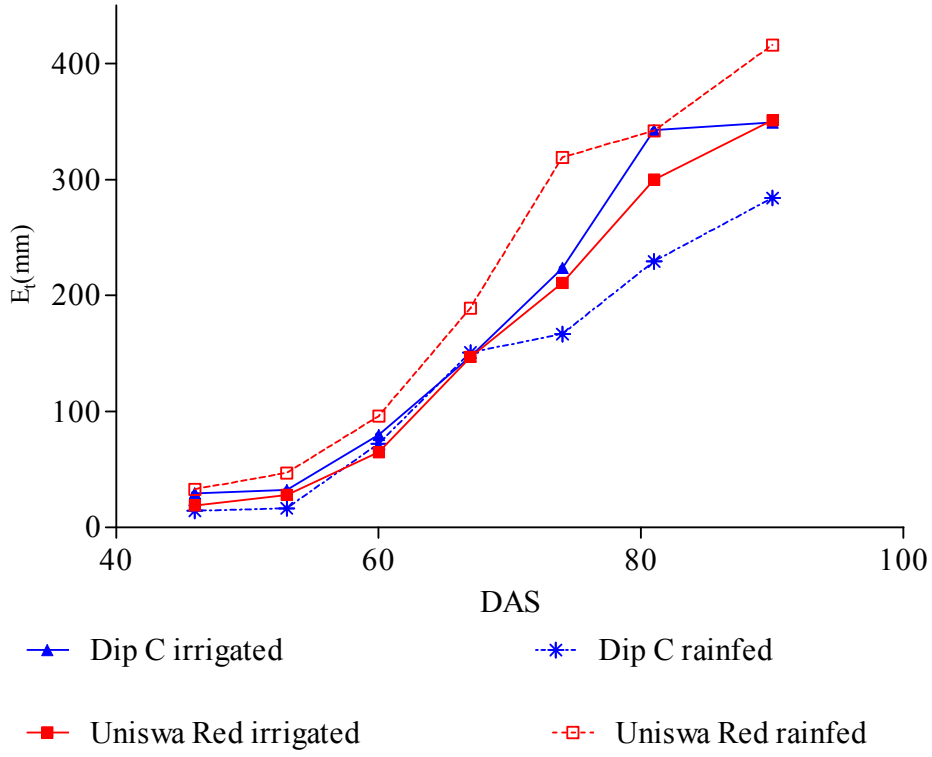

Figure 4.51 Cumulative evapotranspiration (mm) from stands of two bambara groundnut landraces (Dip C and Uniswa Red) grown in Notwane Farm, Botswana College of Agriculture. (First date of sowing) 2007-2008.

Water distribution and extraction from the soil profile

The distribution of water in each layer of the soil profile and the pattern of water extraction for each landrace and treatment in D1 is presented in Figure 4.52. The water distribution throughout the layers was similar in the four treatments. The first layer (20cm) had the lowest moisture throughout the season, while the 120cm layer, had the highest. There was no obvious pattern in the soil moisture because of the frequent rainfall which kept the soil moist for most of the growing period.

Water use efficiency

Figure 4.53 shows the regression results of total dry matter (TDM) against transpired water for D1. There was a significant linear relationship ($P<0.01$) between Transpiration (T) and TDM. A comparison of the regression of T against TDM showed no significant difference between treatments ($P>0.05$).

4.2.1.6 Leaf relative water content

Figure 4.54 shows the leaf relative water content of Dip C and Uniswa Red in rain fed and irrigated treatments. The two landraces in both treatments and during the three dates of sowing managed to keep the relative water content over 75%.

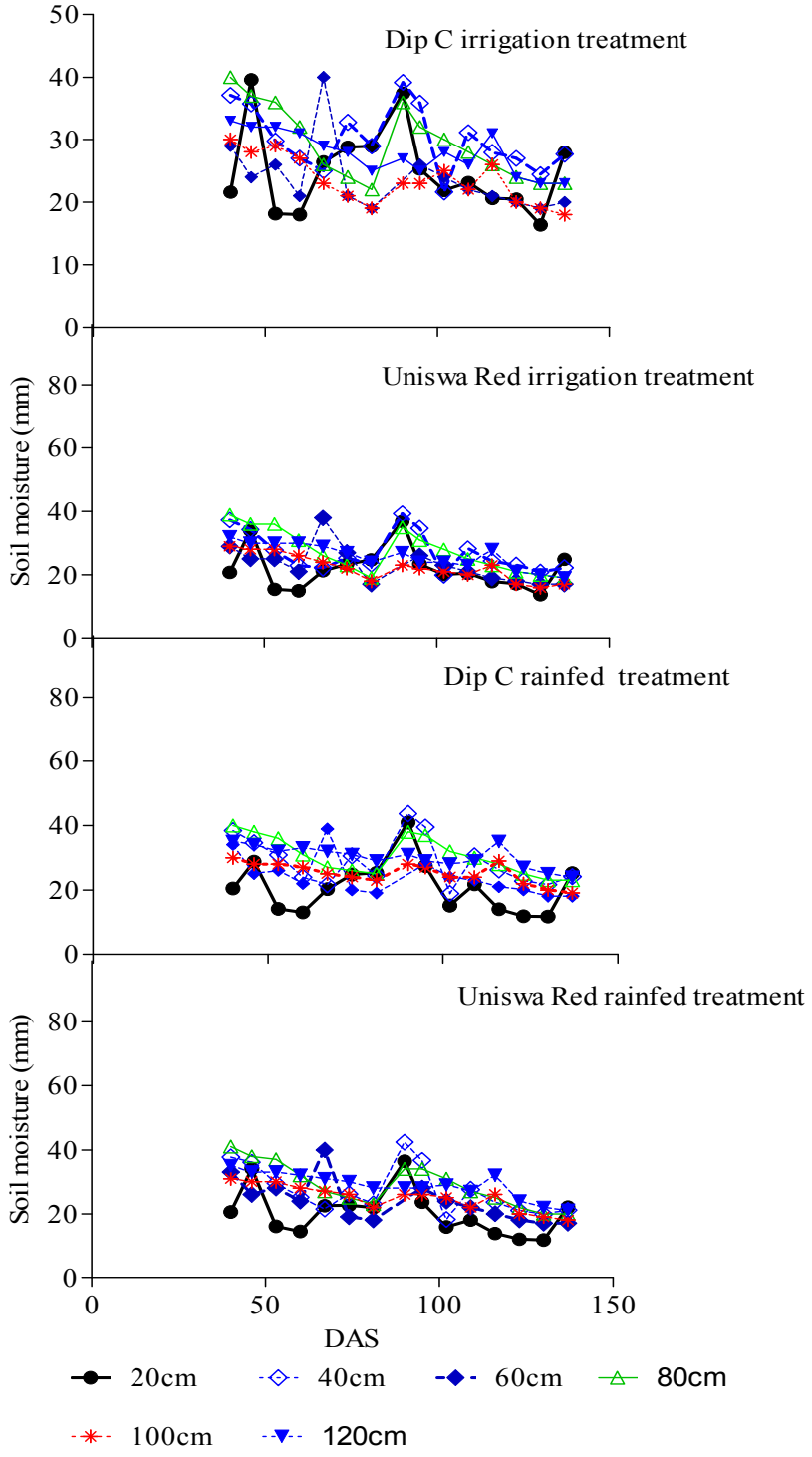

Figure 4.52 Profile soil moisture content (mm) at two water treatment of two bambara groundnut landraces (Dip C and Uniswa Red) grown in in Notwane Farm, Botswana College of Agriculture. (First date of sowing) 2007-2008.

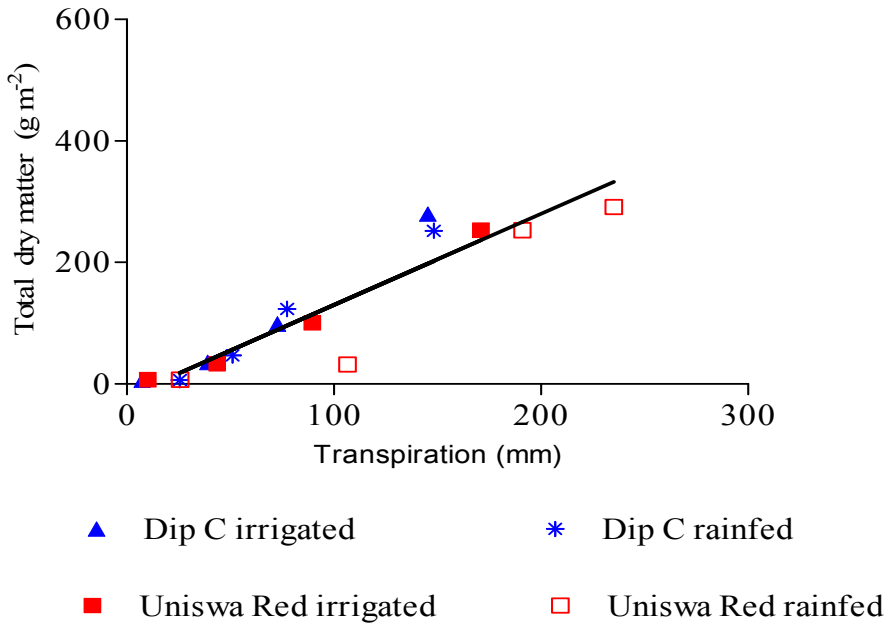

Figure 4.53 Regression of total dry matter (g m^{-2}) against transpiration (mm) for two bambara groundnut landraces (Dip C and Uniswa Red) grown during the experiment of 2007-2008 (First date of sowing) at Notwane Farm, Botswana College of Agriculture. The regression equation is: y= 1.5x-19.9, r^2=91.6.

4.2.1.7 Stomatal conductance

Stomatal conductance of Dip C and Uniswa Red for three dates of sowing is shown in Figure 4.55. The pattern was different between the three dates of sowing. In D1, stomatal conductance started with low values (92-159 mmol m^{-2} s^{-1}) and started to increase with progress in the growing season. By the end of the season, the stomatal conductance dropped down to less than 50 mmol m^{-2} s^{-1} . In D3, the stomatal conductance decreased from 314-366 mmol m^{-2} s^{-1} at 68 DAS to 36-59 m^{-2} s^{-1} at 120 DAS. In D5, Dip C at the rainfed treatment gave the highest stomatal conductance value (330 mmol m^{-2} s^{-1})

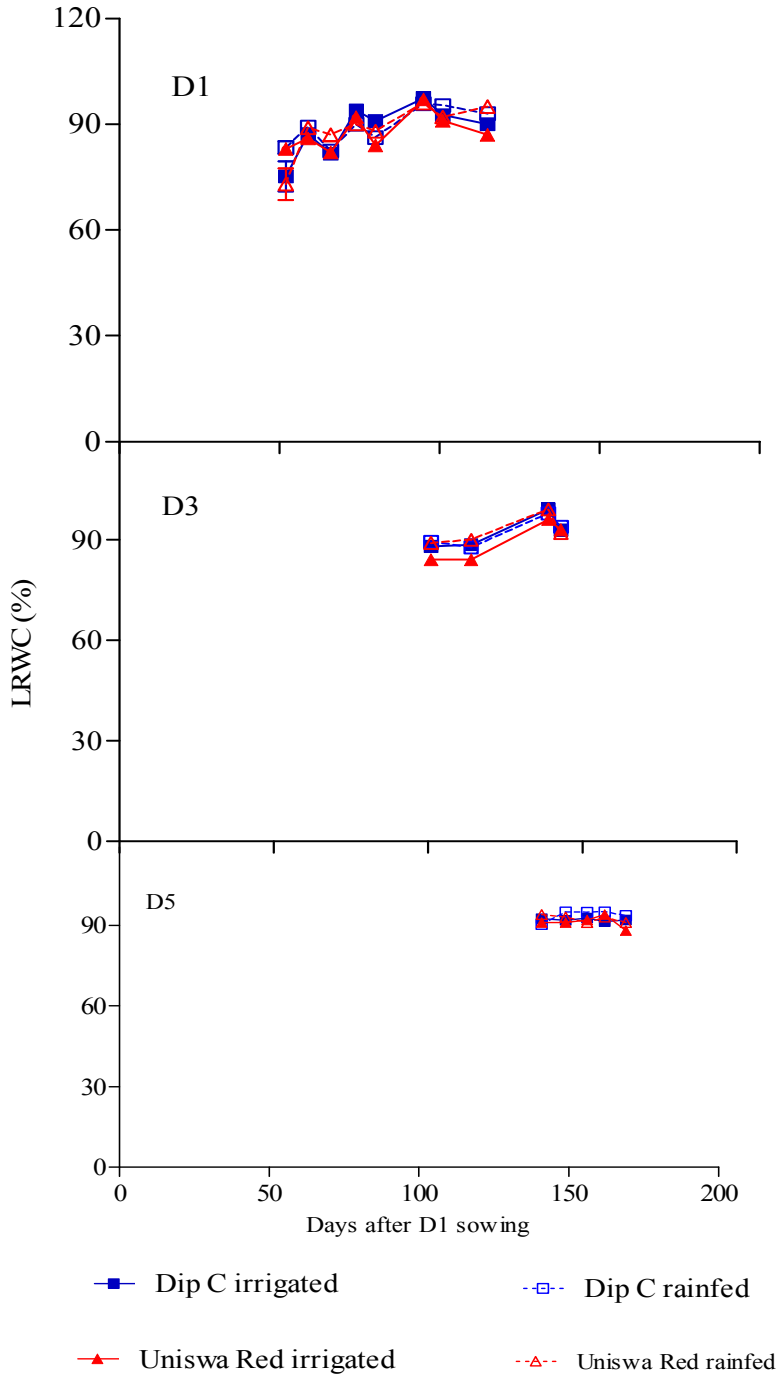

Figure 4.54 The effect of soil moisture and sowing date on the leaf relative water content of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2007-2008.

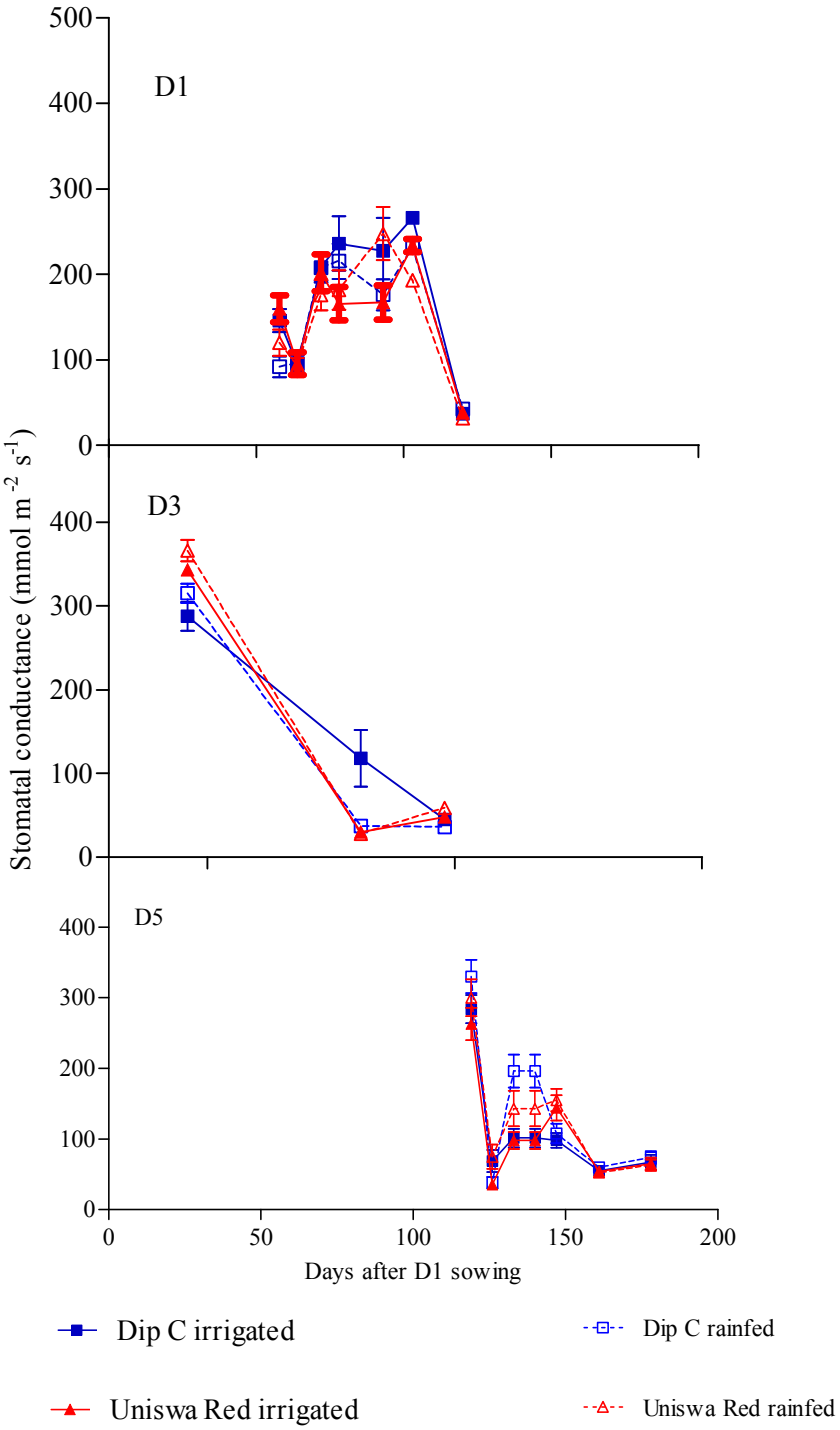

Figure 4.55 The effect of soil moisture and sowing date on the stomatal conductance (mmol m^{-2} s^{-1}) of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2007-2008.

4.2.2 Results of the second growing season 2008-2009

4.2.2.1 Temperature and rainfall

Figure 4.56 shows the maximum, the minimum and the daily mean of temperature at Notwane farm, for D1, D3 and D5. For D1, maximum temperature ranged between 22 ^{o}C and 37^{o}C and the minimum between 4^{o}C and 24^{o}C. The daily mean ranged between 18 to 29 °C .For D3, the maximum temperature ranged between 22 and 35 ^{o}C , and the minimum between 4 to 24, and the daily mean ranged between 18 to 28 ^{o}C. For D5, the maximum temperature ranged between 22 to 28 ^{o}C, the minimum between 4 to 13 ^{o}C the daily mean between 18 ^{o}C and 25 ^{o}C.

The total amounts of rain were 344, 318 and 133 mm, for D1, D3 and D5, respectively. Figure 3.57 shows the distribution of rainfall during the three dates of sowing.

4.2.2.2 Soil moisture

Soil moisture content of each treatment for three dates of sowing is presented in Figure 4.58. In the three dates of sowing, Dip C in the irrigated treatments had the highest soil moisture content. Although the rainfall did not give a chance for drought to occur, it can be seen that there was a decrease in the soil moisture towards the end of the growing seasons. For example, D1, the moisture content for Dip C under irrigation decreased from 203 mm at 35 DAS to 136 mm at 126 DAS.

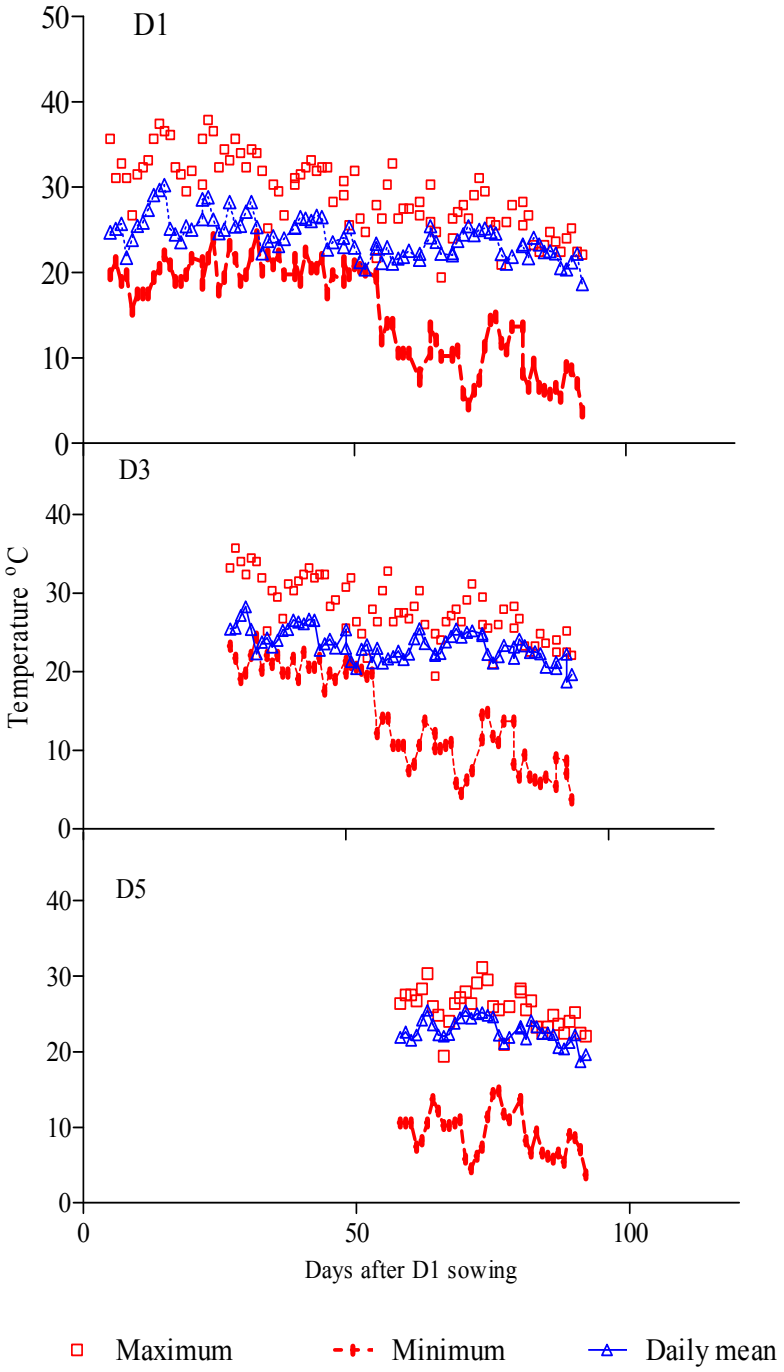

Figure 4.56 Air temperature for three dates of sowing at Notwane, Farm, Botswana College of Agriculture during the experiment of two bambara groundnut landraces (Dip C and Uniswa Red) grown in 2008-2009.

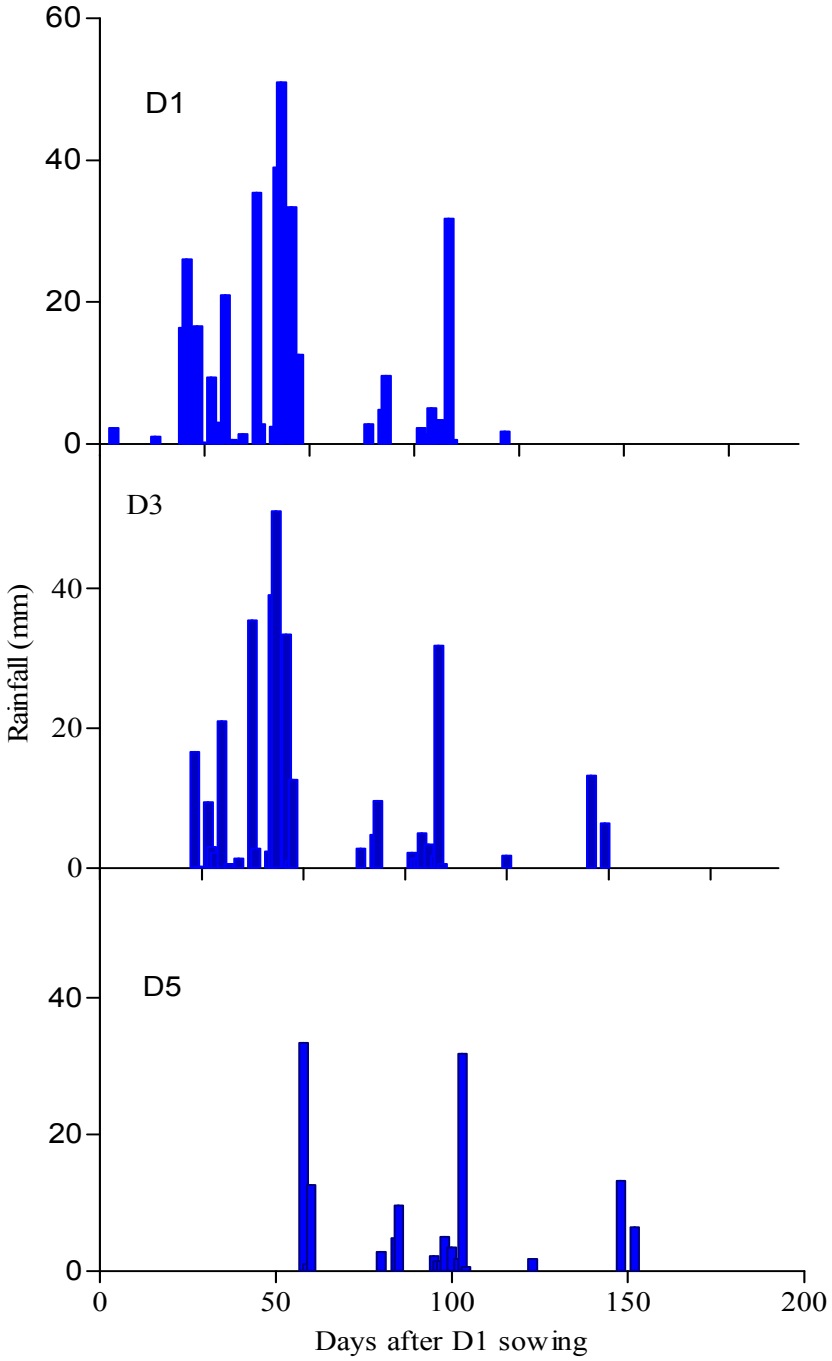

Figure 4.57 Amounts of rain for three dates of sowing in Notwane Farm , Botswana College of Agriculture during the experiment of two bambara groundnut landraces (Dip C and Uniswa Red) grown in 2008- 2009.

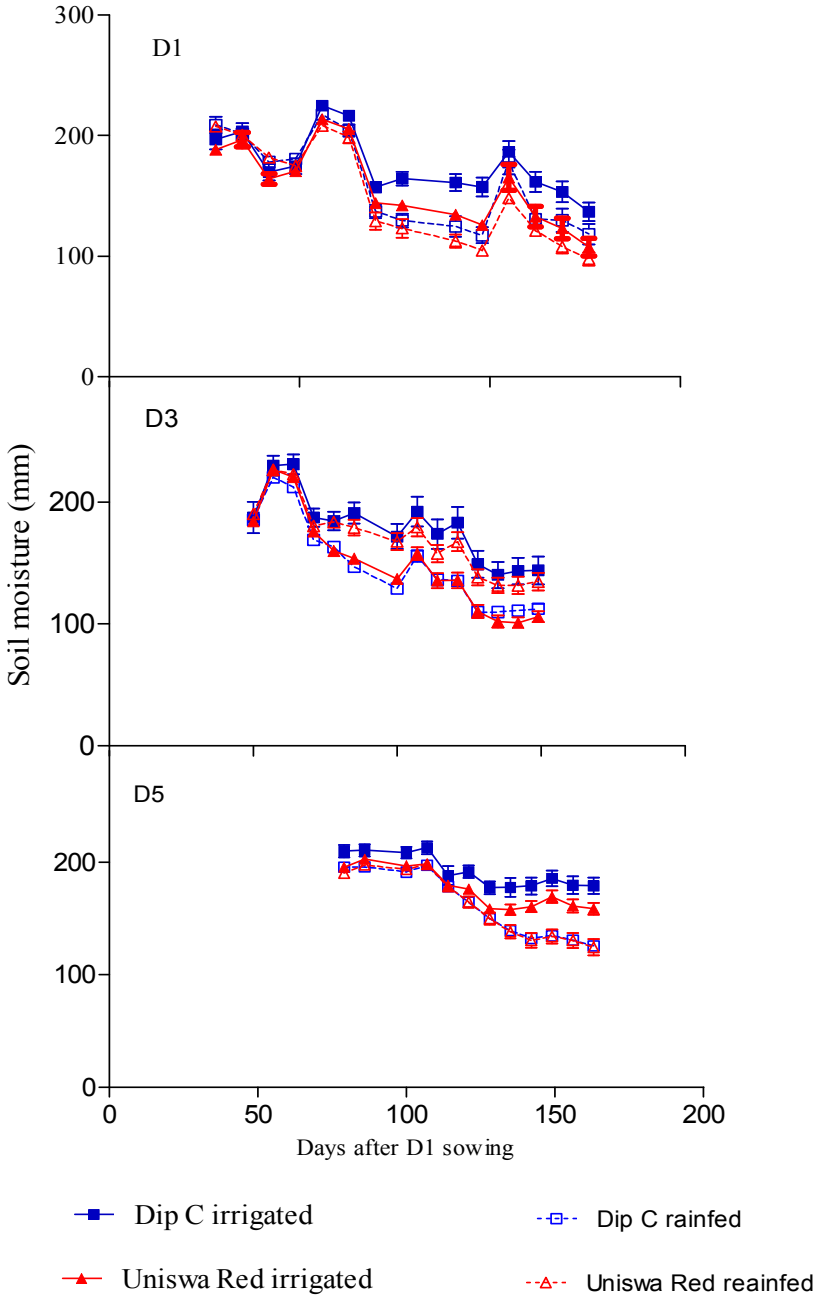

Figure 4.58 Changes in the mean soil moisture content (mm) per treatment throughout the soil profile with time during the experiment of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three sowing dates in Notwane Farm, Botswana College of Agriculture. 2008-2009. The vertical bars present SEM values.

In D3, Dip C under rain fed conditions with Uniswa Red under irrigation had less moisture content than the other two treatments. In D5, the soil moisture was almost similar in the four treatments, but from 135 DAS, the difference between rain fed and irrigated treatments started to be more obvious.

4.2.2.3 Growth analysis

Emergence

The results are presented in Table 4.12 as means of each landrace in the irrigated and rain fed treatments, because at the time of emergence all the treatments are irrigated until 30 DAS when the irrigation was terminated from the rainfed treatment. Both landraces and treatments started emergence at 9 DAS for D1 and D3, and 10 DAS for D5. Dip C had a lower establishment than Uniswa Red in the three dates of sowing. But no significant difference was found between them P>0.05. For the two landraces the highest establishment was achieved in D3.

Table 4.12 Establishment (%) of two landraces of bambara groundnut (Dip C and Uniswa Red) grown in Notwane Farm, Botswana College of Agriculture at three dates of sowing; the first date (D1), the third date (D3) and the fifth date (D5). The values represent the mean of irrigation and rainfed treatments for each sowing date during the experiment of 2008-2009.

	Sowing date		
landrace	**D1**	**D3**	**D5**
Dip C	68	88	66
Uniswa Red	76	90	82

SED = 5.05 P = 0.2 df= 30

Leaf appearance

Figure 4.59 shows the number of leaves of Uniswa Red and Dip C plotted against days after sowing for three dates of sowing. There was no certain pattern of the leaf number production among the three dates of sowing; in D1, Dip C under irrigation had the lowest leaf number throughout most of the growing stages, but in D3, Dip C under irrigation produced more leaves than the other treatments until 89 DAS when the leaf number decreased. This pattern did not exist in D5. All the statistical analysis parameters had no significant effect on the leaf number production ($P>0.05$), except the sowing date effect ($P<0.001$) (Appendix 2). Both landraces produced more leaves in D1 than in D3 and D5. The leaf number reached maximum of 84 leaves per plant by Dip C under irrigation in D1, but only 60 leaves per plant in D5 were achieved by Uniswa Red rain fed treatment.

Figure 4.60 shows the number of leaves plotted against cumulative thermal time in D1 and D3 (There was not enough thermal time data to be plotted with number of leaves from D5 because of a technical fault in the weather station). Regression analysis of leaf number against thermal time showed significant difference between D1 and D3 ($P<0.01$). Phyllochron values were 20 and 6.66 $^{o}C^{d}$ $leaf^{-1}$ for D1 and D3 respectively (Figure 4.61).

Pod number

The number of pods produced by Dip C and Uniswa Red in three dates of sowing is presented in Figure 4.62 Sowing date had a significant effect on pod number production ($P<0.01$) (Appendix2) with delays in sowing reducing pod number.

Figure 4.63 shows the pod number plotted against thermal time for the first and the third date of sowing. Crops on D1 accumulated more thermal time than crops on D5. A regression analysis of pod number against thermal time showed no significant differences between the sowing dates (Figure 4.64).

Leaf area index

Leaf area index in the bambara groundnut landraces (Dip C and Uniswa Red) for three dates of sowing is presented in Figure 4.65 The highest peak of leaf area index (3.2) was reached in D1 by the irrigated Uniswa Red, while the highest peak was 0.5 in D5 reached by the rain fed Uniswa Red. Sowing date had a significant effect on the leaf area index ($P< 0.001$) (Appendix 2).

Figure 4.66 shows LAI plotted against thermal time. For D5 and D3, the crops accumulated less thermal time and had less LAI than D1.

Specific leaf area

Figure 4.67 shows that specific leaf area decreased towards the end of the season for Dip C and Uniswa Red in all three sowing dates. SLA decreased significantly with delay in sowing ($P<0.001$). (Appendix 2). In D1, SLA reached 400 cm^{-2} g^{-1}, but in D5 it reached a maximum of 168 cm^{-2} g^{-1}. No significant differences were found between the landraces or the treatments ($P>0.05$)

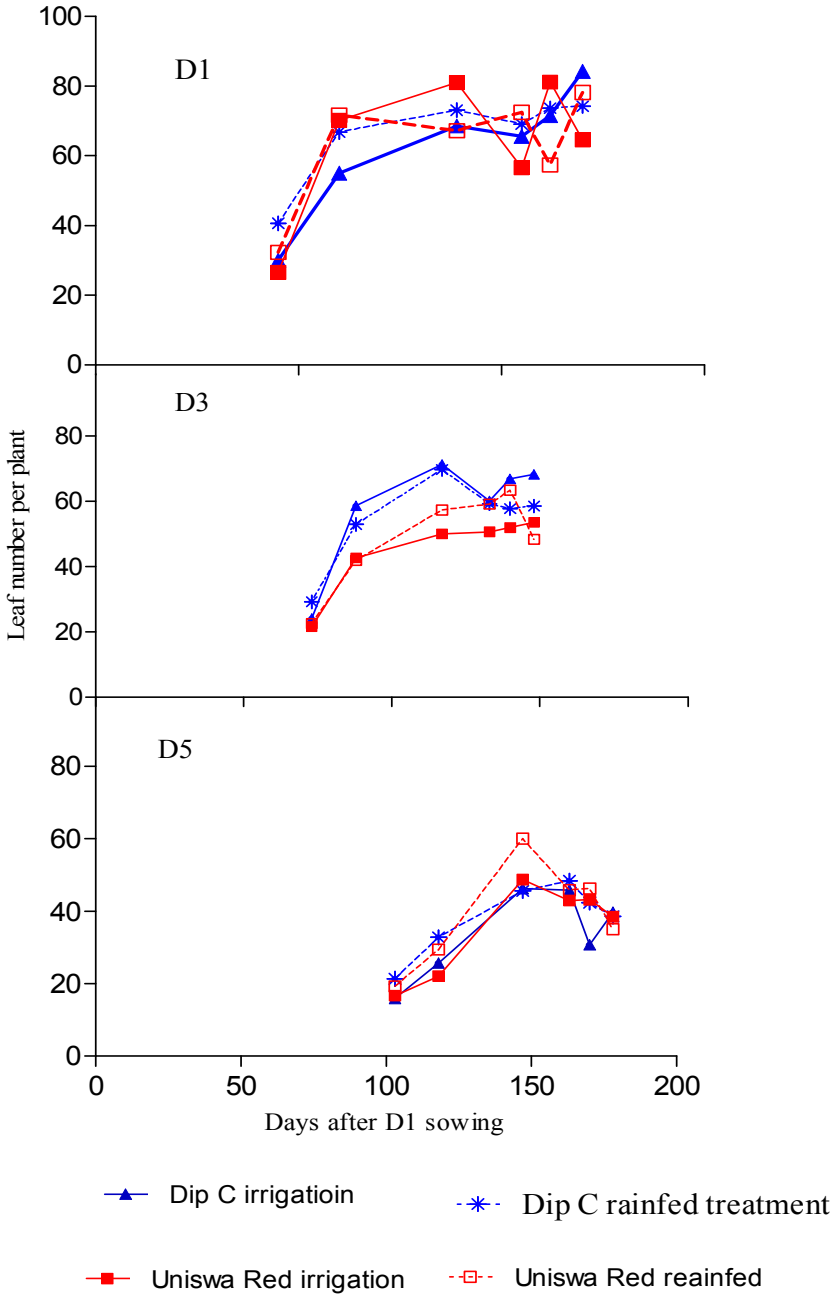

Figure 4.59 The effect of soil moisture and sowing date on the leaf number production of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2008-2009.

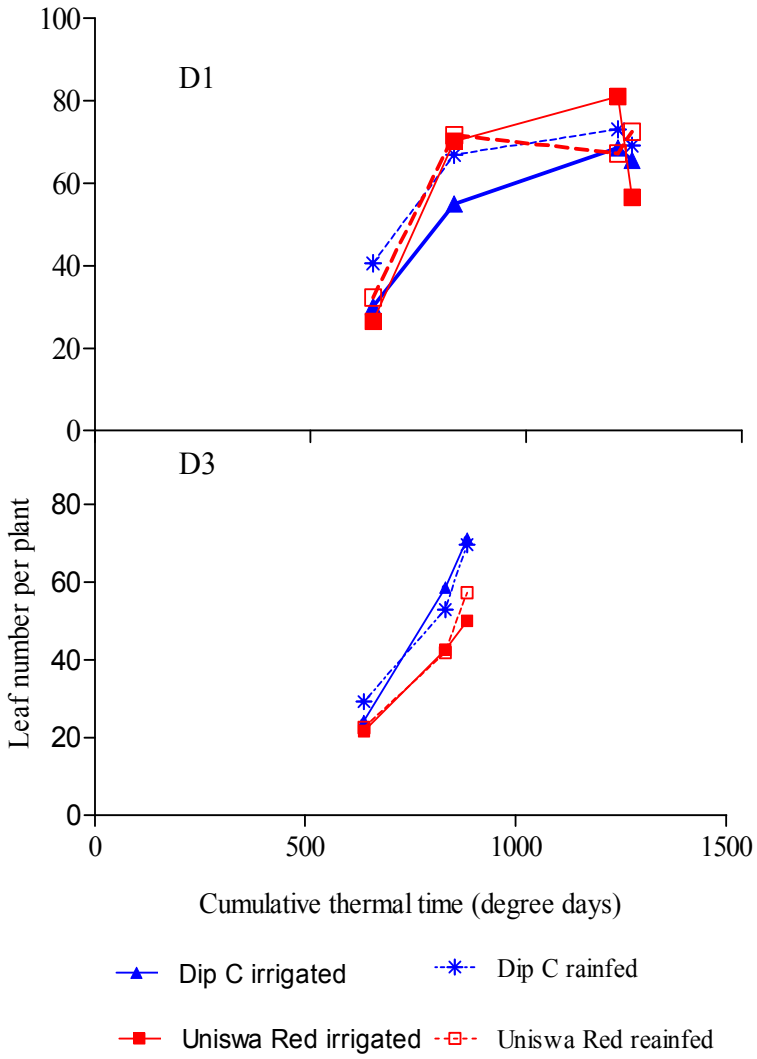

Figure 4.60 Leaf production against cumulative thermal time in two bambara groundnut landraces (Dip C and Uniswa Red) grown at two dates of sowing in Notwane Farm, Botswana College of Agriculture. 2008-2009.

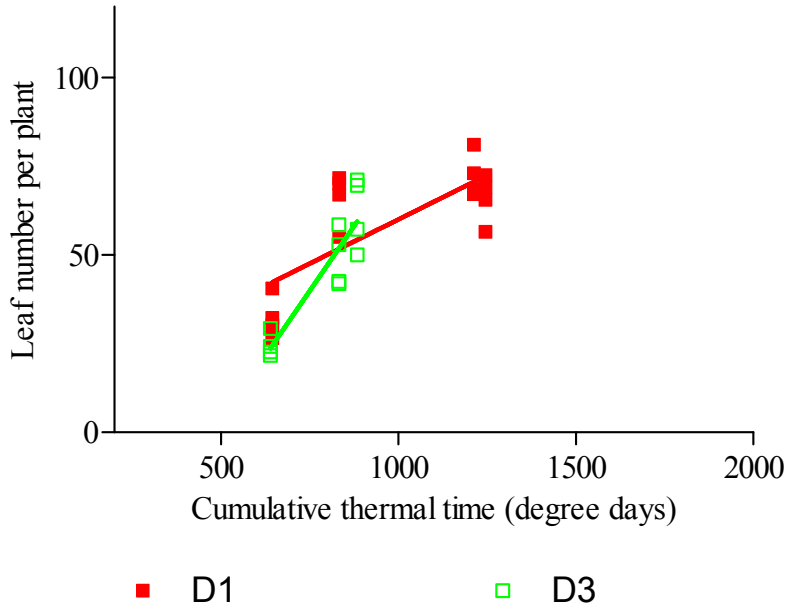

Figure 4.61 Regression of leaf production against cumulative thermal time in two bambara groundnut landraces (Dip C and Uniswa Red) grown at two dates of sowing in Notwane Farm, Botswana College of Agriculture. 2007-2008. r^2= 59.1, slopes and constants are presented in Table 4.13.

Table 4.13 Slopes, constants and phyllochron ($^{o}C^{d}$ $leaf^{-1}$) obtained from the regression of leaf number per plant against cumulative thermal time (degree days) for two bmabar groundnut landraces grown at two sowing dates, the first date of sowing (D1) and the third date of sowing (D3) during the experiments in 2008-09,

Treatment	D1	D3
Slope	0.05	0.15
se	0.01	0.03
Constant	10.10	-69.70
se	10.90	24.50
Phyllochron	20.00	6.70

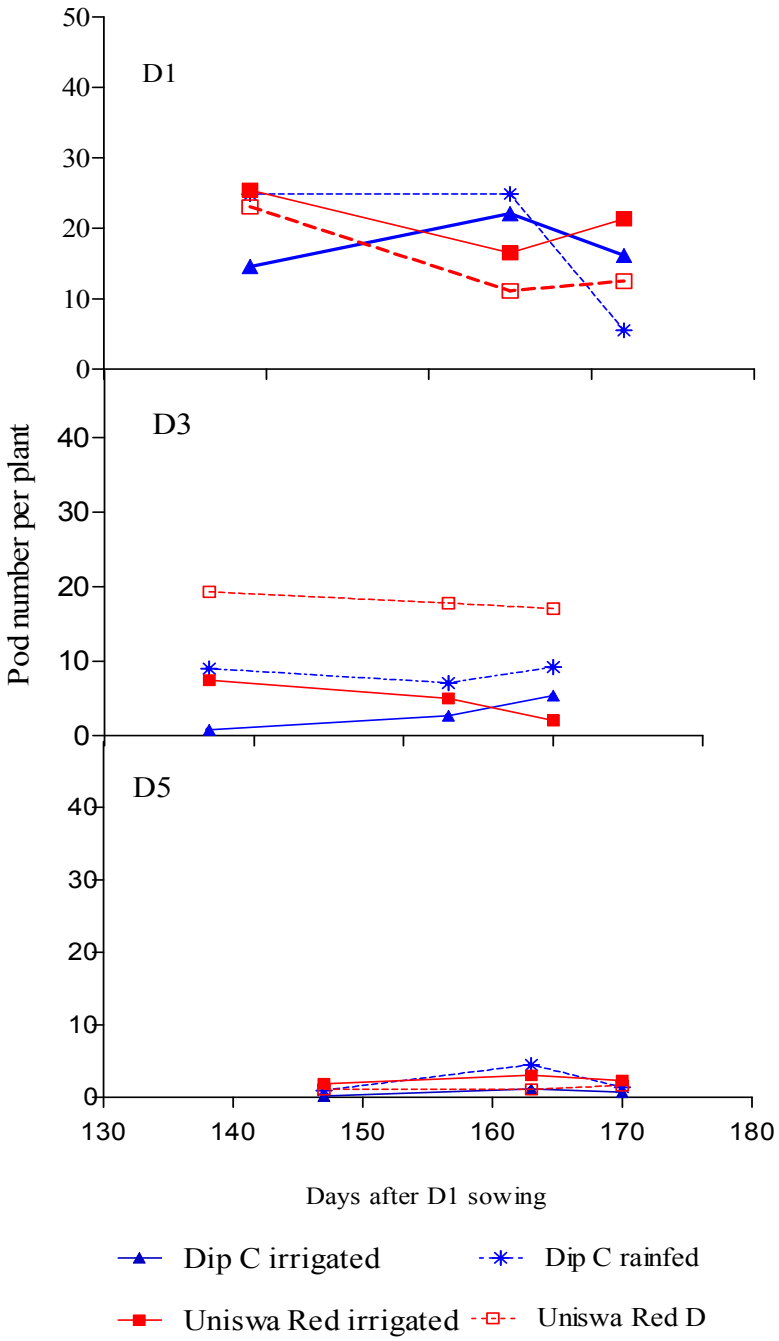

Figure 4.62 The effect of soil moisture and sowing date on the pod number production of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2008-2009.

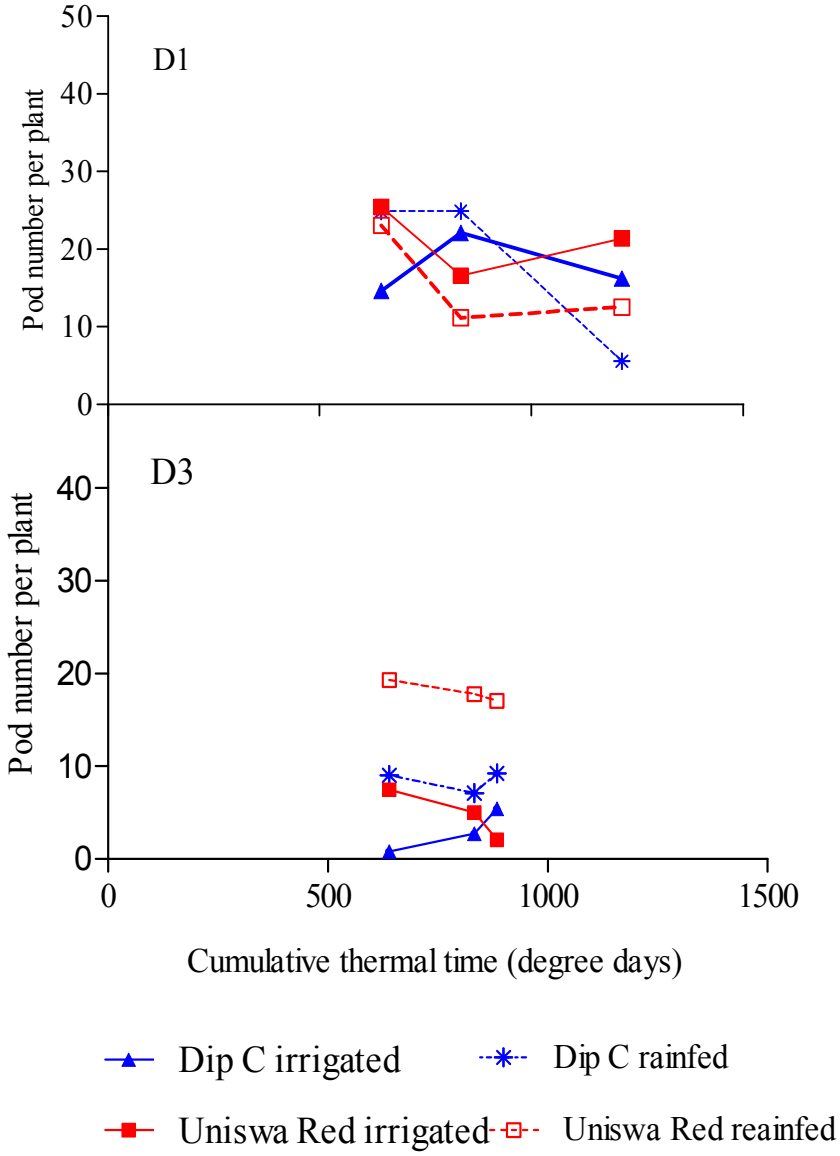

Figure 4.63 Pod production against cumulative thermal time in two bambara groundnut landraces (Dip C and Uniswa Red) grown at two dates of sowing in Notwane Farm, Botswana College of Agriculture, 2008-2009.

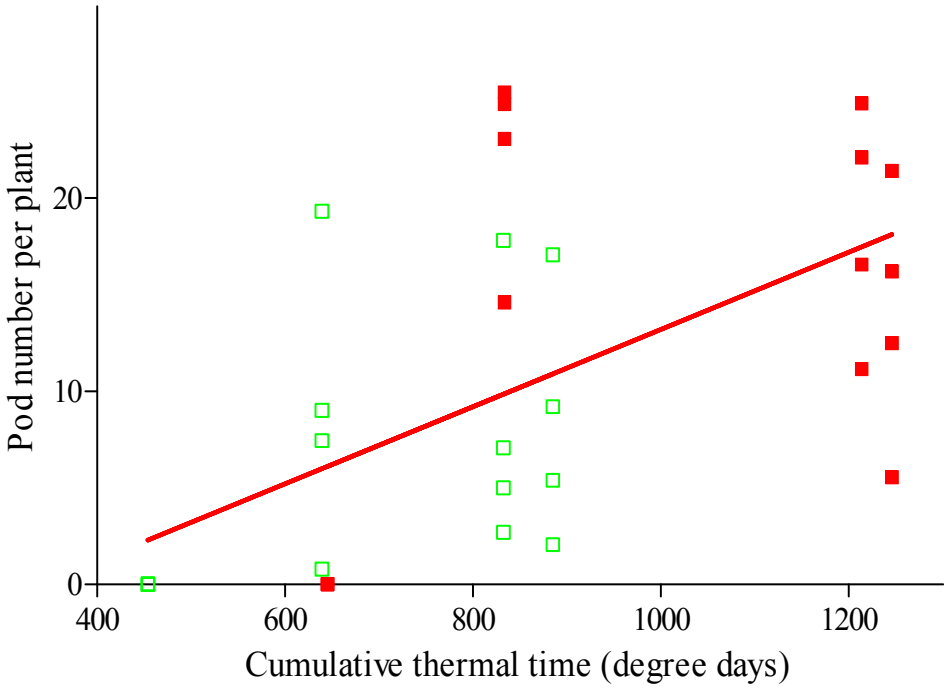

Figure 4.64 Regression of pod number against cumulative thermal time in two bambara groundnut landraces (Dip C and Uniswa Red) grown at two dates of sowing in Notwane Farm, Botswana College of Agriculture. 2008-2009. The regression equation is y = 0.02X-6.8, r^2=31.7

Total dry matter

Figure 4.68 shows the accumulation of TDM in Dip C and Uniswa Red throughout three sowing dates. Sowing date had a very significant effect on the accumulation of TDM ($P<0.001$). The amount of TDM in D1 reached 600 g m^{-2} (irrigated Uniswa Red), but the highest amount of TDM in D5 was less than 200 g m^{-2} and around 293 g m^{-2} in the third DOS in (rain fed Uniswa Red) . No significant differences were found between the treatments or the landraces ($P>0.05$) (Appendix 2, Table 2)

Leaf dry matter

The leaf dry matter (LDM) accumulation throughout three sowing dates in Dip C and Uniswa Red is presented in Figure 4.69. The statistical analysis showed that the sowing date had a highly significant effect on the LDM accumulation ($P<0.001$). In D1, rain fed Uniswa Red, accumulated more LDM than Dip C. The amount of LDM reached close to 300 gm^{-2} in D1, while the maximum amount was less than100 gm^{-2} in D5.

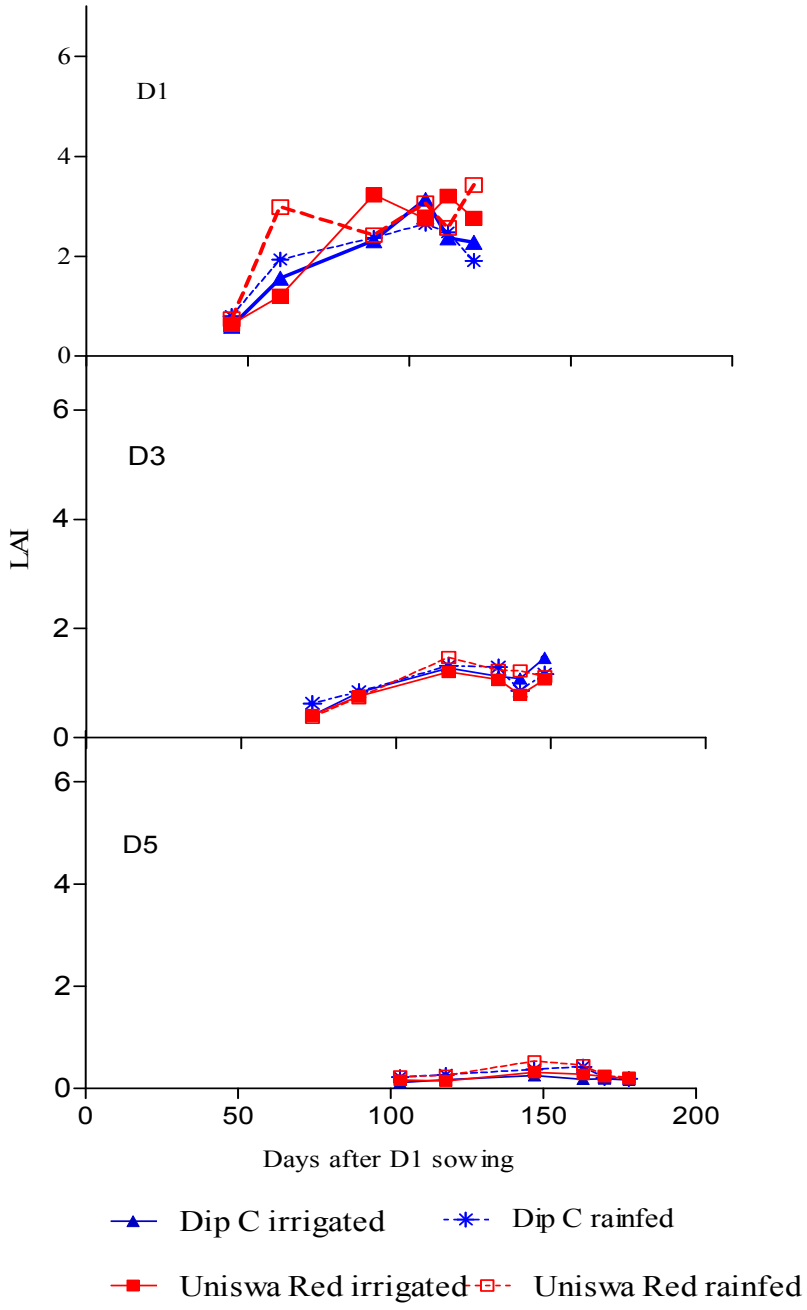

Figure 4.65 The effect of soil moisture and sowing date on the leaf area index (LAI) of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture, 2008-2009.

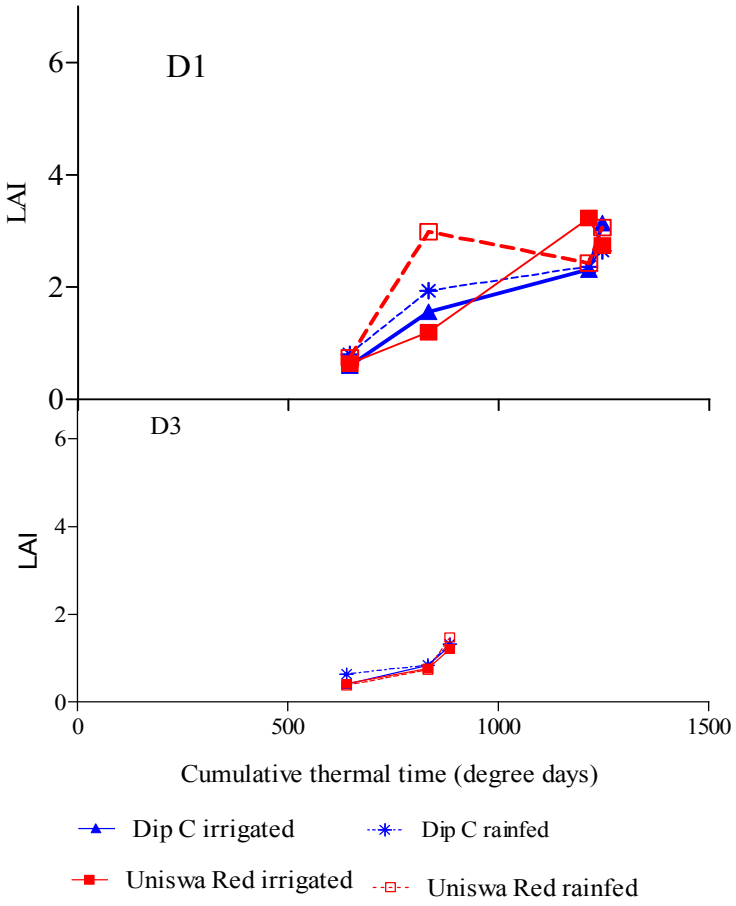

Figure 4.66 Leaf area index (LAI) against cumulative thermal time in two bambara groundnut landraces (Dip C and Uniswa Red) grown at two dates of sowing in Notwane Farm, Botswana College of Agriculture, 2008-2009.

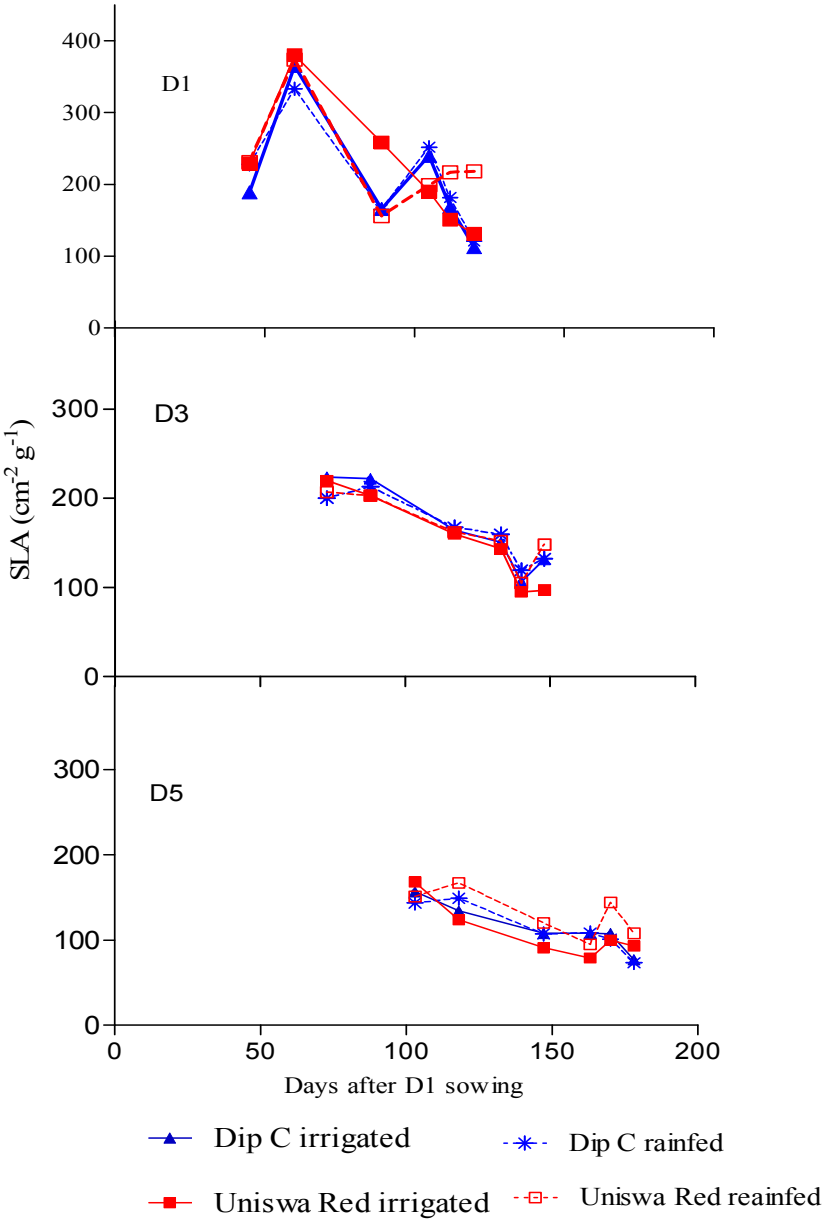

Figure 4.67 The effect of soil moisture and sowing date on the specific leaf area (SLA) of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2008-2009.

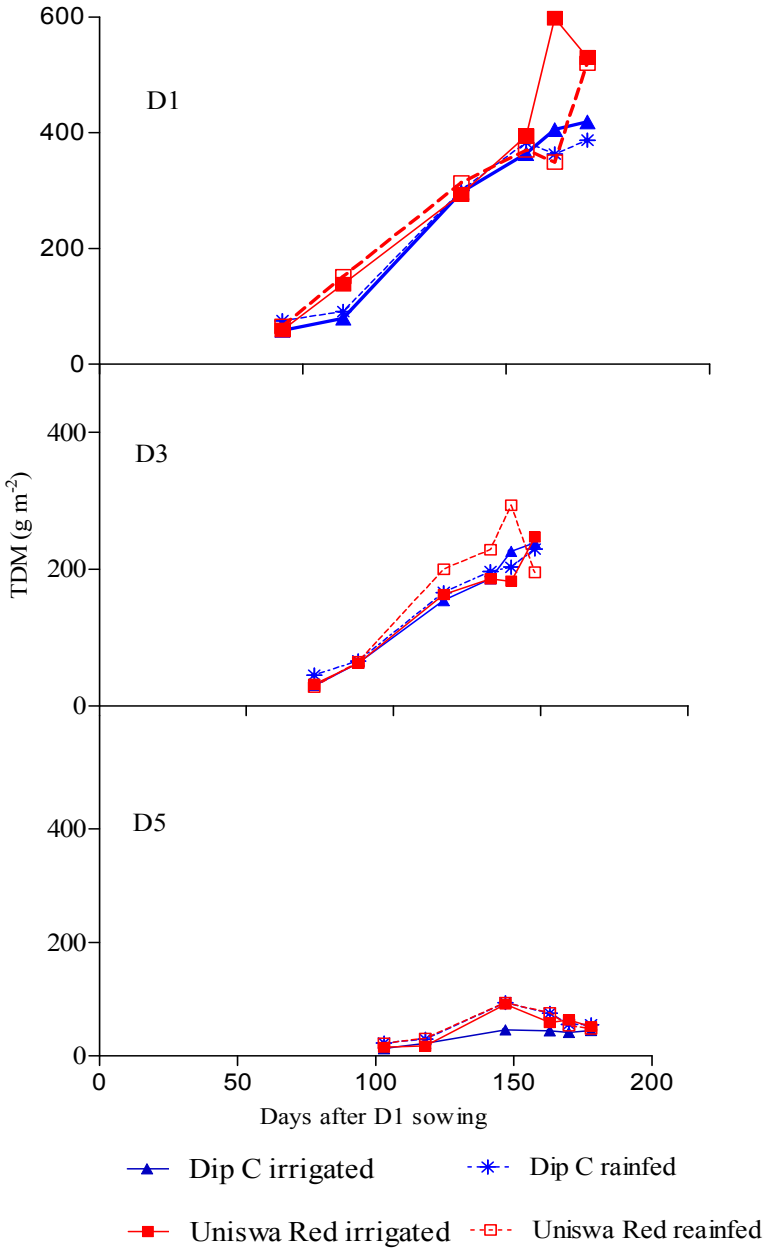

Figure 4.68 The effect of soil moisture and sowing date on the total dry matter (TDM) of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2008-2009.

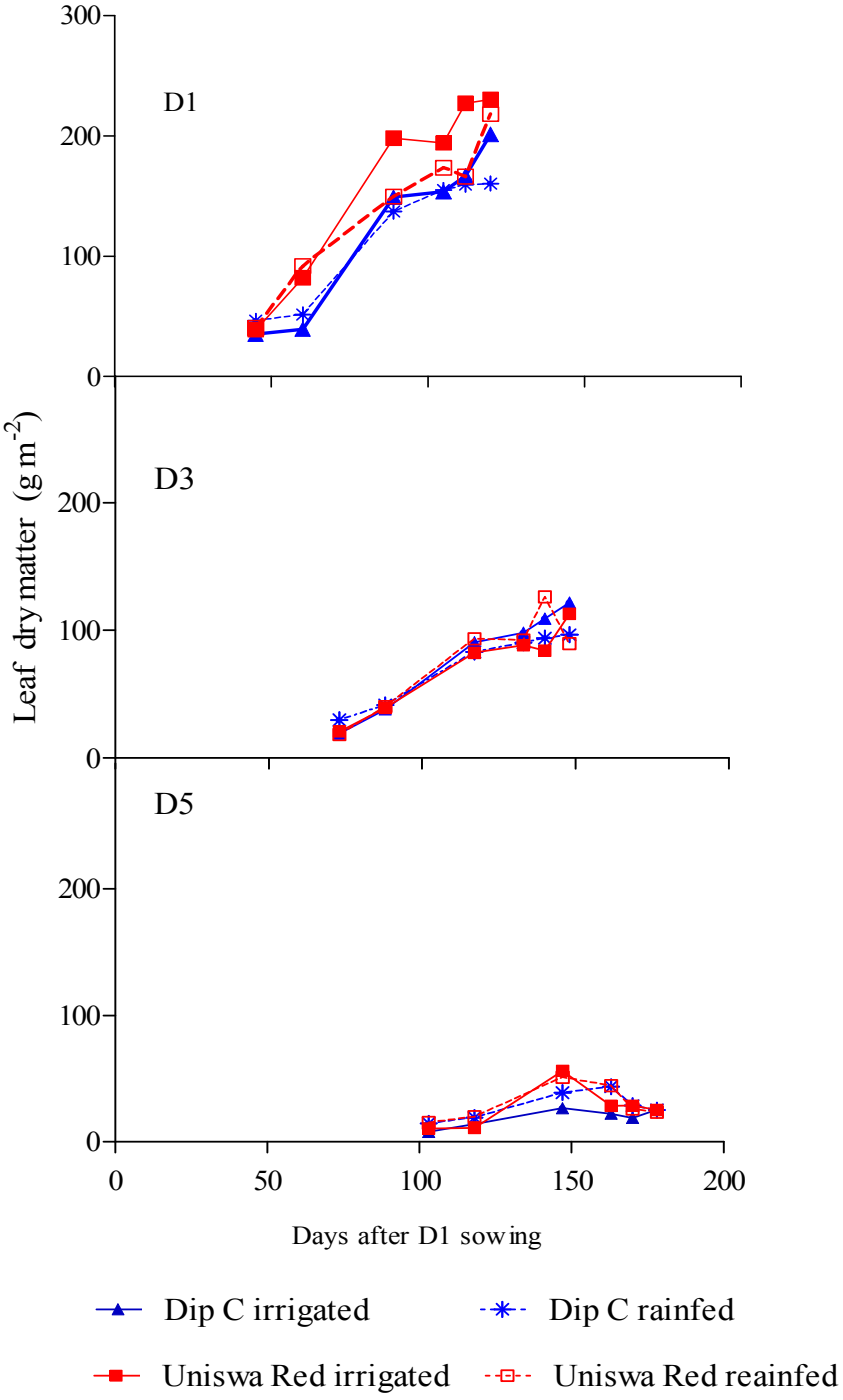

Figure 4.69 The effect of soil moisture and sowing date on the leaf dry matter (TDM) of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2008-2009.

Pod dry matter

Figure 4.70 shows the pod dry matter (PDM) accumulation in Dip C and Uniswa Red throughout three dates of sowing. Sowing date had a significant effect on PDM accumulation ($P<0.001$) (Appendix 2). Although the statistical analysis showed no significant effect of the treatment or the landraces on PDM production, it can be seen from the graph that the irrigated Uniswa Red in D1 gave the highest PDM towards the end of the season. In D3, rain fed Uniswa Red produced the most PDM except for the last growth analysis where the rain fed Dip C produced more PDM than the rest of the treatments. In D5, the landraces hardly produced any pods.

4.2.2.4 Yield and yield component

Table 4.14 shows the yield and the yield components of Dip C and Uniswa Red from three dates of sowing. D1, the highest yield was achieved by the irrigated Uniswa Red (119.6 g m^{-2}) and the lowest by rain fed Dip C, Sowing date had a significant effect on yield ($P< 0.001$) and the landraces has a less significant effect ($P<0.05$). Uniswa Red gave higher yield in both treatment than Dip C in D1, but in D3, Uniswa Red gave higher yield in the rain fed treatments but not in the irrigated treatment. For D5, the highest yield was given by the irrigated Dip C. Generally, the yield decreased with delay of sowing, especially between D1 and 5.

Although the statistical analysis showed a significant effect of landrace on harvest index (HI), there was no clear pattern of HI in or between the sowing dates. For example, in D1, the highest HI was achieved by the irrigated Uniswa Red (0.17), but in D3 and D5 it was achieved by the rain fed Uniswa Red, but generally Uniswa Red had higher HI in D1 and D3. Both landraces accumulated more TDM in D1 than D3 and D5 ($P<0.01$). Like the case in the yield, the irrigated Uniswa Red the highest TDM in D1.

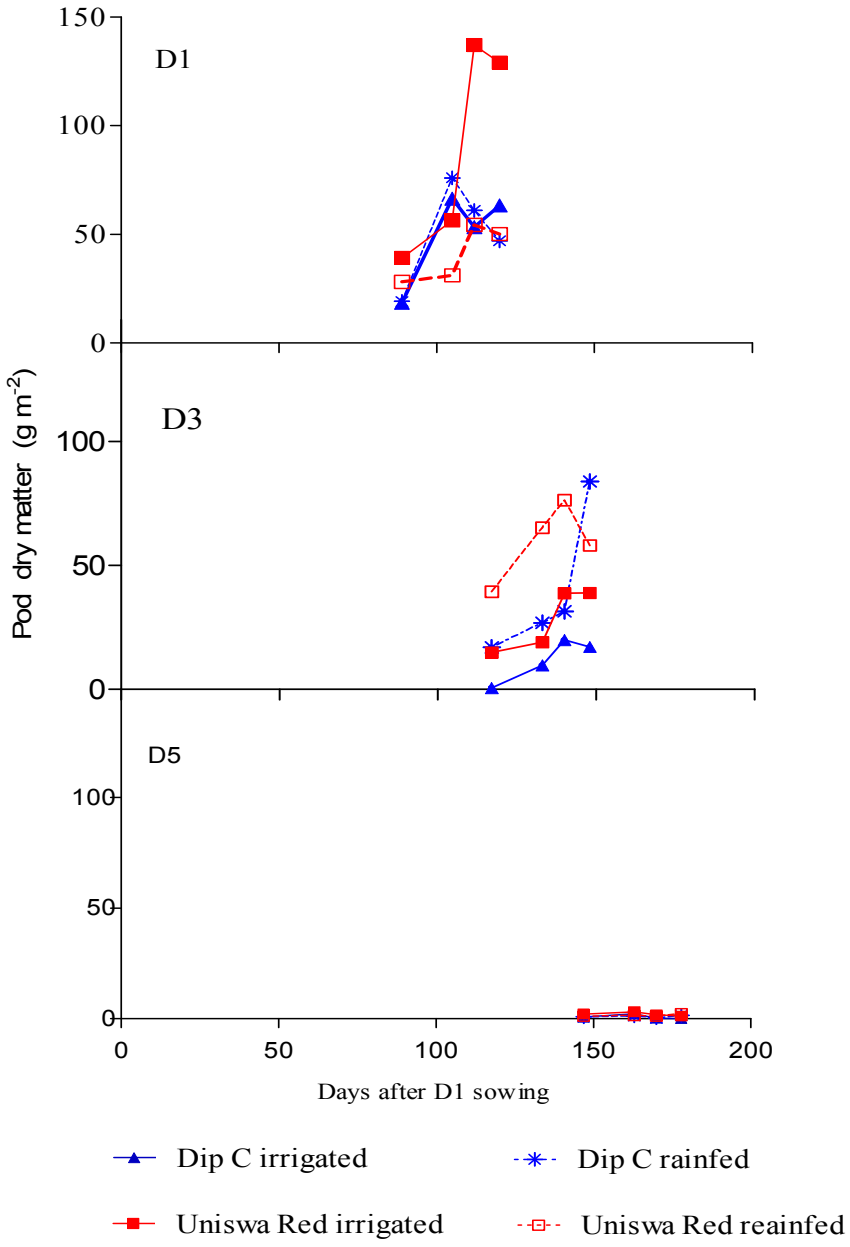

Figure 4.70 The effect of soil moisture and sowing date on the pod dry matter (TDM) of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture. 2008-2009.

Table 4.14 Yield components and yield (gm^{-2}) among two landraces of bambara groundnut (Dip C and Uniswa Red) grown in Notwane Farm, Botswana College of Agriculture at three dates of sowing; the first date (D1), the third date (D3) and the fifth date (D5) under two water regimes; irrigation (irr) and rainfed (rf) during the experiment of 2008-2009.

	Treatment	TDM gm^{-2}	Seed Yield gm^{-2}	Pod Yield gm^{-2}	HI	Shelling %
D1	Dip C irr	418	61.2	82	0.19	26
	Dip C rf	387	29.6	45	0.11	35
	UNI irr	530	119.6	194	0.36	39
	UNIrf	520	68.2	105	0.2	36
D3	Dip C irr	238	13.3	18	0.07	27
	Dip C rf	229	56.8	77	0.33	26
	UNI irr	247	53.1	76	0.3	31
	UNIrf	195	78.5	99	0.5	21
D5	Dip C irr	45	4.2	7.1	0.09	42
	Dip C rf	55	1.5	2.3	0.08	33
	UNI irr	52	0.13	0.23	0.08	43
	UNIrf	48	1.6	2.3	0.15	28

	Yield		*HI*		*TDM*	
	df	***SED***	***df***	***SED***	***df***	***SED***
Landrace	*12*	*.02**	*13*	*7.7**	*3*	*15.4ns*
Sowing date	*14*	*.04ns*	*14*	*15.5**	*30*	*28.1***
treatment	*14*	*.03ns*	*14*	*12.7ns*	*30*	*22.9ns*
*Landrace*sowing date**	*22.4*	*.07ns*	*22.8*	*25.7**	*32.9*	*53.5ns*

Soil surface evaporation (E_s)

Figure 4.71 shows the cumulative soil surface evaporation from the stands of Dip C and Uniswa Red in the three sowing dates. E_s reached 120 mm in D1, but it was less than 100 mm in D5.

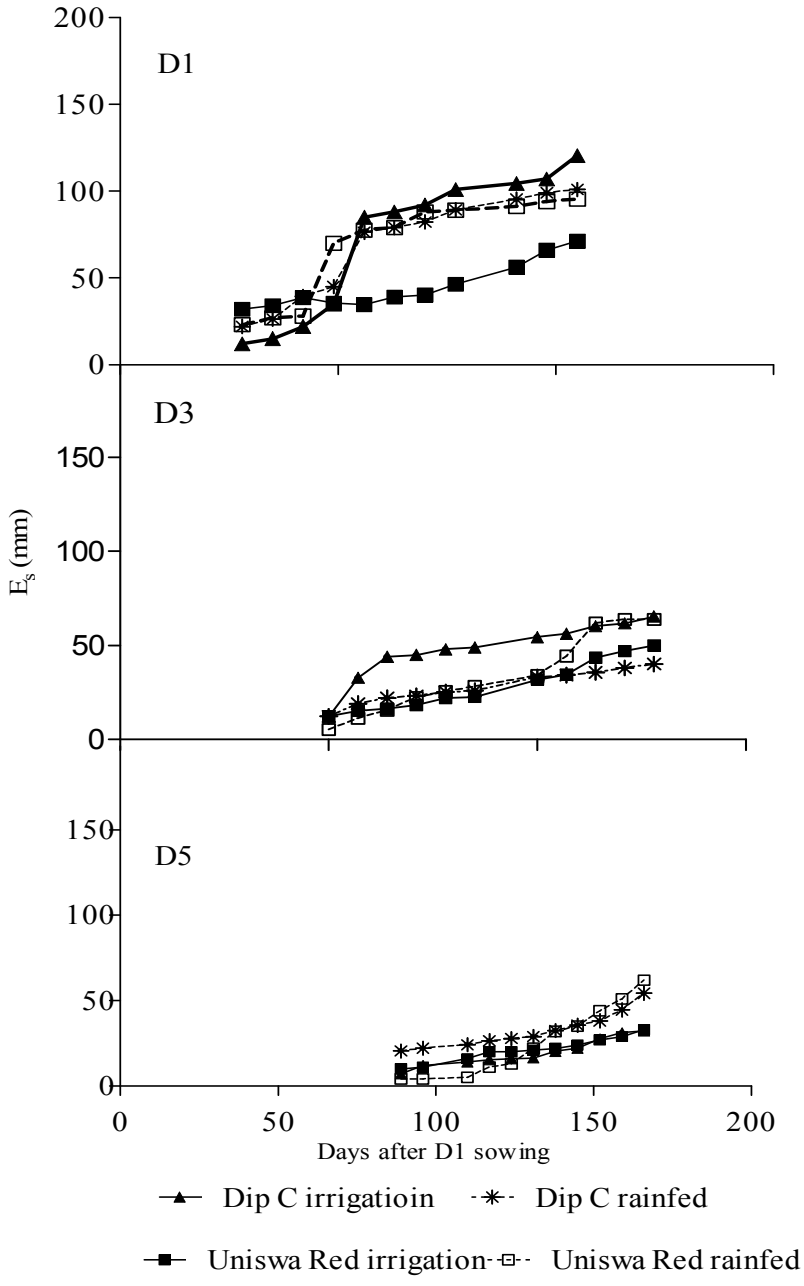

Figure 4.71 Cumulative soil surface evaporation (mm) from stands of two bambara groundnut landraces (Dip C and Uniswa Red) grown in Notwane Farm, Botswana College of Agriculture (2008-2009).

Evapotranspiration (E_t)

In D1, irrigated Dip C had the lowest cumulative E_t. In D3, rain fed Dip C had the lowest cumulative E_t, but it had the highest Et in D5, while the irrigated Uniswa Red had the lowest. Generally, the cumulative E_t was lower in D5 than in D3 and D1. In D1, the cumulative E_t exceeded 300 mm, but in D5, it reached 200 mm as maximum (Figure 4.72).

Water distribution and extraction from the soil profile

The distribution of water in each layer of the soil profile and the pattern of water extraction for each landrace and treatment in three dates of sowing is presented in Figures 4.73-4.75. In all the treatments and sowing dates, soil moisture content in the 20cm layer (0-20cm) was lower than the moisture content in the other measured depths. The soil water distribution changed throughout the growing season in the three dates of sowing. For example, in D1, in rain fed Dip C soil profile, the moisture content in the 80cm layer and the 40cm layer was the highest in the first two weeks of measurements, later on, the moisture content at 40cm layer stayed high until 63 DAS where it started to decrease, but the moisture content in the 80cm layer in D5, in the rain fed Dip C, was always the highest.

Water use efficiency

Figure 4.76 shows the regression results of transpired water against total dry matter (TDM) for three sowing dates. A comparison of the regression of T against TDM showed a significant difference between treatments ($P<0.001$) for the first and the third sowing date, but not for the fifth.

Leaf relative water content

Figure 4.77 shows the leaf relative water content of Dip C and Uniswa Red under rain fed and irrigated conditions. The two landraces in both treatments and during the three dates of sowing, managed to keep the relative water content over 80%

Stomatal conductance

Stomatal conductance of Dip C and Uniswa Red throughout three dates of sowing is presented in Figure 4.78. In the three sowing dates, crops decreased the stomatal conductance towards the ends of the season. In D1, the crops in both treatments started with almost the same rate of stomatal conductance, but towards the end of the season, the irrigated Uniswa Red managed to keep higher stomatal conductance than the rain fed Uniswa Red and Dip C in both treatments. At the early stage of D3, irrigated Uniswa Red had high stomatal conductance, but the difference decreased towards the end of the season. Generally, the crops had similar stomatal conductance in D1 and D3, but it was much lower in D5.

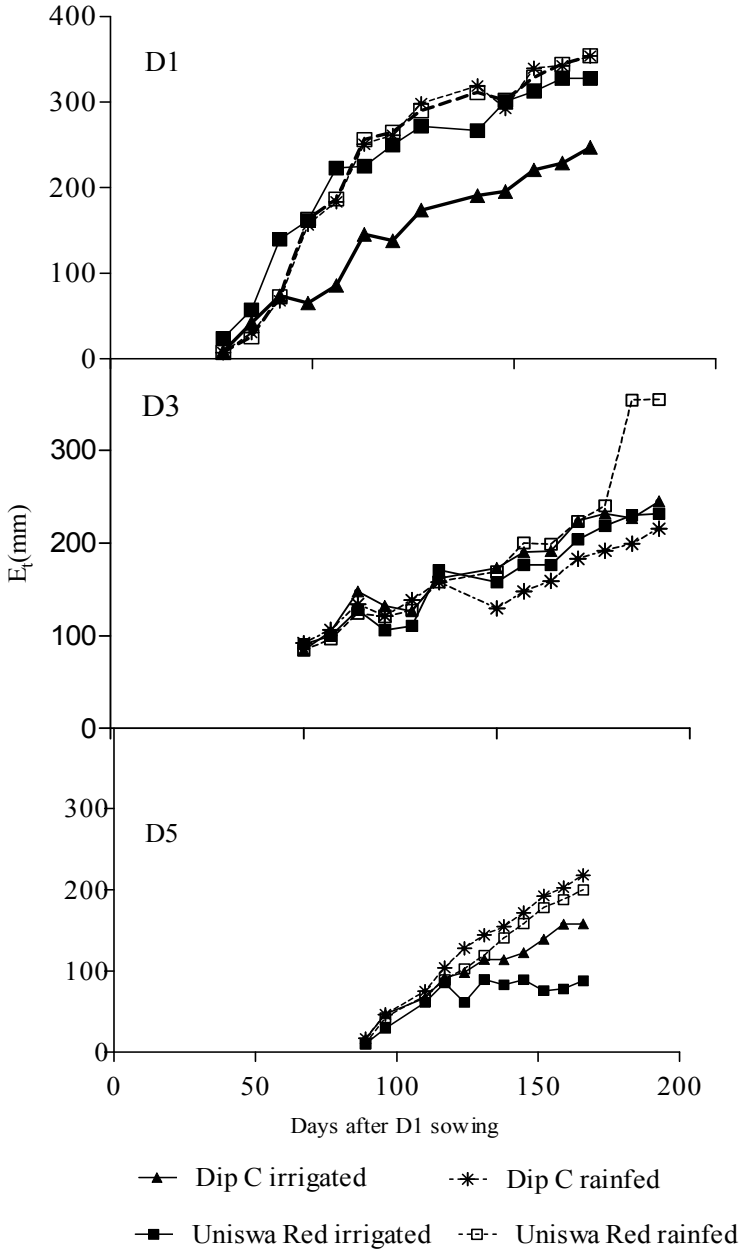

Figure 4.72 Cumulative evapotranspiration (mm) from stands of two bambara groundnut landraces (Dip C and Uniswa Red) grown in Notwane Farm, Botswana College of Agriculture, 2008-2009.

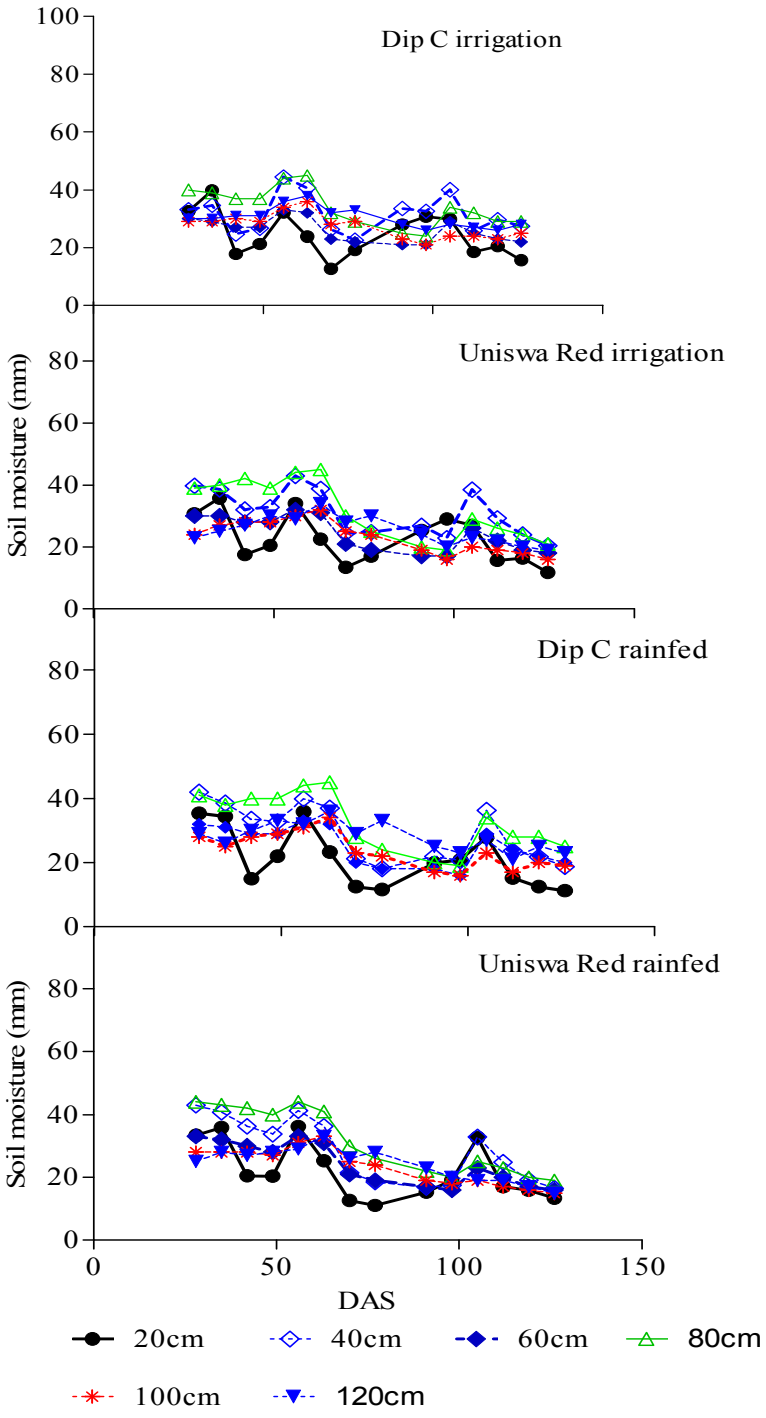

Figure 4.73 Profile soil moisture content (mm) at two water treatment of two bambara groundnut landraces (Dip C and Uniswa Red) grown in in Notwane Farm, Botswana College of Agriculture (First date of sowing) 2008-2009.

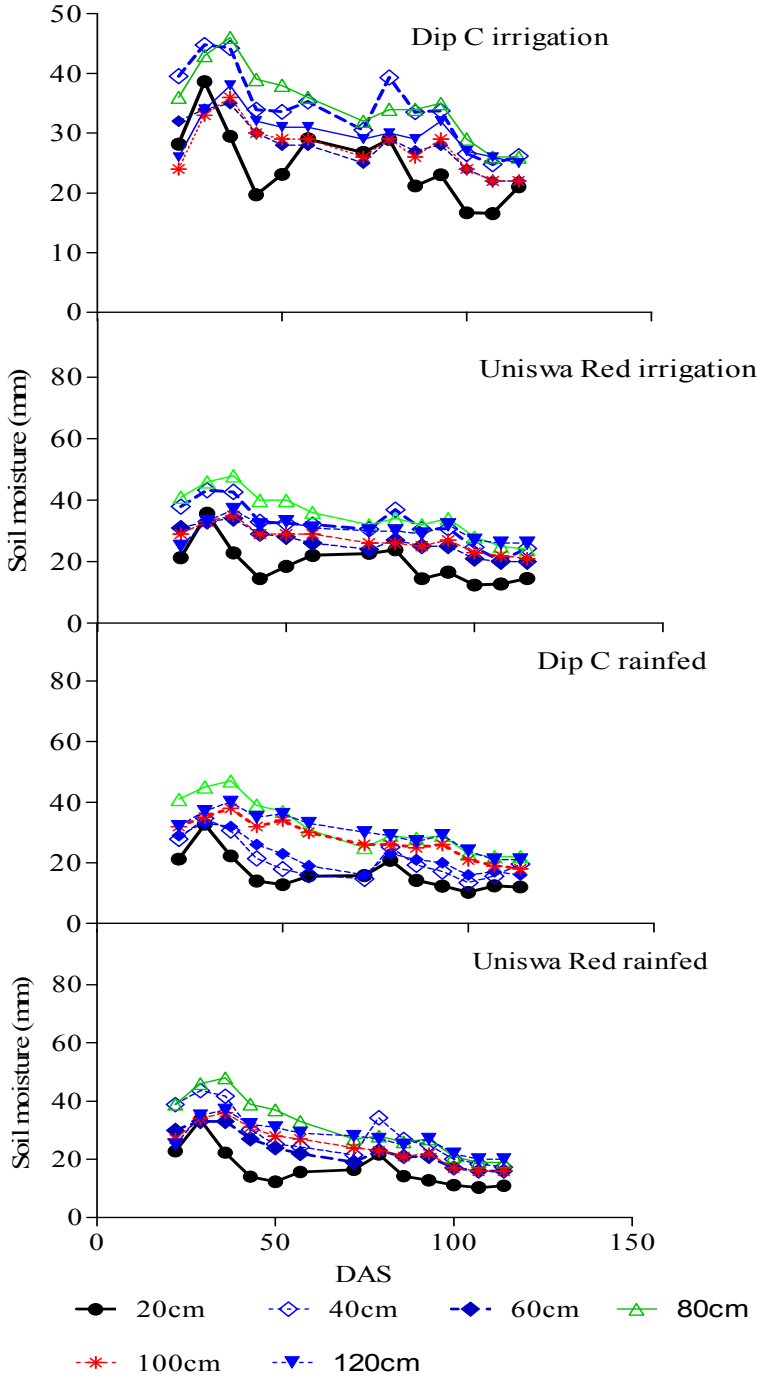

Figure 4.74 Profile soil moisture content (mm) at two water treatment of two bambara groundnut landraces (Dip C and Uniswa Red) grown in in Notwane Farm, Botswana College of Agriculture (third date of sowing) 2008-2009.

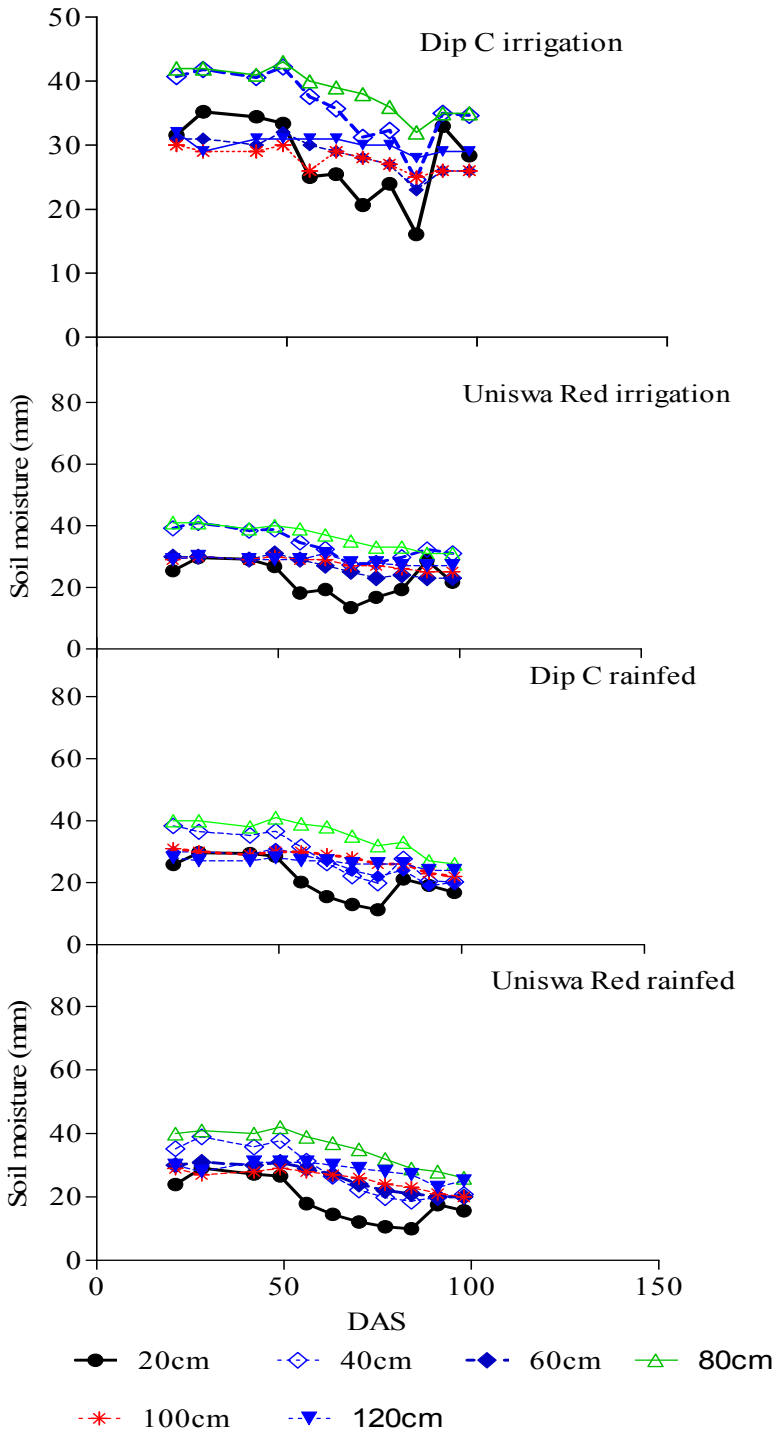

Figure 4.75 Profile soil moisture content (mm) at two water treatment of two bambara groundnut landraces (Dip C and Uniswa Red) grown in in Notwane Farm, Botswana College of Agriculture (fifth date of sowing) 2008-2009.

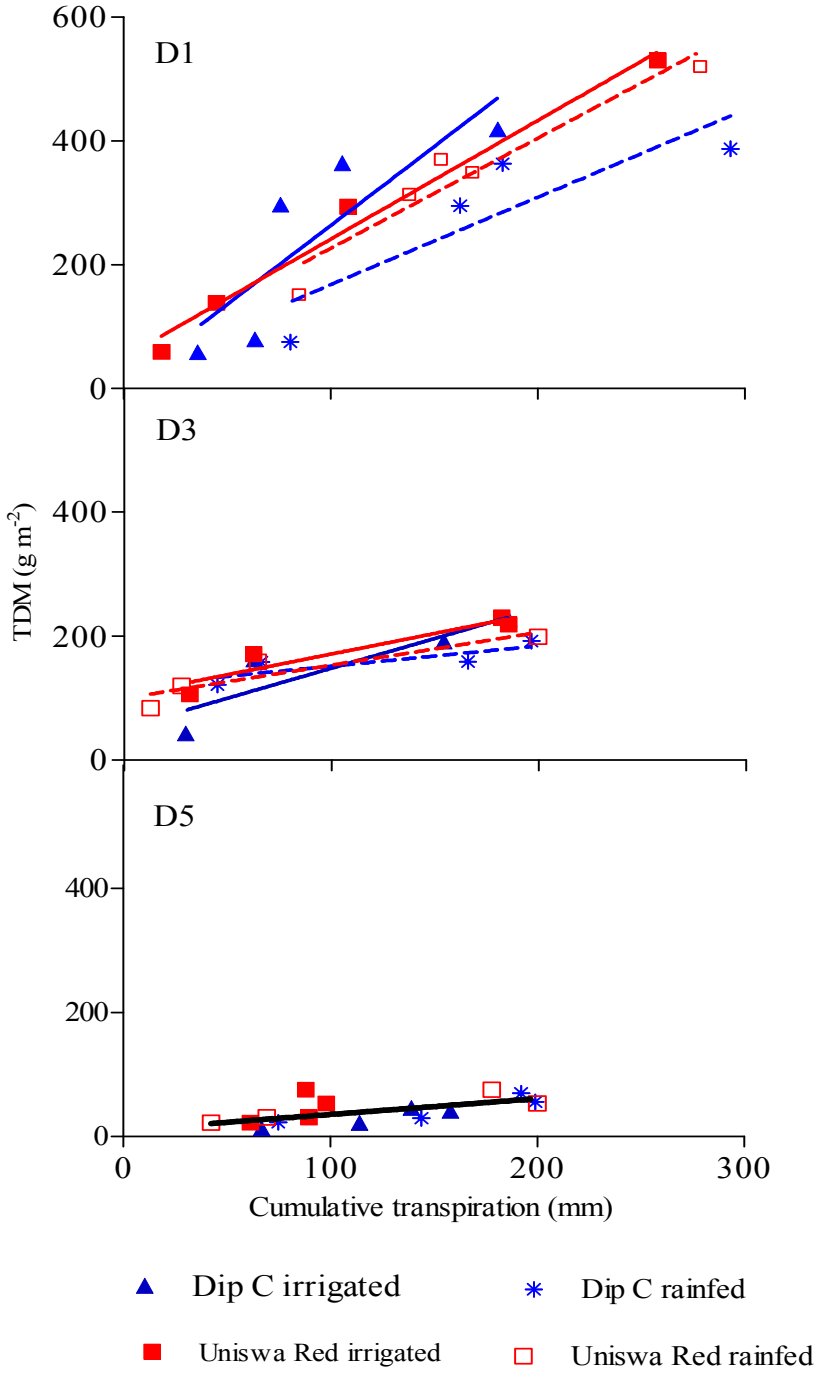

Figure 4.76 Regression of total dry matter (g m^{-2}) against transpiration (mm) for two bambara groundnut landraces (Dip C and Uniswa Red) grown during the experiment in 2007-2008 (First date of sowing) at Notwane Farm, Botswana College of Agriculture. For D5, the regression equation is: y=0.23x+13.2, r^2=34.9, (Slope se=0.076, constant se=10.1). For D1 r^2= 46.2, For D3, r^2=77.7 Slopes and constants for D1 and D3 are presented in table 3.15.

Table 4.15 Slopes and constants obtained from the regression of total dry matter (g m^{-2}) against transpiration (mm) for two bambara groundnut landraces (Dip C and Uniswa Red) grown in Notwane Farm, Botswana College of Agriculture under two water regimes; irrigation (irr) and rainfed (rf) during the experiment of 2008-2009 for three sowing dates; date 1 (D1) and date 3 (D3)

D1

Treatment	Dip C irr	Dip C rf	UNI irr	UNI rf
Slope	2.553	1.412	1.916	1.78
se	0.647	0.473	0.386	0.505
Constant	7.8	26.3	49.5	48.2
se	67.9	92.3	54.8	89

D3

Treatment	Dip C irr	Dip C rf	UNI irr	UNI rf
Slope	0.878	0.42	0.546	0.821
se	0.186	0.207	0.17	0.126
Constant	58.1	112.4	114	85.1
se	28.1	31.2	27.7	20.4

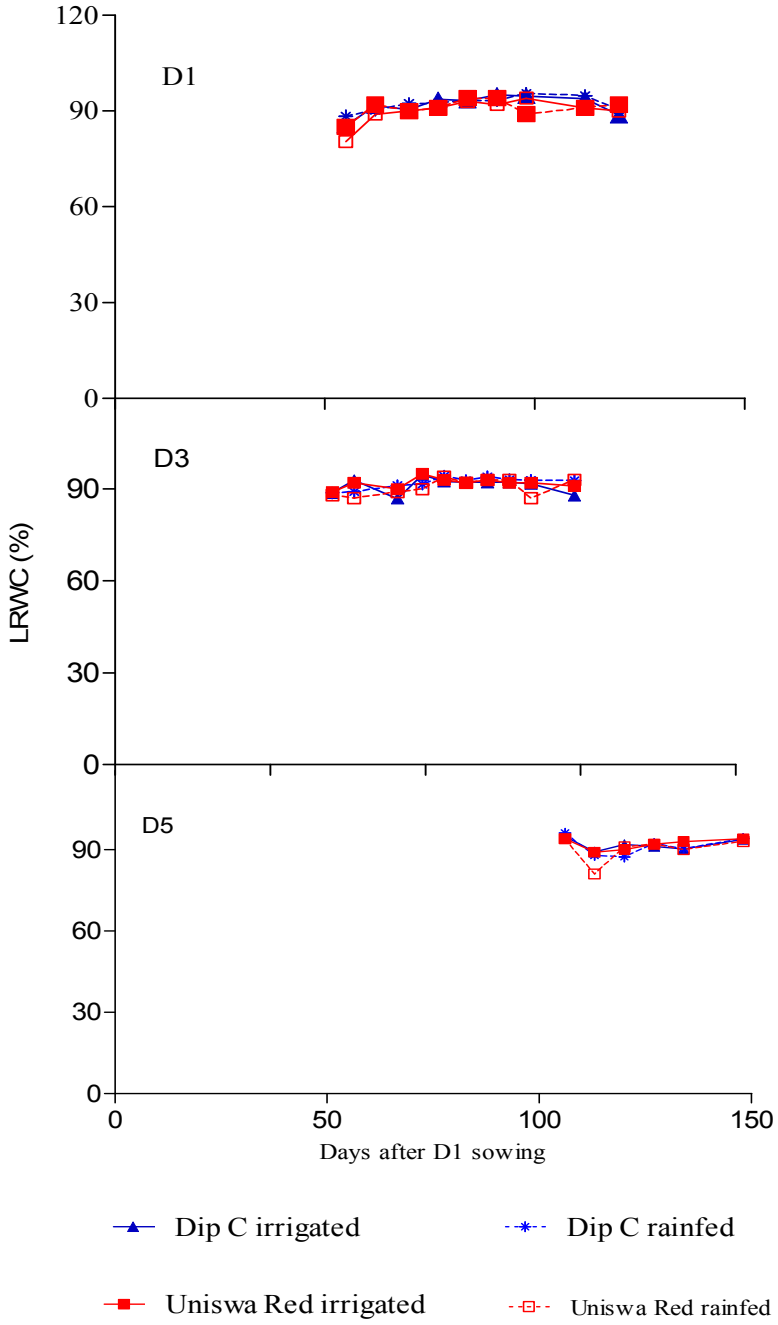

Figure 4.77 The effect of soil moisture and sowing date on the leaf relative water content (LRWC) of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture, 2008-2009.

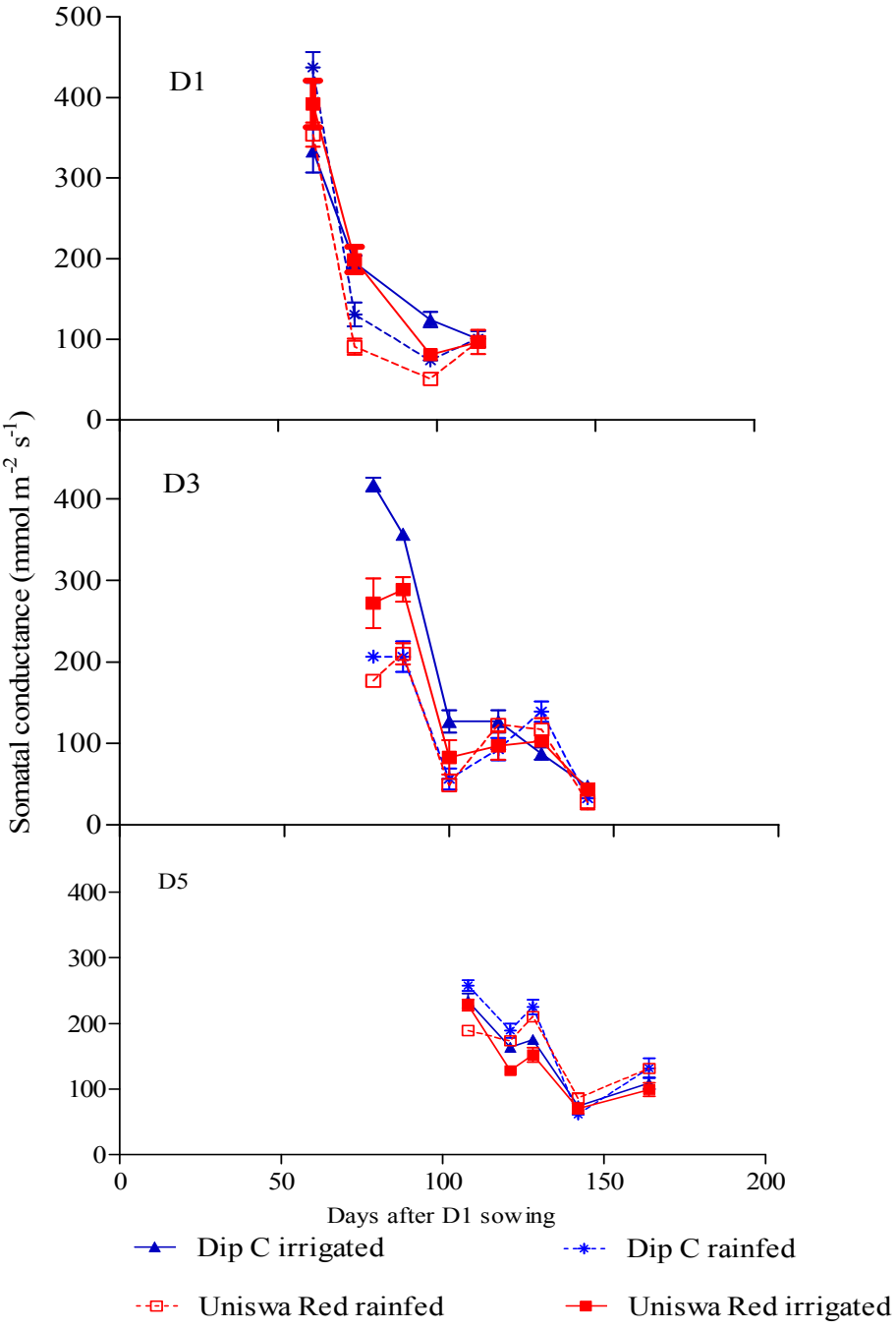

Figure 4.78 The effect of soil moisture and sowing date on the stomatal conductance of two bambara groundnut landraces (Dip C and Uniswa Red) grown at three dates of sowing in Notwane Farm, Botswana College of Agriculture, 2008-2009.

5 Discussion

Crops generally give good yield when grown in areas where they are well adapted. The further a crop is grown away from its region of good adaptation, the more care is necessary for satisfactory production (Martin *et al*., 2006). In sub-Saharan Africa, which is the homeland of bambara groundnut, rainfall is both erratic and low, and most of the rainfall is lost to runoff, drainage and evaporation (Mwale *et al*., 2003)

The lack of water in these areas makes water stress the most important abiotic factor affecting the growth and yield of bambara groundnut. In addition to water, temperature stress exists as a limiting factor of bambara groundnut growth and yield. It has always been an important aim to evaluate the effect of each environmental factor separately, but because these factors are working at the same time in the natural environment, it is difficult to separate the effect of each factor in the field. Most of the physiological studies that have been carried out on bambara groundnut have been in controlled environments. Conducting experiments in the field gives the chance to test the crop growth and productivity in its natural environment, but on the other hand it is difficult to differentiate between the effects of water and temperature. This disadvantage can be recovered by comparing field experiments with those in controlled environments. Accordingly, this study was designed to investigate the growth and yield of bambara groundnut landraces ; in the field, where it is the native environment of bambara groundnut, where conditions should be suitable for the growth of the crops and in a controlled environment where it makes it possible to uncouple the effect of drought and temperature. The experiments were designed to expose the different landraces to similar water and temperature stress by designing a sequence of experiments with no water stress and repeat them with different levels of water stress. In the first glasshouse and field experiments (2006), there was no drought imposed on the crops (the first field experiment is not included in this thesis). The

drought was imposed at pod filling stage in the second glasshouse experiment (2007), and the second field experiment (2007-2008). In the third experiments (glasshouses 2008 and field experiment 2008-2009) the drought was imposed at flowering.

To compare the temperature stress between the field (where temperature cannot be controlled) and the glasshouse (where temperature can be controlled); the field experiments were designed to have five dates of sowing starting from December, which is summer time in Botswana when the temperature is highest (Maximum 30-40 °C). The high temperature in the field is represented in the glasshouse by the high temperature regime (mean of 33 ±5 ºC). With delay in sowing, the temperature decreases until it becomes cold (Maximum 14-25°C and minimum 3-20°C) enough at the fifth sowing date (February) to be compared with glasshouse regime represented by low temperature regime (mean of 23 ± 5ºC). This chapter will discuss the effect of the temperature, soil moisture and sowing date on the landraces tested in this study. The discussion will cover the glasshouses and the field results.

This study was designed to investigate temperature and water stress. The photoperiod effect was eliminated in the glasshouses since it was set to 12 h, but the fact that photoperiod varied with sowing date in the field experiments, made it necessary to highlight its effect in this discussion.

5.1 Environmental conditions

During the three growing seasons, the temperature in the glasshouses was set to high temperature (HT) mean of 33±5ºC and low temperature (LT) mean of 23 ±5ºC, but in fact, it was difficult to maintain the desired level of low temperature, especially in 2006 where the summer was unusually hot.

SD was set not to exceed 4 K Pa at the high temperature and not to exceed 2 K Pa at the low temperature, which was successfully achieved because of the humidifier which sprays a fine mist of water into the glasshouses whenever the saturation deficit rises above the pre-set value.

The soil moisture in the glasshouses decreased towards the end of the season in both years of measurements. The pattern of the soil moisture in the four glasshouse treatments was different between 2007 and 2008, for example, in 2007, the highest moisture content was in S19-3 soil at LT, but in 2008, it was in Uniswa Red soil at LT. Since the plots were irrigated approximately to the field capacity immediately before imposing the drought, this change could be due to changes in the environmental conditions throughout the two years which led to change in the landraces' behaviour as a response to the changes in the surrounding environment. It is difficult to specify the reason for these differences, but it can be linked with TDM production, where the crops produced lower TDM under the low temperature in both years. The other reason could be related to the root system (which has not been investigated in the present study). Ferris *et al*. (1998) found in a study on wheat that the loss of biomass of roots at a mean temperature of 26°C was three-fold greater than at 17°C.

Martin (2006) divided crop areas based on rainfall into four regions; (1) The arid regions where the average annual rainfall is 250 mm or less, in this kind of region irrigation is necessary for successful crop production; (2) Areas where the rainfall is between 250 and 500 mm. (known as semi-arid). To have a successful production in such areas, irrigation or crop varieties adapted to dry environments are needed. (3) Sub humid areas where the rainfall ranges between 500 to 760 mm. The amount of rain is often not enough to have a successful crop production unless methods that utilize the rainfall to best benefits are used. (4) The areas where rainfall is more than 760 mm are regarded as humid areas, in these areas, soil water is not a limiting factor

in crop production. From Table 5.1, the south part of Botswana can be classified as a semiarid, where irrigation is needed for good crop production.

Table 5.1 The average amounts of rain (mm) in Sebele, Gaborone between 1998 and 2008.

YEARS	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEPT.	OCT.	NOV.	DEC.
1998	93.5	32.5	148	0.5	0	0	0	0	14.6	55.9	60.8	60.7
1999	39.5	25.5	35.8	21	38.5	0	0	0	2.8	26.2	14.4	197.8
2000	113	280	75.7	17.3	17.9	1.5	1.5	0	6.8	19	37	58
2001	11	210	43.3	67.3	97.9	0	0	0	17	96	29.3	56.3
2002	27	56.3	13.4	32.8	50	0	0	13.2	0	23.8	21.6	92.2
2003	76.5	55.9	17.6	9	14.9	0	0	0	0.3	66.5	62.3	44
2004	52.9	168	43.6	36.2	0	0	0	0	0	23	13	116.2
2005	52.3	26.6	27	78.5	0	0	0	0	0	0	79.5	52
2006	260	178	91.7	4.9	20.2	0	0	5.5	0	2.8	31.8	63.3
2007	16.8	31.6	13	11.7	0	0	0	0	22	94.8	84.4	152.5
2008	200	55	174	31	26.5	5.5	6	0	0	7.7	121	34.3

Summer in sub-Saharan Africa usually is hot and dry. Table 5.1 shows the amount of rain in eleven years in Sebele, Gaborone from 1998 to 2008. The table highlights the dry winter and summer. There was no consistency in the amount of rain throughout the eleven years. For example, in January 2000 the amount of rain was 113 mm, but in January 2001 it dropped to 11 mm. From 2005 to 2007 the amount of rain between January and May (the growing season of bambara groundnut) was low. According to the meteorological history, the two field experiments were set to impose drought expecting that the amount of rain would be sufficiently small to expose crops to water stress, but the amount of rain during the two experiments was unusual (sum of 456 mm from December to May in 2008 and sum of 366 mm in 2009)

Table 5.2 The monthly averages of maximum temperatures (ºC) in Sebele, Gaborone, between 1998 and 2008.

YEARS	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEPT.	OCT.	NOV.	DEC.
1998	31.5	33.9	32.7	31.1	27.1	26.4	24.5	25.7	31.3	30.5	31.7	31.2
1999	33.5	34	33	30.5	26.6	24.4	22.9	26.6	28.6	30.9	34.1	30.2
2000	82.2	28.4	29.1	26	23.8	22.4	21.9	26.5	29.6	32.2	31.8	32.4
2001	35.7	31.4	29.1	23	23.9	22.2	21.9	26.8	28.4	31.5	28	39.6
2002	33.7	32.3	32.1	29.9	26.7	21.5	23.5	26.6	29	23.9	32.9	32.6
2003	34.8	33	33.1	32	26.1	21.9	23.3	25	29.5	33.4	30.2	35.3
2004	32.4	29.9	28	27.1	26.2	22.3	22.4	27.3	28.4	32.3	34.9	32.3
2005	34.1	34.3	31.8	26.6	27.1	25.9	24.2	28.6	32.6	34.7	34.9	32.7
2006	29.3	29.1	27	26.3	23.3	22.7	24.6	24.6	29.2	33.4	32.5	35.1
2007	34.4	35.7	34.1	29	25.6	22.1	22.4	26	31.6	27.8	31.4	28.9
2008	29.3	31.6	27.9	26.8	25.1	23	22.8	27.2	31.6	34.3	31.8	33.9

Table 5.3 The monthly averages of minimum temperatures (ºC) in Sebele, Gaborone, between 1998 and 2008

YEARS	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEPT.	OCT.	NOV.	DEC.
1998	19	19.4	18.6	14.3	7.4	3.7	4.6	7.1	13.1	15	17.7	18.2
1999	18.6	19.6	18.4	14.6	10.6	6.3	6.7	8.1	11.6	15.4	19.2	18.8
2000	17.6	18.7	17.9	11.8	6	6.1	3.3	7.2	11.9	16.3	15.7	18.1
2001	20	19	17	14.2	8.1	4.2	3.5	7	10.6	15.7	16.5	17.5
2002	18.2	17.9	15.9	12.1	5.9	4.8	2.7	8.3	9.7	14.1	13.9	15.1
2003	15.6	16.8	12.5	10.2	6.1	5.6	1.3	3.3	10.2	15.4	17	18.4
2004	18.8	17.9	16.2	12.3	5.9	2.1	0.8	5.2	8.2	14.7	18	18.6
2005	19.8	19.1	16.4	13.3	6.7	4.9	2.6	8.6	12.1	16.9	20.3	17.6
2006	19	18.4	15.5	10.6	3.9	2.4	3.5	5.3	8.1	16.2	17	19.7
2007	19	19.2	17.9	14.4	5.5	2.6	0.5	4.9	12.9	15.3	16.7	17.4
2008	18.2	18	15.1	9.3	7.4	2.8	2.2	5.2	8.5	16.1	18.3	19

In sub-Saharan Africa, rainfall is the most critical factor that affects crop production. In marginal areas it is a common experience that rainfall has a poor distribution through the growing season even if the annual amount looks adequate for crop requirements. In some areas, rain may fall outside the growing season. Because of that rainfall reliability is expressed as co-efficient of variability (CV) which gives a better indicator of the rain reliability than the annual amount of rain (Kumar *et al*, 1993).

Figures 4.36 and 4.56 show the temperature distribution throughout the field growing seasons. Opposite to rainfall, the temperature between December and March was as high as expected and the effect of temperature was clear from the high vegetative production at the first sowing date (D1), and it was as cold as expected by the end of the season in the fifth sowing date (D5) when the temperature went down to 9ºC. Tables 5.2 and 5.3 show the maximum and minimum temperature throughout 11 years in Sebele. The unusual amount of rainfall during the two growing seasons did not give a chance for the interaction effect between temperature and water stress, and the only effect existed was the temperature stress.

Severity of the stress that the crop experiences in water stress studies is critical to the interpretation of the results obtained. If water stress is significant for the purpose of the study, the stress should be enough to cause some physiological response in the crop (Mwale *et al.*, 2003). The same reference emphasized that the drought should be severe enough to enable one to discern differences among varieties, landraces or species. The same concern was considered in this study, because of that the drought was increased throughout the three years of glasshouse experiments (full irrigation 2006, drought imposed 77 DAS in 2007 and at 30 DAS in 2008). There was no chance to follow the same method in the field experiments because of unusual amount of rain. In addition, one of the most important points which was considered at the start of the experiments was to make sure that the soil moisture is similar in all plots when drought was imposed to get the uniformity of the conditions in the glasshouses with respect to the soil moisture content, thereby, making it possible to compare the response of the landraces to the soil moisture stress. Again, this uniformity was hard to achieve in the field. There were no measurements of drainage in the field experiments, but because soil moisture did not exceed field capacity most of the

season's growth durations and because the experimental sites were level, drainage and surface runoff assumed to be zero. The same method was used in Anwar, *et al*. (2003)

The soil moisture measurements in the field were carried out in D1 2007-2008 experiments. Although the soil moisture content was not measured for the rest of sowing dates, because of high rainfall, it can be assumed that soil moisture was not a limiting factor. In 2008-2009, the soil moisture decreased by the end of the season in the three dates of sowing, but was not enough to stress the crops.

5.2 Crop development

The longer the crop is able to grow, the greater is its biomass. This is due to more time to intercept radiation and greater opportunity to take up nutrients, especially under low input conditions (Evans, 1993). In many crops, identifying the morphological, physiological and biochemical tolerant varieties to heat and drought stress has been given a higher priority. The selection of crops according to their contrasting responses to heat and drought was used for different crops (Craufurd *et al*., 1993).

A number of factors affect crop establishment and emergence: crop type, variety, seed quality, depth and method of planting; seedbed preparation; soil temperature, aeration and moisture (Rowland and Whiteman, 1993). It is very important in dry lands to get rapid emergence, because that will shorten the period over which seedlings are susceptible to stresses and the quicker the roots develop, the more likely the young crop is to withstand drought.

In both growing seasons of the glasshouse experiments, days to emergence varied between 9-12 DAS, and because both treatments were under irrigation at emergence and had the same source of light, the only possible reasons for this variation is the

temperature and landraces. In the first field experiment, D1, the landraces started emergence at the same time (7 DAS), and between 9-10 DAS in the second experiment. Seedling emergence and seed germination are very important as an indicator of crop establishment, which was very similar among the landraces in the present study. The differences in emergence and establishment were small and non significant. This can be an indicator that when soil moisture is non-limiting factor, genotype is not an important factor in determining the success of crop establishment. This finding is supported by a study of Mwale (2005) on the same landraces at 28 ºC in the TCRU where he found no significant differences between the establishment of the landraces in the absence of soil moisture stress.

Ensuring a good germination of planted seeds and proper establishment is very important in agriculture. The growth cycle of plants depends on germination, emergence and establishment, because those determine the density of the stand obtained and the yield. In arid and semi-arid zones, where the soil surface evaporation is high, emergence problems and poor establishment could exist. The seed may germinate but the seedling might not be able to survive because of the high fluctuation of temperature which causes high rates of soil surface evaporation (Hillel, 1972). In D1 2007-2008, establishment was 76% for Dip C and 81% for Uniswa Red. Komutunga (1994) found in a study in growth room on bambara groundnut (Zimbabwe Red) that the seeds sown at 30^{o}C started emergence at 5 DAS while those sown at 20^{o}C started emergence at 10 DAS, and the establishment was higher at 30^{o}C (82%) than 20^{o}C (65%). A study on Uniswa Red and Dip C, carried out by Moreno (2000) in TCRU glasshouses, found that days to emergence were 6 at 28^{o}C which is the optimum temperature for bambara groundnut. In a study on emergence of cow pea by Warrag and Hall (1984), the earliest seedlings were observed at 2,3,5 and 6 DAS at soil temperature of 33, 27, 23 and 19ºC respectively, which are earlier than the emergence of bambara groundnut in this study.

The statistical analysis showed significant effect of temperature on leaf number during 2007 and 2008 glasshouse experiments. The difference between the leaf number at HT and the leaf number at LT is clear, especially in 2007 when the soil moisture was not a limiting factor. The decrease in the difference between the leaf number at HT and LT in 2008, suggests that when crops are under temperature and water stress they respond to drought more than their response to temperature stress. That might leads to a conclusion that, in the tropics, crops can do better if they were under temperature stress only. For example, if a crop is under heat stress but with sufficient water supply, it will be able to transpire enough water to cool the leaves and keep a canopy temperature at the level where the crop can operate with less physiological stress, but this is not always the case; In 2006, although Uniswa Red had sufficient amount of irrigation, but the crop hardly produced any pods at the high temperature, and most of the dry matter accumulated in the vegetative part (more details in the discussion of yield).

Uniswa Red always gave the highest leaf number at HT and S19-3 had the lowest at LT. Leaf number decreased with drought, it reached over 100 in 2006, and less than 100 in 2007 and it went down to maximum of 60 in 2008. Leaf number in 2006 and 2007 was higher than the values reported by Mwale *et al*. (2007a) for Uniswa Red and S19-3 at the optimum temperature under non limiting soil water. The decline in the leaf number had always started at HT before LT. This pattern was reported by Squire (1990) where he indicated that leaves remain green at the low temperature longer than the leaves grown at high temperature. He reported that leaves of Cassava in Colombia remained on the plants for five months at 20 ºC and for two months at 28 ºC. Craufurd *et al*. (1993) found that sorghum reduced leaf number under heat and drought stress.

In both field experiments, sowing date had a significant effect on leaf number. The leaf number decreased from maximum of 88 at D1 to maximum of 64 at D3. In a study by Linnemann (1993) on the effect of photoperiod on three bambara groundnut landraces collected from Nigeria, she found that the rate of leaf appearance was similar for all the daylength regimes up to 52 DAS when all treatments had started to flower. From then on, the rate of leaf appearance decreased under 10 h d^{-1} photoperiod while the other treatments continued to produce one leaf per day, and plants at photoperiods 12, 12.5, 13 and 14 h d^{-1} reduced leaf production from 80-100 DAS while plants at 16 h photoperiod maintained producing one leaf per day until 129 DAS. Photoperiod in the present study might also play a role in reducing the leaf number where it decreased from 14.5 h d^{-1} in D1 to 10.5 hd^{-1} in D5. The results of the field study is in agreement with a study of Collinson *et al*. (2000) on the effect of three sowing date (4Jan., 4 Feb. and 4 March) on two bambara groundnut landraces ; Dod R and Dod C in Tanzania in the semi-arid central region which has short rainy season from January to March. They found that leaf production declined with later sowing where the leaf number declined from a maximum of 66 at D1 to about 30 at D3.

In the glasshouse experiments, drought reduced mean leaf number at HT of the two landraces from 66 leaves per plant in 2006 to 30 leaves per plant in 2008, resulting in the reduction of LAI by 52% (from 2.8 to 1.5). Drought reduced the mean leaf number at LT from 31 per plant in 2006 to 17 leaf per plant in 2008 resulting in reduction of 34% in LAI. Reduction at HT (52%) is higher than LAI reduction (34.5%) in bambara groundnut because of drought imposed at 42 DAS at 28ºC reported by Mwale (2005) and higher than reduction of 30% reported by Shamudzarira (1996).

Several terms have been used interchangeably to describe the rate of leaf appearance: plastochron, auxochron, and phyllochron. It is defined as the interval between

formation of two successive stage of development as a reference point (such as initiation of leaf or bud) (Wilhelm and McMaster, 1995). A number of environmental factors have been reported to affect the phyllochron, like temperature and drought. Superthermal temperatures appear to enhance development (Masle *et al*., 1989). Nutrient availability at non-extreme levels has little effect on the phyllochron (Bauer *et al*., 1984). The angular coefficient (slope) of the linear regression of leaf number against cumulative thermal time is the leaf appearance rate (LAR) (i.e. leaf per degree day, or leaf °C $^{-1}$ day). In the present study, the phyllochron was estimated by the inverse of the slope of the linear regression of leaf number against thermal time (Streck *et al*., 2005 and Mwale, 2005). It has been well established that temperature is a major factor affecting the rate of leaf appearance (Massawe *et al*., 2003b; Yin and Kropff, 1996; Cao and Moss, 1989). The thermal time requirements for leaf production (phyllochron) in the glasshouse experiments differed between temperatures and landraces. Throughout the three years of the glasshouse experiments, phyllochron at high temperature was always lower than the phyllochron at low temperature except for S19-3 in 2008 where phyllochron was similar at both temperatures and had also the same rate of leaf appearance (0.04 leaves °C^{-1} day). That is likely because of drought which slowed down LAR at HT from 0.065 leaves °C^{-1} day to 0.04 leaves °C^{-1} day. Drought reduced LAR for Uniswa Red at HT from 0.094 leaves °C^{-1} day under full irrigation to 0.055 leaves °C^{-1} day at early season drought. Uniswa Red at HT had always had the highest LAR which is consistent with the highest LAI and highest leaf number Uniswa Red had throughout the seasons.

When calculate thermal time, a correction may be applied to the mean temperature if temperature during part of a day falls bellow T_b or rises above T_o (Squire, 1990). In the present study temperature rose above T_o at several occasions during the period of glasshouse experiments at LT treatment and

during all the period of growing seasons at HT treatments. Temperature fell below the T_b during the field experiments. That might be one of the reasons of the differences between the treatments which had different patterns when leaf number was plotted against thermal time (Figure 4.6 and Figure 4.41). The analysis of development in relation to thermal time is sometimes used indiscriminately and inappropriately. It needs knowledge of T_b, which should be ideally measured in controlled conditions for at least one developmental process (Squire, 1990). This has not been done in this study and T_b was assumed to be 10 °C, but that might not be absolutely true; Massawe (2000) studied T_b for ten landraces of bambara groundnut, but S19-3 and Uniswa Red were not included in his study. He found that the landraces had different T_b. This might be another reason for the differences in the relations between leaf number and thermal time. Moreover, Squire (1990) reported that the attributes of a certain genotype are influenced by the environment which the cultivars were obtained. For example, the millet genotype with widest interval between T_b and T_c temperature (T_b=8 °C, T_c= 46 °C, an interval of 38 °C) came from Niger, a climate of extreme upper and lower diurnal temperature, whereas the genotype with narrowest interval (T_b=13.5 °C, T_c= 42 °C, an interval of 28.5 °C) came from a coastal area of Senegal, where the diurnal temperature range is much smaller. Accordingly, the different origin of the landraces studied in the present study, should have played a role in the differences in thermal time. The increase in thermal duration is greater for the slowly developing individuals, so the spread of thermal time between the leaves to emerge increases (Squire, 1990). Figure 4.41 shows that plants in D5 accumulated less thermal for leaf production than plants in D1 and D3, but on

the other hand, relation between leaf number and thermal time in D5 was not linear and leaf rate appearance was the lowest (0.017leaves $°C^{-1}$ day), probably due to low temperature during D5.

Birch *et al*. (1998) reported that maize grown in shaded sites had higher phyllochron than the plants grown in full sun. That was related to the effect of irradiance and temperature. The author reported that with higher temperature, phyllochron declined, except in treatments where irradiance was low in controlled environments. In the present study, since the treatments had the same source of irradiance (natural light), the differences were due to temperature and genetic variation. In the present study, sowing date affected phyllochron significantly in both growing seasons. D3 had always the lowest phyllochron, which means leaf initiation will take shorter time, as the results shows D3 had the highest LAR (0.087 $°C^{-1}$ day). Although high temperature was reported to reduce phyllochron (and it did so in the glasshouse experiments), D5 had the highest phyllochron which could be due to low irradiance.

The phyllochron values obtained in the glasshouse and field are lower than the mean value of 44.9$°C^{d}$ reported on 10 landraces of bambara groundnut (Massawe *et al*., 2003). However, the study by Massawe *et al*. (2003b) was carried out up to 60 DAS only under environmental conditions that were different from those in the present study. Mwale (2005) reported that drought had no significant effect on the phyllochron of S19-3 and Uniswa Red grown at 28°C and he reported a value of 25.2$°C^{d}$ as a mean drought and irrigation.

Generally, in the glasshouse experiments, there was a reduction in the LAI throughout the three growing seasons, especially in 2007 and 2008. The results of this study are supported by Collinson *et al*. (1997) who reported that bambara groundnut tolerates

drought by reducing leaf area. Mwale *et al*. (2003) reported that S19-3 at optimum temperature did not reduce leaf area under drought, but in this study LAI of S19-3 decreased from 2.7 in 2006 to 1.2 in 2008 at HT and from 1.2 in 2006 to 0.6 in 2008 at LT. This disagreement could be due to difference in temperature between the two studies. The highest (peak) LAI value of 6.4 in this study is higher than the values of Dip C reported by Mwale *et al*. (2003) and Collinson *et al*. (1997). This is because of the high temperature used in this study (33 ±5 ºC) which makes the crops accumulate more dry matter in the vegetative part (Lahav and Trochoulias , 1982). The values of LAI obtained in the present study in the three glasshouse and the two field experiments are less than the maximum value of 7 reported by Kiniry *et al*. (2005) in groundnut.

Emergence, leaf initiation and leaf expansion rate, are governed by a similar T_b, the rise of LAI can be expressed in relation to the passage of thermal time from sowing. This is a useful analysis for comparing canopies that have the same T_b (Squire, 1990). Figure 5.1 shows LAI against thermal time for millet and groundnut which have the same T_b. These canopies were established at the same population, but groundnut expanded more slowly in thermal time because it is thermal duration were greater and thermal rates smaller.

The effect of temperature on the rate of leaf expansion per plant gave rise to large differences in the increase of LAI in relation to chronological time. However, when data were expressed in thermal time, the differences in the range between HT and LT were not apparent until the crops accumulated around 1000 units of thermal time when the leaf area at HT started to increase rapidly and in consequence the differences between the two temperatures in terms of leaf expansion started to get wider.

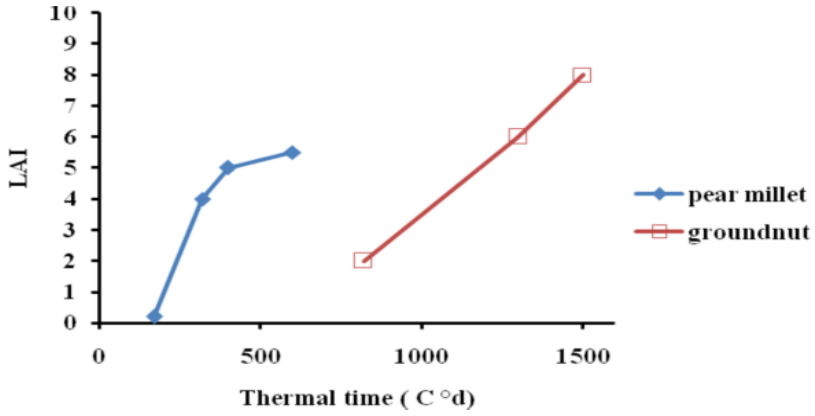

Figure 5.1 Canopy expansion in thermal time for pearl millet and groundnut grown at 28 °C (replotted from Squire, 1990).

Leaf thickness is important for leaf and plant functions. The amount of light absorbed and CO_2 pathway depends, at least partially on leaf thickness (Vile *et al*., 2005). Leaf thickness has been used as a tool to screen species for productivity because of the negative relationship between leaf thickness growth rate and photosynthetic rate (White and Montes-R, 2005). The determination of leaf thickness is not straight forward, because of the fact that leaf thickness is a relatively small and it is difficult to be measured directly. Because of that it is usually measured as SLA (the ratio of leaf area to leaf dry weight) (Vile et al., 2005; Mwale, 2005 and Charvalho, 2010). The results of the glasshouse experiments showed that plants at HT had higher SLA than plants at LT in 2006 and 2007, but not in 2008 when drought was severe. The relationship between SLA and cumulative thermal time showed different pattern to the leaf number against thermal time, which means thermal time units for leaf production was not exactly similar to units needed for leaf thickness.

The effect of sowing date on leaf number was significant in both field experiments. The number of leaves declined from maximum of 84 per plant in D1 to 71 leaves per

plant in D3 and 60 leaves per plant in D5 which led to reduction in LAI from 3.4 in D1 to 1.4 in D3 and to 0.5 in D5. The effect of sowing date on leaf area of mungbean was reported by Asghar *et al*. (2006) who reported a decline in leaf area from 1465 cm^{-2} in D1 (third week of June) to 1141 cm^{-2} in D3 (third week of July).

The regression of pod number against thermal time showed no significant differences in both years of the field experiment. Pod initiation was much lower in the second experiment, but it is difficult to know the reason as the regression of the second year was for D1 and D3 only.

5.3 Dry matter production and radiation capture

In the glasshouse experiments and in both regimes of temperature, TDM was strongly affected by drought. The decrease in dry matter production as a result of drought is correlated with closure of stomata to save water (Mwale *et al*., 2003) CO_2 fixation will decrease when stomata close, which leads to reduction in dry matter production. Reduction in dry matter production under drought conditions was reported by several studies (Singh, 1991; Mwale *et al*., 2003, Ghassemi-Golezani, *et al*., 2009 and Jaleel *et al*., 2009).

Leaf dry matter and pod dry matter was also affected by drought and temperature. Throughout the three years of the glasshouse experiments, the TDM results showed that the accumulation was higher at HT especially in 2006 and 2007. These results are in agreement with a study of Marshall *et al*. (1992) who reported that TDM of groundnut grown at mean temperature of 31ºC was eight-fold of that grown at 19 ºC.

Mwale *et al*. (2007a) reported that TDM of bambara groundnut of 650 g m^{-2} at optimum temperature and non-limiting soil moisture at the TCRU glasshouse and Shamudzarira (1996) reported values of 850 g m^{-2} for Dip C under non-limiting soil moisture. These values are higher than the values obtained in the glasshouses and field experiments reported in this study (583 g m^{-2} and 598 g m^{-2}, respectively). However, the values obtained in the present field and glasshouse studies are higher than the values reported by Collinson *et al*. (2000) from a field study in Tanzania where the maximum TDM obtained from bambara groundnut at D1 (January) was 422 g m^{-2} and TDM obtained from pea was 541 gm^{-2} (Kanton and Dennett, 2008). The results of the present study showed that TDM production was higher at HT than at LT. That might give an impression that high temperature increases the TDM production, but in fact, the values of TDM obtained in this study at the two temperature regimes, are less than the values reported by Mwale (2005) at 28ºC. That leads to conclude that high temperature decreased TDM. That is supported by Gawronska *et al*. (1992) who found on a study on Potato that the rising of temperature caused reduction in producing dry matter and Craufurd *et al*. (2002) who reported that the high temperature reduced total dry matter production about 23 % and 35% in two different genotypes of groundnut when they were exposed to two different day/night temperatures of 28/22 ºC and 38/22 ºC, respectively. Figure 5.1 compares TDM in 2006 in the three glasshouse experiments with TDM reported by Mwale (2005) for Uniswa Red and S19-3 grown at 28°C. For the two landraces, the maximum values in 2005 were higher than the values obtained at the present study. S19-3 produced the highest amount of TDM in 2005 and 2006. That shows the wide range of S19-3 adaptation to temperature and drought stress. Moreover, the amount of TDM produced by Uniswa Red and S19-3 at drought treatment in 2005 was almost similar to the amount produced by the same landraces at 23±5 °C in 2006. The relationship between thermal time and TDM showed that the landraces at HT accumulated more thermal and more TDM than the

landraces at LT. The results also show that the thermal time requirements from planting to maturity increases with drought at both temperatures.

The results of the present study are also supported by Thakur *et al*. (2010) who reported that the low temperature stress caused reduction in dry matter production in grain crops. In both glasshouse and field experiments, crops continued to produce pods along with leaves and stems. In some legumes (Thomas *et al*., 2004) and some cereals (Kamara *et al*., 2003), pod filling is associated with decrease in the dry matter content of some vegetative parts of the plant due to a redistribution of dry matter in the plants. The non dry matter redistributing behaviour found in this study was in agreement with the findings of Norman (1992); Collinson *et al*. (2000) and Mwale (2005).

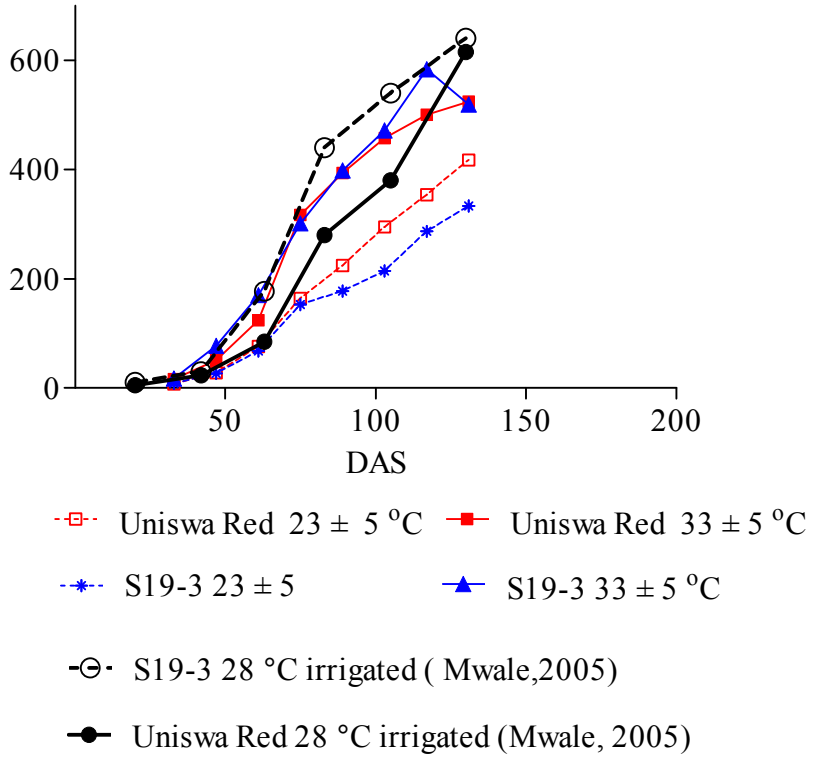

Figure 5.2 Comparison of total dry matter (g m^{-2}) obtained from the glasshouse experiments in 2006, with the amount reported by Mwale (2005)

When plants take their water from a drying soil, the length of the root system increases in association with a decrease in the canopy area. This will cause a greater root mass in a drying soil, but usually a much larger root to total dry matter mass ratio (Squire, 1990). No root measurements were carried out in this study to see if there is a redistribution of dry matter between roots and above ground dry matter, but Shamudzarira (1996) reported that drought increased the ratio of root dry weight: total dry weight in bambara groundnut Figure (5.2).

TDM in 2008 glasshouse experiment reached 271 gm^{-2} as maximum. This was higher than the value of 200 gm^{-2} reported by Shamudzarira (1996) for Dip C under drought conditions. Craufurd *et al*. (2002) found that heat stress of 10 ºC above the optimum temperature at non-limiting soil moisture reduced the yield of groundnut by up to 80%. This is similar to the finding of 2006 glasshouse results where the yield of Uniswa Red at the high temperature (55 gm^{-2}) was 25% of the yield at the low temperature (209 gm^{-2}).

Wheeler *et al*. (1997) reported that groundnut produced less dry matter TDM (30.2 g $plant^{-1}$) at 45/24 °C day/ night regime than the amount (61.3 g $plant^{-1}$) produced at 35/24 °C. They also found that there was a delay of 11.7 days in pod filling for a sensitive genotype to high temperature. The same authors found a variation between the genotypes in the response to heat stress during both vegetative and pod filling stages and yield of the sensitive genotype to high temperature was half of the yield of the tolerant genotype. The authors found that the optimum temperature for the vegetative part was 25-30 ºC and for pod growth usually cooler 26-28 ºC. The results of Wheeler *et al*. (1997) can be linked with the results of the glass house results where Uniswa Red yield at the high temperature (55 gm^{-2}) was one third of the S19-3 at the high temperature (149 gm^{-2}) at full irrigation in 2006.

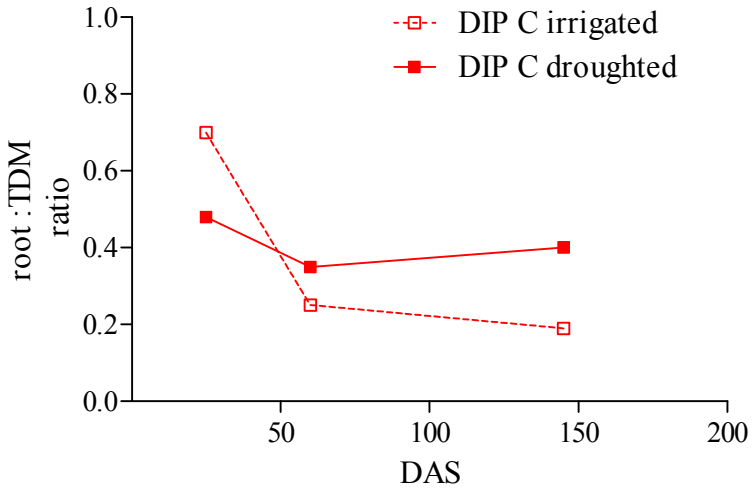

Figure 5.3 Effect of drought on the root: total dry matter (TDM) ratio (replotted from Shamudzarira, 1996)

Dry matter accumulation is not the only parameter of crop productivity, but more important is the effective partitioning to the harvested part (Kumar *et al*., 2006). S19-3 produced more yield in 2007 than in 2006 which could be due to more dry matter partitioning to pod when crops are under moderate drought. Kumar *et al*. (2006) reported in a study on rice that the partitioning to grain increased under drought. The same authors reported decrease in total dry matter production because of drought and greater redistribution of dry matter from leaves and stems to grain yield especially when drought is severe.

Duration of grain fill is reduced by the combination of drought and heat stress more than either treatment alone. The consequences of drought on the developmental and physiological process are more severe at high temperature than low temperature (Barnabas *et al*., 2008). In a study on groundnut, Ong (1984) reported that the rate of foliage development increased to a maximum at 28-30 ºC, whereas the rate of crop

photosynthesis was remarkably conservative over a range of mean temperatures of 19-31ºC. The author reported that groundnut under high temperature stress produced fewer pegs and pods and that under high temperature the stem and leaf growth compete directly with reproductive organs for assimilates. This might be an explanation for the low pod production and high vegetative matter in Uniswa Red under the high temperature in the glass house experiments. Leong and Ong (1983) reported that high temperature causes longer stems in groundnut which prevents pegs from reaching the ground, this might be the case in Uniswa Red where it was noticed that there some pods above the soil surface. Ong (1984) reported an effect of high temperature on pollen viability in groundnut.

Knowledge of moisture sensitive periods is important for irrigation scheduling. Timing of these periods is different among crops. The most critical period for chickpea is usually considered to be flowering stage (Anwar *et al*., 2003), but faba beans do not show any particular sensitive period (Hebblethwaite, 1982). There is not much work about the sensitive stages of water stress in bambara groundnut. The present study was more about the effect of late and early drought rather than the sensitive period, because when drought was imposed, the crop had access to stored water only until harvest. The results show that imposing drought at flowering in 2008 had stronger effect on crop growth and development than imposing drought at podding stage.

In a study on the high temperature effect on chickpea during reproductive development, Wang *et al*. (2006) grew chickpea under three temperature day /night regimes; 20/16, 28/16 and 35/16 ºC for 10 days at flowering stage and pod filling stage . They found that high temperature at flowering decreased pod production of two genotypes by 34% and 22% and the seed yield by 35% and 42%; whereas high temperature stress at pod filing stage reduced significantly pod production by 22% and

11% and seed yield by 32% and 36%. Although the design of this experiment is different to the study produced in this thesis, it provides supporting evidence of the negative high temperature effect on pod production in Uniswa Red. The seed yield values obtained in the present study are less than the values of 486 g m^{-2} reported for bambara groundnut by Kouassi and Zoro (2010).

Some cultivars of chickpea could produce moderate pod set under low temperatures even when night temperature was 0 ºC as long as day temperature was 20 ºC or more (Srinivasan *et al*., 1998). This suggests that high day temperature may partly compensate the negative effects of low night temperature. This can be linked to the results of this study in the field for D3 where the minimum temperature started to go down to 10 ºC starting from 59 DAS but the maximum temperature did not go below 26 ºC, and in this range of temperature the crops produced considerable amount of pods (76 g m^{-2}). Srinivasan *et al*. (1998) reported much less pod production in chickpea in 15/5 and 15/0 ºC day/night temperature than at 20/5 ºC and 20/0 ºC day/night time temperatures. That might be an indicator that lower day time temperature induces floral abortion. Similar pattern was noticed in the present field study when the temperature dropped at pod filling stage to 22/4 ºC day/night temperature in D5 and the crops hardly produced any pods.

Exposing plants to cold temperature stress during reproductive stages causes a reduction in the metabolic rates leading to low yields. Functional abnormalities in reproductive organs might be caused by cold stress, leading to failure of fertilization or causing premature abortion of seeds (Thakur *et al*., 2010). There has been a disagreement between studies about the most chilling-sensitive reproductive phase in chickpea ; some suggest that pollen production is the most sensitive stage, and some reported that stage from meiosis in spore mother cells to fertilization and seed development are more susceptible to cold (Thakur *et al*., 2010). The effect of cold

stress was clear in D5 through the reduction in dry matter and pod production. The results of the present study are consistent with the findings of Sesay *et al*. (2008) who reported in a study on six sowing dates of bambara groundnut in Swaziland a decline in yield dry matter of 75 % between the first sowing date (the hottest) and the last sowing date (the coldest).

In a study of Thalji and Shalaldeh (2006) on faba bean, the crop was planted at three sowing dates 25 November, 25 December and 25 January under optimum growing conditions in Jordan. The yield of the first sowing date was 157% more than the yield produced under the third sowing date. In the present study, D5 produced 50% of D1 yield in the first field experiment and 30% in the second. The highest grain yield reported by Thalji and Shalaldeh (2006) of faba bean was 136.9 g m^{-2} which is higher than the highest yield of 119 g m^{-2} obtained in the present field study.

While variation in bambara groundnut planting date is expected to impact on the pattern of bambara groundnut growth and development, few reports have examined this issue in detail. The decline in yield observed as planting was delayed highlights the importance of early sowing for maximising the yield potential. These results are consistent with the results of the sowing date effect on soybean (Bastidas *et al*., 2008).

In days longer than the optimum (12 h d^{-1} for bambara groundnut) the crop will take longer to reach pod filling and maturity will be delayed, this might be the reason, in addition to heat stress, the crops produced low yield in D1 when the photoperiod was around 13h d^{-1} at the pod filling stage. The field yield was low compared with the yield in the glasshouse, and compared with yield of other legume crops. The crops grown in D5 produced few pods. This is likely because of cold stress which reduced the growth of the crops to the extent that they were not able to produce pods.

Landraces with high reproductive partitioning will increase pod yield due to an increase in biomass production. The capacity of the plant to increase its pod yield in response to an increase in its TDM can be taken as an indicator of reproductive partitioning. The risk of heat stress increases with lack of water, when soil water deficit leads to stomatal closure and reduces plant transpiration (Lecoeur and Guilioni, 2010). The non-linear regression of pod dry matter against total dry matter showed significant differences between the treatments. For the low temperature, in the three glasshouse experiments. TDM production was positively related to pod dry matter, but not at HT where the positive relationship was disturbed due to drought. That is shown in the graph of pod dry matter against DAS where the plants were not able to produce any pods after 120 DAS. The change of the relationship at the high temperature in 2008 suggests that dry matter accumulation is important to yield formation up to a certain level of stress. The disturbance of crop physiology because of heat stress was also reported for pea when air temperature exceeds 25°C (Lecoeur and Guilioni, 2010). The regression of pod dry matter against total dry matter showed that the plants must reach a minimum vegetable biomass (Squire, 1990) before assimilates are portioned to pods. The landraces at LT needed less minimum TDM than the landraces at HT to start producing pods. The exponential curve means that there was an increase in pod dry matter at a constantly growing rate where pod dry matter is a proportional to TDM.

The harvest index (HI) values of 0.46 reported by Mwale (2005) as a mean of droughted and irrigated bambara groundnut and the value of 0.59 (seed HI) for groundnut reported by Kiniry *et al*. (2005) are either comparable or less than the values obtained in the present glasshouse study. Although the statistical analysis showed no significant difference in 2007, HI of Uniswa Red at HT was 45% of HI at LT, while HI of S19-3 LT was slightly less than HI of S19-3 HT. Again, in 2008, the difference was not significant, but in both landraces, HI was much lower at HT. HI

was reduced by drought except for S19-3 at LT. The negative effect of high temperature on HI is in agreement with the results reported by Prasad *et al*. (2000) on groundnut.

Dip C and Uniswa Red behaved similarly in response of HI to sowing date. The means of HI from the three sowing dates and the two years of experiments were 0.19, 0.23 and 0.07 for Dip C at D1, D3 and D5 respectively, and 0.28, 0.31 and 0.08 for Uniswa Red at D1, D3 and D5 respectively. The values are lower than the values obtained from the glasshouse experiments which might be due to the different growing conditions or the genetic variations. Uniswa Red had always higher HI than Dip C in the three sowing dates. This pattern is opposite to the pattern of HI in the glasshouse experiments where S19-3, which originated from the same environment as Dip C, always had higher HI than Uniswa Red. This difference between S19-3 and Uniswa Red, or may be between Uniswa Red used in the glasshouse and in the field, this difference leads to the probability of genetic variation between the landraces which could be very interesting in breeding approach.

To analyse such differences in dry matter production between the present study and the other comparable studies, and to analyse the differences within TDM production in the present study, the first step is to determine the amount of intercepted radiation and the efficiency of radiation use to produce dry matter.

The conversion efficiency depends on several factors. These can be divided into two groups, (i) the dimensions and duration of the canopy that determine f and (ii) that determine the rate of photosynthesis and respiration, and therefore TDM production rate per unit of radiation intercepted.

The contribution of these two groups can be determined by expressing dry matter as a function of intercepted solar radiation. Although the intercepted radiation in the present study was higher than the values reported by Mwale (2007b), TDM production in this study was less than Mwale (2007b). This is due to the lower RUE in the present study, which emphasise on the previous studies which reported that higher intercepted radiation, does not mean necessarily higher dry matter. The correlation between RUE and TDM supports the hypothesis of the positive relation between TDM and RUE. On the other hand, this principle could not be applied on the relation between WUE and TDM production, where in 2008 glasshouse experiment, crops with higher WUE produced less TDM.

The data presented in this thesis show the effect of drought and temperature on both the capture of radiation and its conversion to dry matter. In the present study, capture of radiation depends on soil moisture, temperature and saturation deficit. Drought had an effect on the total intercepted radiation (S_t) in the four treatments in both years; 2007 and 2008. The crops in the present study intercepted more radiation in 2007 than in 2008 as the drought was more severe in 2008. These results are in agreement with those reported before in bambara groundnut (Mwale *et al*., 2007b), cowpea (Craufurd and Wheeler, 1999) and finger millet (Maqsood and Azam-Ali, 2007). The fractional interception (f) did not differ between 2007 and 2008. This result is not in agreement with Mwale *et al*. (2007b) who indicated that drought reduced f in bambara groundnut. This disagreement could be due to the different temperature and soil water conditions in the present study and Mwale *et al*. (2007b).

Although the statistical analysis showed no significant difference between the total amount of intercepted radiation by the crops grown at LT and the crops grown at HT, the intercepted radiation and f were higher at the high temperature in both years. For Uniswa Red at the high temperature, the intercepted radiation was reduced from 1200

MJ m^{-2} in 2007 to 942 MJ m^{-2} in 2008 (22% reduction), and reduction of 29 % for S19-3 at the high temperature. These percentages of reduction are less than the reduction from irrigation to drought (30%) reported by Mwale *et al*, (2007b).

The total seasonal intercepted radiation in both years and both temperatures was higher than the values reported by Maqsood and Azam-Ali (2007) for finger millet grown in the TCRU in drought and irrigation treatments (661MJ m^{-2} and 698 MJ m^{-2} respectively). The higher intercepted radiation and *f* in the high temperature is linked with LAI; where both crops had higher LAI under HT, and in both temperatures the maximum *f* periods were consistent with the periods of maximum LAI, and *f* started to decline with LAI decline.

Accumulated solar radiation of a stand depends on irradiance receiving rate and on *f* which is controlled mainly by LAI and the extinction coefficient (Squire, 1990). The amount of solar radiation intercepted depends on the duration of the foliage, because of that, S19-3 which had shorter life cycle than Uniswa Red, S19-3 in both years intercepted less radiation than Uniswa Red. Accordingly, it might be useful to describe the crops' canopies in terms of a seasonal value of *f* as Squire (1990) suggested. The means of *f* in 2007 were 0.80, 0.50, 0.70 and 0.55 for Uniswa Red HT, Uniswa Red LT, S19-3 HT and S19-3 LT respectively. For 2008, averages of *f* values were; 0.75, 0.63, 0.76 and 0.60 for Uniswa Red HT, Uniswa Red LT, S19-3 HT and S19-3 LT, respectively.

The seasonal value of *f* is influenced by population density which affects the period at the beginning of the season when *f* is small, but the influence decreases later in the season when *f* is large (Squire, 1990). In the present study, the crops were grown with same density in both temperatures, and the differences between the treatments were

due to temperature and soil water effects. Squire (1990) indicated that temperature has a stronger effect on the duration of stands than population and thereby on seasonal *f*.

Drought delayed Uniswa Red HT from reaching the maximum *f* from 82 DAS in 2007 to 86 DAS in 2008. Similar pattern happened with S19-3 at LT which reached the maximum *f* at 77 DAS in 2007 and at 81 DAS in 2008. No such pattern happened with S19-3 at HT which reached maximum *f* at 79 DAS in 2007 and at 72 DAS in 2008 and Uniswa Red at LT which reached maximum f at 86 DAS in 2007 and 75 DAS in 2008. These results are similar to the results (71 DAS) reported for pea by Kanton and Dennett (2008).

Increased temperature increases the rate of canopy expansion in indeterminate crops (e.g. groundnut), but has no direct effect on the duration of canopy expansion or canopy longevity, at least within the limits of the growing season, which are usually determined by factors such as supply of water. Accordingly, the size of the canopy, the radiation interception and the dry matter, at any time after emergence, all increase with rise in temperature between base and optimum temperature (Marshall *et al.,* 1992). In 2007, the maximum *f* values were 0.94, 0.74, 0.94 and 0.75 for Uniswa Red HT, Uniswa Red LT, S19-3 HT and S19-3 LT reached at 82, 86, 79, and 77 DAS respectively. Maximum values of *f* in 2008 were 0.92, 0.75, 0.9 and 0.71 reached at 86, 75, 72 and 81 DAS for Uniswa Red HT, Uniswa Red LT, S19-3 HT and S19-3 LT, respectively. Two cultivars of maize reached the maximum *f* of 0.73 and 0.68 at 99 DAS under non-limiting soil moisture (Kanton and Dennett, 2008). Reduction in *f* under water stress in bambara groundnut was reported in previous studies; (Collinson, *et al*., 1999) and (Mwale *et al*, 2007b)

In a study on groundnut, Marshall *et al*. (1992) found that *f* increased with rise in mean temperature from 19 ºC to 28ºC, but when they grew the crop under mean of 31

ºC *f* did not increase further . In the present study, maximum *f* increased with rise in mean temperature from 23ºC to 33ºC, from less than 0.8 to 0.94. According to Mwale (2005), bambara groundnut reached maximum *f* of 0.8 at 28 ºC under full irrigation. This might be an indicator that bambara groundnut is different to groundnut, where *f* can increase further with rise in temperature above the optimum level. This shows bambara groundnut as a crop which has a wide range of ability to grow and develop under conditions of stress.

The extinction coefficient (K) in both years found of this study (0.57 in 2007 and 0.59 in 2008) are less than the values of bambara groundnut (0.62) reported by Chikweyeye from the 2006 glasshouse experiment for the four treatments under full irrigation. The values obtained in the three years of this study are higher than the value of (0.46) reported by Mwale *et al*. (2007b) out of the mean of drought and irrigation treatments of three bambara groundnut landraces grown under optimum temperature in the TCRU glasshouses and slightly higher than the value of 0.53 reported by Collinson *et al*. (1999). However, the values in the present study are lower than the values of 0.63 and 0.89 reported by Tesfaye (2006) for chickpea under mid season drought and late season drought, respectively. There was no significant difference between the treatments in both years and it was not affected by drought.

Squire (1990) reported that k varies greatly within species, especially if the genotypes differ in morphology. In the present study where the landraces are quite morphologically similar, no significant differences were found. Drought did not affect K between 2007 and 2008, but 2006 value was slightly higher than 2008. The results are in a good agreement with a study by Rido *et al.* (1996) on peas where he found no effect of drought on k, however, the same study found a k reduction in water stressed faba bean. They attributed the difference between the two crops to the ability of faba bean to change leaf angle under drought. Leaf size and orientation are the main factors

affect k (Tesfaye, 2006). In a study on chickpea, bean and cowpea, grown under different soil water regimes, chickpea had the lowest k in all the soil water regimes (Tesfaye, 2006). The author attributed that to the more horizontal leaves that bean and cowpea had than chickpea. No measurements of heliotropism were carried out in the present study, but it has been noticed that the crops change the leaf angle at the midday, moreover, heliotropism in bambara groundnut in response to drought was reported by Collinson *et al*. (1999)

Radiation use efficiency (RUE) of bambara groundnut was affected by drought in both temperatures and landraces. There were reductions in the radiation conversion coefficient (ε_s) of 42%, 33%, 32% and 36 % from 2007 to 2008 in Uniswa Red HT, Uniswa Red LT, S19-3 HT and S19-3 LT respectively. Reduction in ε_s because of drought was reported in different crops; finger millet (Maqsood and Azam-Ali, 2007), Soybean (De Costa and Shamugathasan, 2002) and cowpea (Craufurd and Wheeler, 1999)

The values obtained from the 2006 glasshouse experiment (reported by Chickweyeye, 2006) are higher than the values obtained in 2007 and 2008. In 2007, Uniswa Red had the same radiation conversion coefficient (ε_s) at both temperatures, but for S19-3, ε_s at LT (0.66 g MJ^{-1}) was half of the value obtained at HT (1.31 g MJ^{-1}). In 2008 the effect of temperature on Uniswa Red was clearer when there was a reduction of 23 % in ε_s (0.4 g MJ^{-1} and 0.31 g MJ^{-1} at HT and LT, respectively). This is in agreement with a study by Marshall *et al*. (1992) on groundnut in the TCRU under different means of temperature, reduction in ε_s of 30% was found between a stand grown at 31 ºC (2.13 g MJ^{-1}) and a stand grown at 22 ºC (1.5 g MJ^{-1}) (values are based on total intercepted radiation). The values of ε_s based on total intercepted radiation for soybean, mungbean, and cowpea grown under well-watered conditions were 0.88 g MJ^{-1}, 0.94 g MJ^{-1} and 1.05 g MJ^{-1}, respectively (Mucho *et al*., 1993). These values are in the range

of the values obtained in the present glasshouse study in 2007, but higher than 2008 values.

Using the factor 0.45 to convert the ε_s (based on total solar radiation) to ε_s (PAR based) as proposed by Kiniry *et al*. (2005); the values of ε_s in 2007 will be 2.08 g MJ^{-1}, 2.04 g MJ^{-1}, 2.9 g MJ^{-1} and 1.46 g MJ^{-1}, and in 2008 will be 0.88 g MJ^{-1}, 0.68 gMJ^{-1}, 0.93 g MJ^{-1} and 0.53g MJ-1 for Uniswa Red HT, Uinswa Red LT, S19-3 HT and S19-3 LT respectively. A PAR-based value of 2 g MJ^{-1} in groundnut was reported by Kiniry *et al.* (2005) and value of 1.45 g MJ^{-1} in soybean was reported by Purcell *et al*. (2002). A value of PAR-based value of 1.52 g MJ^{-1} from above ground dry matter was reported by O' Connell *et al*. (2004).

Tesfaye *et al*. (2006) reported a reduction in both LAI and ε_s due to drought in a study on three legumes (bean, chickpea and cowpea) grown under two different regimes of temperature; the first regime with seasonal maximum mean of 35.5 °C and seasonal minimum mean of 22.2 °C; the second had 30 °C as seasonal mean of maximum and the seasonal minimum was 16.3°C. The crops were exposed to mid season drought from 58 to 71 DAS. LAI and the ε_s at high temperature were higher in the three legumes. This is consistent with the observations in the present study where crops had higher LAI and ε_s at the high temperature. PAR- based values of ε_s obtained in the present study in 2007 are higher than the values reported by Tesfaye *et al*. (2006) although the drought was more severe in the present study, however, the values obtained in 2008 are still reasonable comparing with the long drought the crops were exposed to. This puts bambara groundnut in a very good position among the other legumes in terms of radiation capture and conversion. Reduction in ε_s was related to reduction in LAI, but it was also related to reduction in photosynthesis. This relation between ε_s and photosynthesis was reported by Squire (1990).

The corresponding reduction in *f* is usually proportionally similar to the concomitant reduction in ε_s because of the asymptotic relation between leaf area and *f* and because many herbs can move their leaves in order to intercept less radiation. As a result, dry conditions might affect leaf area more than photosynthesis (Squire, 1990). The orientation of leaves in some legume crops during the day is well known as a response to environmental stress, like soybean, kidney bean and cow pea (Isoda *et al*., 1993). Bambara groundnut has the ability to move leaves from horizontal to vertical position during the middle of the day when the load of incident radiation increases; that might explain the similarity in photosynthesis in the present study in both temperatures throughout the three growing seasons.

Throughout the life of the canopy, ε_s might be decreased because of the increase in SD. It has been demonstrated that ε_s of sorghum and maize is sensitive to SD even under non-stressed conditions (Squire, 1990). In the present study, when SD was used to normalize the amount of water transpired, the difference between the εs values at high and low temperature increased. For example, ε_s of Uniswa Red in 2007 was 0.94 g MJ^{-1} at HT and 0.92 g MJ^{-1} at LT, but after normalizing, the values increased to 1.81 g MJ^{-1} kPa^{-1}at HT and decreased to 0.86 g MJ^{-1} kPa^{-1} at LT. SD also changed the differences in 2007 and 2008. For example, ε_s for Uniswa Red at LT in 2007 was 3 times greater than ε_s of Uniswa Red at the same temperature in 2008, after normalizing; Ω_s for Uniswa Red at LT in 2007 became almost three and half times Uniswa Red Ω_s at LT in 2008. Table 5.4 shows SD, ε_s, and Ω_s of pearl millet and groundnut. The values of ε_s and Ω_s of bambara groundnut in this study, compare favourably with pearl millet and groundnut in terms of RUE.

Table 5.4 Comparison of crop dry matter excluding roots (W), transpiration ($\sum$ E), saturation deficit (D), dry matter: transpired water ratio (ε_w), transpiration equivalent (Ω_w), accumulated intercepted radiation ($\sum S_i$), conversion coefficient for intercepted

radiation (ε_s), and radiation equivalent (Ω_s) for stands of pearl millet and groundnut growing in experimental glasshouse at the University of Nottingham and the field in central India or West Africa. (Azam-Ali *et al*., (1994)

Crop and region	W(gm^{-2})	$\sum E_t$ (kg)	D (kPa)	ε_w (g kg^{-1})	Ω_w g kg^{-1}k	$\sum S_i$ (MJ m^{-}	ε_s (g MJ^{-1})	$\Omega_{w(}$ g MJ^{-1} kPa^{-1})
Pearl millet								
Nottingham	1440	220	1.4	6.55	9.16	550	2.62	3.67
India	660	150	2.4	4.4	10.56	450	1.47	3.52
India	320	70	2.3	4.57	10.51	300	1.07	2.45
Africa	170	80	4	2.13	8.5	297	0.57	2.29
Mean	**648**	**130**	**2.53**	**4.41**	**9.68**	**399**	**1.43**	**2.98**
CV%				**41**	**10**		**61**	**24**
Groundnut								
Nottingham	270	52	1	5.19	5.19	191	1.41	1.41
Nottingham	250	76	1.4	3.29	4.61	175	1.43	2
Nottingham	200	82	1.6	2.44	3.9	136	1.47	2.35
Nottingham	110	72	2	1.53	3.06	130	0.85	1.69
India	220	110	2.1	2	4.2	420	0.52	1.1
India	420	220	2.5	1.91	4.77	900	0.47	1.17
Mean	**245**	**102**	**1.77**	**2.73**	**4.29**	**325**	**1.02**	**1.62**
CV%				**49**	**17**		**46**	**30**

5.4 Water capture and water use efficiency

The containers used in the present study to measure soil surface evaporation were successfully used in several field and glasshouse studies (Lascano *et al.*, 1987; Simmonds and Williams, 1989; Shamudzarira, 1996 and Mwale *et al*., 2007b). Shamudzarira, (1996) indicated that several process involved in measuring E_s with trays may cause error in estimating E_s, these processes include (i) Vertical and lateral re-distribution of water between the soil in the tray and the surrounding soil might be obstructed. (ii) Within the container, there is no active root system in the soil. (iii) Redistribution of the soil during filling of the container might change the soil hydraulic properties. However, despite of errors involved, measuring soil evaporation with this technique is simple and useful and has been reliable while it was used in several studies, moreover, the measurement of soil evaporation in the present glasshouse studies started after the last irrigation and amount of lost water from the soil surface was very small and could be ignored. The only concern which may exist is about the field measurements where E_s was high because of rainfall. The same concern was raised by Allen (1990) while using microlysimeters method during

precipitation. E_s accounted for 5.3%, 5.4%, 5% and 5% from E_t in 2007 and 16.8%, 7.6%, 3.9% and 2.4% in 2008 from the stands of S19-3 HT, Uniswa Red HT, Uniswa Red LT, and S19-3 LT respectively. In dry land agriculture, the loss of water by E_s is usually small, but it can be large if the canopy is wetted frequently by small amount of rainfall, especially if the stand is sparse, E_s can constitute 50% or more of the total loss (Squire, 1990). This can be linked with the results of E_s in the field study where rain fell frequently and the space between rows was relatively wide (50 cm). In the three sowing dates, soil moisture decreased towards the end of the season.

Cumulative E_t in the glasshouse experiments (which could be considered as transpiration due to small E_s) was reduced under drought at HT in both landraces, but it was less affected at LT (reduction of 40% and 23 % from 2007 to 2008 at HT in S19-3 and Uniswa Red respectively). The results demonstrate that decrease in leaf area in both landraces is an important mechanism for transpiration control under water stress. Same findings were reported by Shamudzarira (1996) in sorghum and bambara groundnut. The results of E_t for the first field growing season showed that the rain fed Uniswa Red had the greatest E_t, but the highest TDM was produced by Dip C at rain fed treatment. For the second field experiment, E_t in D5 was less than D3 and D1 and that was related to the low LAI and consequently less transpiration. The lowest amount of cumulative E_s was in D5 due to the low amount of rain D5 had, and also with delay in sowing, air temperature decreased and reached the lowest range by D5.

The effect of cold stress is not only on the above-ground growth, but since the soil temperature also decreases following the air temperature, root yield is also affected by the decrease in soil temperature. This will affect the ability of roots to extract minerals and water from the soil. The effect of sowing date on root yield of sugar beet was reported by Sogut and Ariogly (2004). In the glasshouse experiments, the moisture content at 100cm was always the highest, but the content in 2008 was less than 2007

in the four treatments. That supports the finding of Mwale (2005) that bambara groundnut increases the root depth under drought to extract more water from deep layers.

The irrigated Dip C had the highest amount of soil water in the three sowing dates. The soil water profile showed that most of the extracted water was from the closest layer to soil surface (20 cm). This finding indicates that if sufficient water is available in the top soil to meet E_s demand, then water extraction will occur preferentially from that layer, as reported by Shamudzarira (1996).

Although SD was uniform under the same temperature in both years of the glasshouse experiments (2007 and 2008), E_t was higher in 2007, because the crops had more water in 2007. That suggests bambara groundnut responds more to SD when it has more water and it can resist the effect of SD under drought conditions. No root measurements were carried out in the present study, but Shamudzarira (1996) reported higher root length densities under medium or high SD when compared to low SD under both stored moisture and drought conditions. Although most of the water was extracted from depths of 10-40 cm, there was also a decrease in the amount of water at 60 cm and 100cm layers in both years which might be an indicator to the depth of water extraction under limited soil moisture. Mwale (2005) reported a length of more than 100cm of bambara groundnut roots under both irrigated and drought conditions. Root characteristics and behaviour determine the amount of available water that can by extracted by a crop (Azam-Ali and Squire, 2002) .

The results of the 2007 glasshouse experiment showed no significant differences in ε_w between the four treatments, but in 2008 there were significant differences. Mwale *et al*. (2007) reported a decrease of 20% in ε_w under drought and optimum temperature for three landraces of bambara groundnut (values of 2.05 g kg^{-1} and 1.65 g kg^{-1}under

irrigation and drought, respectively). ε_w in 2007 (3.02 g kg^{-1}) is as same as the values of 3 g kg^{-1} for bambara groundnut reported by Shamudzarira (1996) and higher than the values reported by Mwale *et al*. (2007b). The value is within the range of 1.17 to 3.87 g kg^{-1} reported by Siddique *et al*. (2001) for seven legumes.

The values of ε_w in 2008 glasshouse experiment are less than the values reported by Craufurd *et al*. (1999) of 2.7 g kg^{-1} and 3.3 g kg^{-1} obtained from water stressed groundnut grown on 50% available soil water and mean temperature of 34 ºC and 27 ºC respectively. However, the values of ε_w often vary between sites and /or seasons even for the same crop. Azam-Ali and Squire (2002) suggested that three factors cause the variation in ε_w; the contribution of roots to TDM, variation in SD and variation in E_s. Despite the fact that heat stress is an important component of drought stress, the reports of the effect of high temperature alone or in combination with drought on bambara groundnut are few. Craufurd *et al*. (1999) found no interaction effect of temperature and drought on ε_w of peanut. The effect of temperature on ε_w in 2008 was consistent with the effect of temperature reported by Craufurd (1999) where he found a decrease in ε_w under heat stress.

The calculation of ε_w is usually based on the relationship between TDM produced and transpired water. This might be misleading for crop plants where the most crucial parameter for crop improvement is yield. That was demonstrated from the results of 2007 when the difference between the four treatments ε_w based on TDM was not significant, but when ε_w was calculated based on pod dry matter, significant differences were found ($P<0.05$).Moreover, in the result of HT 2008, ε_w in S19-3 was higher than Uniswa Red by 50%, but pod yield in Uniswa Red was 22% of TDM, while it is 40% in S19-3. That means S19-3 produced higher yield per unit of water used by Uniswa Red. When WUE was calculated on pod dry weight instead of TDM, ε_w of S19-3 at HT in 2008 was higher than Uniswa Red by 80%.

For the first field experiment, ε_w was measured for D1 only as the soil moisture measurements were carried out in D1 only. There was no drought effect, and no significant differences were found.

ε_w obtained in the first field experiment is less than the values reported by Mwale *et al*. (2007b) and Shamudzarira, (1996). Delay in sowing had a negative effect on ε_w . Dip C had higher ε_w than ε_w of Uniswa Red in D1 and D3, but not in D5 where the differences were not significant (ε_w of 0.23 g kg^{-1}, R^2= 0.34.9 for the four treatments). That shows the difference of the two landraces in response to the effect of temperature; in D1 and D3, Uniswa Red (originating from cool environment) had lower ε_w than Dip C which originated from hot/ dry environment.

With delay in sowing there was a decrease in WUE and TDM production. Mwale (2007a) reported that the importance of keeping high photosynthetic rate at pod filling stage to give good yield, but in the present study, although the ability of Uniswa Red maintained high photosynthetic rate during pod filling, it was not able to produce pods, while S19-3 was able to produce pods. This addresses the hypothesis that bambara groundnut landraces differ in the drought and heat tolerance according to their physiological characteristics.

Squire (1990) reported three factors cause differences in TDM apart from solar radiation; plant density, the stand composition and temperature. These factors affect three main attributes of a stand in several ways; leaf area, conversion ratio and duration.

The reports on the effect of temperature alone or in combination with water deficit on TDM and WUE in legumes are very few (Craufurd *et al*., 1999). In a study on

groundnut grown at mean temperature of 28°C and 32°C, Stronach *et al*. (1994) reported that temperature had no effect on WUE. This is in agreement with the results of 2007 glasshouse experiments when the soil moisture deficit was not limiting but not in 2008 where drought was more severe. This can be used as an indicator of the interaction effect of drought and temperature on WUE.

Temperature clearly affected crop growth and resource capture and conversion. The most striking differences were magnitude of the effect between low water-stressed crops (2007) and high water-stressed crops (2008). The higher values of ε_w and ε_s in 2007 in both landraces indicates that landraces adjusted to high temperature when the soil moisture is not a limiting factor, whereas high temperature interacted strongly with drought and exacerbated its effect when drought was more severe.

The different origin of the two landraces, which means different adaptation to heat and water stress, affected their responses which is very clear in the differences between ε_w and ε_s, and more clear in the WUE based on pod dry matter. Uniswa Red is extremely sensitive to high temperature, and low yield in both years indicated that thermal injury affected the crop directly instead of indirectly by interacting with drought.

Shamudzarira (1996) reported that SD adequately predicts canopy transpiration when there are no temperature measurements, and he pointed out that SD mis-represents the driving force for diffusion when canopy and air temperature are different. He suggested using leaf-to-air vapour pressure D' (which was not measured in the present study) to solve this issue. D' as the previous reference reported, is more accurate to represent the difusional driving force for vapour pressure deficit. However, when SD was used to normalise the amount of water transpired, the differences between the treatments in 2007 became significant.

Azam-Ali *et al*. (1994) summarized the dry matter: transpired water ratio ε_w and transpiration equivalent Ω_w g kPa kg^{-1} estimates presented by Squire (1990) for stands of groundnut and pearl millet grown in field in Africa, India, and in the TCRU glasshouses and they found Ω_w was more conservative than ε_w estimates (Table 5.4). The coefficient of variation reduced from 41% for ε_w to 10% for Ω_w in pearl millet and from 49% to 17% in groundnut. In the present study, the CV increased from 29% for ε_w to 47% for Ω_w. This result supports the Shamudzarira, (1996) finding about the inappropriateness of using SD as a normalising factor when air temperatures are different.

5.5 Gas exchange and leaf relative water content

One of the mechanisms for a plant to avoid becoming dehydrated under stress is reduction in leaf area. With a reduction in leaf area, surface transpiration loss becomes less. On the other hand, keeping large leaf area during drought is important to ensure high carbon input for photosynthesis (Purwanto, 2003). Many physiological processes are affected by heat stress, such as photosynthesis, respiration, translocation and membrane permeability. Photosynthesis is the most heat sensitive among these processes (Li *et al*., 1990).

The rate of photosynthesis (A) decreased towards the end of the three growing seasons. The range was similar in both temperature and landraces in the three growing seasons, but the rate decreased faster in 2008. The values in the present study are higher than the range of the values of bean, cowpea and chickpea reported by (Tesfaye, *et al*., 2008). The means of A in the present study were; 10.8, 9.2 for 2006 at LT and HT respectively; and 9.7, 11.7 for 2007 at LT and HT respectively and 12.7, 10.3μmol m^{-2} s^{-1} for 2008 at LT and HT respectively.

The pattern of A was not consistent with stomatal conductance pattern. That shows the effect of non- stomatal factors on A. One such factor, which affects photosynthesis indirectly, is leaf temperature (which was not measured in the present study). The same finding of non related A and g_s was reported by Tesfaye, *et al*. (2008).

Stomata have the ability to regulate water loss, which provides an important mechanism for reducing water loss during drought (Shamudzarira, 1996). The same author reported that drought reduced stomatal conductance by more than 60% in sorghum. In the present study, there was a reduction of 20% and 40% in Uniswa Red and S19-3 at LT between 2006 and 2008. This reduction did not exist in the landraces at HT. Generally, g_s rate fluctuated in both landraces and both temperatures. This fluctuation could be due to the variation in SD and irradiance during measurements. In 2007, g_s for Uniswa Red at low temperature was 50% of g_s at HT and for S19-3 at LT was less than g_s at HT by 26% . This difference between g_s in the two temperature regimes is high likely due to difference in SD. Black and Squire (1979) reported a strong effect of SD on g_s of well watered pearl millet and cowpea.

In 2007 and 2008, leaf transpiration was high at HT. This is due to the effect of high temperature where plants use transpiration to cool down the leaf temperature. Generally, drought did not affect the rate or the mean of leaf transpiration. Tesfaye (2008) found that decrease in soil moisture from 50% to 32% did not affect E in chickpea and cowpea where E was 2.73 mmol m^{-2} s^{-1} at 50 % of available soil water and 2.54 mmol m^{-2} s^{-1} at 32% for chickpea and was 2.64 mmol m^{-2} s^{-1} at 50% and 2.35 at 32% for cowpea . C_i in 2008 was lower than C_i in 2007. This reduction is usually related to stomatal closure and decrease in (A). The values in the present study are within the range of 114 ppmv to 395 ppmv reported by Tesfaye (2008). McDonald *et al*. (1997) reported that pea has higher photosynthesis rate at temperature 30/25 ºC than 20/15 ºC. The same study reported a photosynthesis rate of 11.6 µmol m^{-2} s^{-1} at

20/15 ºC day/night temperature and 13.3µmol m^{-2} s^{-1} at 30/15 ºC day/night temperature. In a study on water stressed soybean, Ohashi *et al*. (2006) reported a reduction of 34%, 30% and 30% of A, g_s and E. The study indicated that stomatal closure limited leaf photosynthetic capacity in the water stressed plants. In the present study A was higher at HT than LT, but since the optimum temperature for bambara groundnut is 28 ºC, it is difficult to conclude that high temperature of 33 ºC has a positive effect on A. Decrease in A under high temperature was reported for mungbean (Karim *et al*., 2003). The CO_2 assimilation at high temperatures may be limited by a disturbance in carbon metabolism regulation related to down regulation of ribulose-1, 5-biophosphate carboxylase /oxygenase (Karim *et al*., 2003).

Generally, g_s did not follow any clear pattern throughout the three years of glasshouse measurements. For example, the mean of g_s in Uniswa Red at HT was 672 mmol m^{-2} s^{-1} in 2006. In 2007 the mean went up to 1494 mmol m^{-2} s^{-1}, means two fold of 2006 mean, but in 2008 the mean declined to 96 mmol m^{-2} s^{-1}. That mean g_s of Uniswa Red in 2007 was 14 times greater than the 2008 mean. It is well documented that drought reduces g_s; Anyia and Herzog (2004) reported a decline of g_s by 80% between well-watered and flowering stage water stressed cowpea, but the decrease in the present study between 2007 to 2008 was very sharp, possibly due to technical fault, especially as different instruments were used in each year.

The great reduction in g_s in 2008 and the maintenance of almost the same rate and means of A and LRWC, showed that the crops could assimilate a reasonable amount of CO_2 even with reduction in g_s. This might be evidence of the ability of the crops to resist drought. The response of A and E to drought and temperature was quite similar. The results of the present study are in agreement with Hall and Mutters (1992) who found A to have decreased less than g_s in cowpea under water stress conditions. Leong and Ong (1983) reported that the drought avoidance in cowpea is linked with tighter

control of stomatal water loss when leaf issue water content declines. In this study there were no large differences in stomatal conductance between species, suggesting that once soil water contents largely declined, the avoidance of radiation load through paraheliotropic (soybean), leaf movement (cowpea) and leaf rolling (pigeon pea) may have contributed to the enhanced leaf survival in those species.

In the three sowing dates, g_s decreased towards the end of the season. The field g_s values were within the range of 2008 glasshouse experiment, but they were less than 2006 and 2007 values. It is not possible to know the reason for that, whereas there are several factors affect the field g_s values, like wind speed, relative humidity and irradiance

It is well documented that photosynthesis is closely related to dry matter in most crops and changes in the photosynthetic rate can be used as a reflection of plant responses to biotic and abiotic stress (Anyia and Herzog, 2004). In a study on three tropical foliage legumes, Wang *et al*. (2006) found that the crops with higher WUE had also higher photosynthetic rate.

LRWC has been widely used to assess the water status of plants (Siddique *et al*., 2000; Collinson *et al*., 1997; Yamasaki and Dillenburg, 1999; Anyia and Herzog, 2003; Mwale, 2005). The values of LRWC in the present study are within the range of values between 86.2-95.8% and 74.8-92.2% in well-watered and water stressed 10 genotypes of cowpea, respectively (Anyia and Herzog, 2004). In a study of Likoswe and Lawn (2008) on the impact of drought and heat stress on pigeon pea , cowpea and soybean, where grown under temperature ranged between 33-45 ºC for the maximum temperature mean of 40 ºC and the minimum ranged between 21-30 ºC, and saturation deficit daily mean of 3.2 K Pa and drought imposed on 26 DAS (which is similar to the 2008 glasshouse experiment where drought was imposed at 30 DAS); LRWC

dropped to 73.8% in cowpea and to 36.4% in pigeon pea and to 55.9% in soybean. Cowpea stayed alive for 60 DAS, pigeon pea for 49 DAS and soybean 28 DAS. In the glasshouse experiment both bambara groundnut landraces under the two temperature regimes stayed alive longer than the previously mentioned crops. That shows bambara groundnut as one of the most resistant crops to drought and heat stress. All these values are less than LRWC in bambara groundnut which dropped to 75% as minimum in both glasshouse and field experiments.

Maintaining high LRWC is important to keep some degree of stomatal conductance, which allows CO_2 intake and also avoids excess rise of leaf temperature (Mwale, 2005). Unlike in the present study in which LRWC was kept above 75% in both field and glasshouses experiments, Nautiyal *et al*. (2002) reported values as low as 31-38% in water-stressed cowpea plants. The gradual decrease in LRWC did not exist in the present study where the crops were able to keep LRWC above 75% as long as they were green. Unlike in most other crops where LRWC decreases gradually (chickpea; Moinuddin and Khanna-Chopra, 2004; groundnut; Nautiyal *et al*., 2002). The results of the present study are consistent with the results of Brown (1991) and Mwale (2005). In a study on eight chickpea cultivars, Moinuddin and Khanna-Chopra (2004) found that the cultivars that had high osmotic adjustment also maintained high LRWC under drought. This finding suggests that bambara groundnut may also have the ability to keep high LRWC by retention of high osmotic adjustment. Collinson, *et al*. (1997) indicated that both LRWC and osmotic adjustment are among the several strategies that bambara groundnut uses in withstanding drought. During water stress, stomatal closure is important in protecting against severe dehydration since the guard and subsidiary cells control over 95% of the gaseous exchange between leaves and the atmosphere (Collinson, *et al*., 1997). Siddique, *et al.*, (2000) reported a reduction of 45% in LRWC of wheat under water-stressed conditions. The same study reported a decline in photosynthesis associated with decrease in LRWC. In the present study, the

ability of bambara groundnut to maintain high photosynthesis, might be because of the high LRWC.

5.6 Implications of the results of the study

To improve yield and yield stability under soil moisture deficit conditions, the best option is to develop drought tolerant crop varieties. Between the several approaches, the physiological approach is the basis for the other approaches. Breeding is essential for deep understanding of the yield determining process (Siddique *et al*., 2000). The present study covered a wide range of physiological stress aspects in bambara groundnut. Intensive measurements were made in this study and the combination between field and glasshouse experiments has not been made before on bambara groundnut. The study puts a wide physiological base for genetic and breeding studies. Among the three landraces, S19-3 behaved very interestingly; shorter life cycle and high yield at both high and low temperatures, while Uniswa Red performed well at the low temperature only. Although the landraces showed a lot of individual variation, especially in the field, the data still very useful for breeding and genetic studies.

In addition to genetic and breeding approaches, the results of the study were used in the modelling for bambara groundnut growth and yield. The more knowledge crop breeders and modellers have about the physiological characteristics of a crop, the more efficiently they can use relevant physiological mechanisms to improve crop performance. Azam Ali *et al*., (1994) reviewed the types of crop models that exist and they explained how these models may help in the understanding of the way that crop system capture and use resources.

For bambara groundnut, there are two publications of simulation model,; the BAM nut model (Azam-Ali *et al*., 2001) and BAMGRO (Karunaratne *et al*., 2010) BAMGRO used the results of the present study to test and validate the model. BAMGRO adapted previous bambara groundnut models; BAM nut and BAMFOOD. Like this study, BAMGRO is a part of the achievement of BAMLINK research project. BAMGRO is able to predict canopy development, biomass production and yield formation of bambara groundnut landraces.

5.7 Conclusions

Soil water availability is the most critical factor for crop productivity. Soil water is usually limiting in most agricultural systems in the world, especially arid and semi-arid areas. Soil water deficit is usually associated with heat stress. This study investigated the effect of soil moisture and heat stress and the effect of sowing date on the growth and development of three bambara groundnut landraces. From the results, the following can be concluded:

1- Bambara groundnut growth and development is greatly affected by severe soil moisture deficit. Leaf number, leaf area, total dry matter and yield were reduced by soil moisture stress. The crop can grow well and give considerable yield when the drought is moderate.

2- Yield and yield components for S19-3 and Uniswa Red showed sensitivity to timing of drought. Imposing drought at podding stage did not affect the yield, whereas yield was reduced when drought was imposed at flowering stage.

3- Bambara groundnut tolerated drought in different physiological mechanisms; retention of LAI, retention of LRWC, high ε_w and high rate of photosynthesis.

4- Drought reduced the total amount of intercepted radiation but not K. ε_w and ε_s were also reduced due to drought

5- The landraces behaved similarly in some of their responses to temperature stress, but they differed in other responses. Both of landraces accumulated a large amount of dry matter in the vegetative part. Uniswa Red gave very low yield at HT compared to yield at LT, whereas S19-3 yield was affected by HT only when drought became more severe. HI was always higher at LT in both landraces and years of glasshouse experiments.

6- S19-3 and Uniswa Red intercepted more radiation and had higher f at the high temperature due to the higher vegetative growth, while temperature did not affect K. HT reduced ε_w and increased the amount of transpired water in both landraces.

7- Delay in sowing reduced the growth, development, yield and harvest index in bambara groundnut. Throughout the three dates of sowing, Uniswa Red had higher yield and HI than Dip C.

5.8 Future work

The main aim of this study was to investigate the interaction effect of temperature and drought stress on bambara groundnut in both field and controlled environment. The glasshouse experiment was successful in achieving the objective, but the aim of the

field study was only partially achieved because of the wet seasons. More studies should be carried out in drier environments.

The effect of temperature stress was studied as a constant mean from sowing until harvest. Timing of temperature stress is important in the physiological studies since it is more representative of the real crop conditions. Soil plant interaction is very important in plant physiology studies. This area represents one of the least studied areas in bambara groundnut. While this study has provided a significant contribution to the understanding of temperature and soil stress in interaction, further studies are needed to consolidate the results presented in this thesis.

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6 Appendices

Appendix1: Summary of analysis of variance (ANOVA) results from growth analysis and gas exchange in TCRU experiments in 2007 and 2008.

Table A. An example of the structure of ANOVA tables for analysis of treatment effects in the experiments conducted in the TCRU glasshouses. The ANOVA table presented below is for leaf weight g m^{-2} at 89 DAS in 2008

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
GLASSHOUSE stratum					
Temp	1	90788	90788	23.03	0.017
Residual	3	11826	3942	0.9	
GLASSHOUSE.Plot stratum					
LANDRACE	1	3403	3403	0.78	0.443
LANDRACE.Temp	1	1933	1933	0.44	0.554
Residual	3	13170	4390	2.99	

Tables 1.1-1.4 Summary of analysis of variance (ANOVA) results from growth analysis in TCRU experiments in 2007

Table 1.1

Variable	DAS	UN 23	S19-3 23	UN 33	S19-3 33	Temperature P	Landrace P	Temperature. Landrace	sed1	df1	sed2	df2	sed3	df3
Leaf No	26	3.25	2.7	3.6	3.65	0.3	0.44	0.28	0.55	3.8	0.3	2	0.26	2
Leaf No	33	2.9	3.15	4.17	4.52	0.018	0.189	0.78	0.322	4.58	0.25	2	0.2	2
Leaf No	47	8.35	7.05	12	18.15	0.003	0.112	0.088	1.44	3.8	1.83	2	1.5	2
Leaf No	75	20.6	19.4	40.1	52.6	0.077	0.16	0.17	10.5	3.65	5.19	2	4.24	2
Leaf No	89	26	20.1	71.3	74.2	0.035	0.93	0.57	15.16	4.26	10.37	2	8.47	2
Leaf No	103	29.3	22.5	80.1	72.8	0.009	0.45	0.97	11.58	4.9	12.3	2	10.05	2
Leaf No	124	28.1	19.8	81	69.3	0.079	0.16	0.76	20.11	3.36	7.53	2	6.15	2
Leaf No	145	27.5	11.4	57	49.3	0.004	0.156	0.49	6.55	4.29	7.85	2	6.41	2
LAI	26	0.04	0.041	0.043	0.048	0.46	0.48	0.98	0.0095	5.99	0.01	3	0.008	3
LAI	33	0.031	0.05	0.067	0.081	0.026	0.15	0.74	0.01	4.9	0.011	2	0.009	2
LAI	47	0.17	0.12	0.24	0.47	0.082	0.13	0.11	0.09	4.6	0.075	2	0.06	2
LAI	75	0.72	1.45	1.8	2.59	0.136	0.01	0.68	0.55	3.12	0.12	2	0.09	2
LAI	89	1.28	0.94	3.95	4.7	0.062	0.46	0.28	1.17	3.7	0.59	2	0.48	2
LAI	103	1.55	0.9	4.09	5.22	0.016	0.005	0.001	0.69	3.01	0.049	2	0.04	2
LAI	124	1.35	1.05	4.43	4.4	0.096	0.39	0.4	1.34	3.06	0.2	2	0.16	2
LAI	145	1.21	0.42	3.18	2.9	0.03	0.5	0.62	0.79	4.9	0.82	2	0.67	2

Sed1= Standard error of difference for comparing means on different temperatures
Sed2= Standard error of difference for comparing landraces at 23 degrees C
Sed3= Standard error of difference for comparing landraces at 33 degrees C

df1= degrees of freedom for comparing means on different temperatures
df2= degrees of freedom for comparing means on at 23 degrees C
df3= degrees of freedom for comparing means on at 33 degrees C

Table 1.2

Variable	DAS	UN 23	S19-3 23	UN 33	S19-3 33	Temperature P	Landrace P	Temperature. Landrace	sed1	df1	sed2	df2	sed3	df3
Leaf weight	26	1.87	2.43	2.29	3.04	0.32	0.16	0.8	0.54	4.9	0.4	2	0.44	2
Leaf weight	33	1.6	2.5	2.7	4.2	0.03	0.009	0.12	0.39	3.6	0.19	2	0.15	2
Leaf weight	47	8.04	6.2	11.7	23.8	0.06	0.08	0.07	4.2	4.4	3.1	2	2.5	2
Leaf weight	75	39.3	53.5	74.4	100.6	0.11	0.13	0.56	20.8	4.13	13.5	2	11.07	2
Leaf weight	89	85.2	65.8	166.9	208.6	0.06	0.17	0.07	39.2	3.29	13.04	2	10.65	2
Leaf weight	103	98.1	58.1	182.4	216	0.03	0.57	0.03	30.78	3.3	10.45	2	8.5	2
Leaf weight	124	95	75.1	220.7	210	0.12	0.35	0.73	62.81	3.23	18.7	2	15.3	2
Leaf weight	145	94.9	31.7	172	143.4	0.06	0.19	0.52	39.3	4.9	34.7	2	28.4	2
Pod No.	26													
Pod No.	33													
Pod No.	47													
Pod No.	75	1.9	9.6	0	0	0.001	0.03	0.02	0.94	4.4	1.3	3	1.06	3
Pod No.	89	6.5	13.8	0.37	7.9	0.06	0.2	0.98	4.5	3.07	6.2	2	5.08	2
Pod No.	103	20.2	22.6	5.2	28.7	0.37	0.06	0.11	5.8	4.9	6.05	2	4.9	2
Pod No.	124	33.5	25.3	14	68.8	0.49	0.05	0.05	16.9	4.2	11.3	2	9.2	2
Pod No.	145	31.9	19.2	22.2	67.9	0.39	0.22	0.15	23.6	4.8	20.4	2	16.65	2

Table 1.3

Variable	DAS	UN 23	S19-323	UN 33	S19-3 33	Temperature P	Landrace P	Temperature.Landrace	sed1	df1	sed2	df2	sed3	df3
Pod weight	26													
Pod weight	33													
Pod weight	47													
Pod weight	75	0.6	5.8	0	0	0.004	0.001	0.001	0.42	3.2	0.11	2	0.09	2
Pod weight	89	13.5	14.8	1.3	11	0.41	0.09	0.18	8.7	3.36	3.2	2	2.9	2
Pod weight	103	61.8	85.1	6.5	49.7	0.06	0.13	0.5	21.5	4.9	22.5	2	18.4	2
Pod weight	124	117.9	185.3	23.1	238.9	0.55	0.03	0.14	44.14	4.8	48.2	2	39.4	2
Pod weight	145	223	153	80	311	0.9	0.11	0.07	84	4.5	65.4	2	53.4	2
TDM	26	2.4	3.08	3.02	3.87	0.3	0.2	0.8	0.7	4.9	0.63	2	0.51	2
TDM	33	2.3	3.4	3.7	3.08	0.54	0.98	0.53	1.5	5.3	1.9	3	1.55	3
TDM	47	10.7	8.3	15.4	18.7	0.14	0.91	0.76	9.4	4.2	13.3	3	10.8	3
TDM	75	55.5	76	112.5	85.3	0.14	0.86	0.61	45.9	3.9	66	3	53.9	3
TDM	89	131	103	263	193	0.08	0.58	0.83	99.9	4.3	139.9	3	114.3	3
TDM	103	199	163	299	234	0.27	0.62	0.89	118	5.8	155.2	3	126.8	3
TDM	124	246	285	374	339	0.41	0.97	0.83	185	4.9	245	3	200	3
TDM	145	369	204	410	329	0.27	0.58	0.84	200.3	3.6	294.8	3	240.7	3

Table 1.4

Variable	DAS	UN 23	S19-3 23	UN 33	S19-3 33	Temperature P	Landrace P	Temperature. Landrace	sed1	df1	sed2	df2	sed3	df3
SLA	26	221.9	178.1	187.4	185.5	0.578	0.052	0.041	22.68	3.46	9.40	3	7.67	3
SLA	33	191.9	194.3	201.4	200.2	0.271	0.974	0.817	8.84	4.41	10.42	2	8.51	2
SLA	47	214.2	204.1	214.7	192.0	0.536	0.088	0.387	10.19		8.89	2	7.26	2
SLA	75	180	233	241	257	0.210	0.226	0.418	32.4	4.85	28.2	2	23.0	2
SLA	89	158.4	149.9	233.6	230.6	0.032	0.799	0.892	27.37	4.97	28.10	2	22.94	2
SLA	103	154.3	153.1	247.0	234.0	0.019	0.769	0.835	31.31	4.02	38.85	2	31.72	2
SLA	124	153.8	135.2	202.2	221.7	0.030	0.602	0.113	18.78	3.90	10.88	2	8.88	2
SLA	145	141.9	131.7	190.8	211.1	0.022	0.292	0.121	15.71	3.90	9.08	2	7.41	2

Tables 1.5-1.8: Summary of analysis of variance (ANOVA) results from growth analysis in TCRU experiments in 2008**.**

Table 1.5

Variable	DAS	UN 23	S19-3 23	UN 33	S19-3 33	Temperature P	Landrace P	Temperature. Landrace	sed1	df1	sed2	df2	sed3	df3
Leaf No	28	3.8	4.05	6.5	8.9	S0.007	S0.004	S*0.01	0.6	3.67	0.29	3	0.24	3
Leaf No	47	10.05	12.45	22.5	26.33	0.006	0.26	0.78	3.03	5.66	3.7	3	3.02	3
Leaf No	61	14.65	19.8	39.17	38.5	0.016	0.63	0.44	5.48	5.57	5.1	3	4.16	3
Leaf No	75	25.3	22.7	61.3	39.8	0.011	0.06	0.14	6.75	5.99	7.3	3	6.17	3
Leaf No	89	30.8	25.5	53.7	40	0.011	0.043	0.26	4.5	5.9	4.8	3	3.9	3
Leaf No	103	32.2	25.4	58.4	34.2	0.4	0.004	0.028	5.65	4.03	3.4	3	2.78	3
Leaf No	117	30	14.5	48.2	13.4	0.23	0.05	0.34	10.46	5.17	13.56	3	11.07	3
Leaf No	131	5.85	2.2	14.4	3.4	0.32	0.12	0.41	5.6	5.9	6.02	3	4.9	3
LAI	28	0.065	0.098	0.2	0.24	0.019	0.58	0.99	0.06	4.5	0.088	3	0.07	3
LAI	47	0.3	0.43	1.06	1.47	0.01	0.12	0.4	0.21	5.9	0.22	3	0.18	3
LAI	61	0.46	0.85	1.98	2.3	0.021	0.32	0.91	0.44	5.9	0.46	3	0.38	3
LAI	75	0.9	0.95	2.9	2.2	0.058	0.23	0.3	0.62	4.6	0.46	3	0.37	3
LAI	89	1.07	1.3	2.6	2.25	0.014	0.61	0.32	0.3	5.9	0.4	3	0.34	3
LAI	103	1.198	1.096	2.29	1.6	0.047	0.061	0.169	0.29	4.76	0.2	3	0.18	3
LAI	117	1.22	0.58	2.18	0.72	0.11	0.09	0.45	0.54	4.5	0.74	3	0.61	3
LAI	131	0.94	0.26	1.5	0.35	0.46	0.003	0.1	0.41	3.4	0.16	3	0.13	3

Table 1.6

Variable	DAS	UN 23	S19-323	UN 33	S19-333	Temperature P	Landrace P	Temperature. Landrace	sed1	df1	sed2	df2	sed3	df3
Leaf weight	28	3.46	5.4	11.8	12.4	0.003	0.71	0.81	8.18	3.6	13.2	3	10.8	3
Leaf weight	47	12.3	18.9	40.5	52.6	0.01	0.21	0.69	8.4	5.8	9.05	3	8.09	3
Leaf weight	61	26	41.8	95.2	98.5	0.02	0.35	0.28	14.5	4.2	9.42	3	7.7	3
Leaf weight	75	54.4	63.8	152.7	120	0.049	0.34	0.23	28	4.9	22.08	3	18.03	3
Leaf weight	89	77.7	76.8	148.2	129.4	0.017	0.44	0.55	18.6	5.9	20.9	3	17.11	3
Leaf weight	103	105	82	185	103	0.28	0.22	0.5	55.1	6	60	3	49	3
Leaf weight	117	86.8	50	141	48.1	0.28	0.07	0.37	33.5	5.5	41.7	3	34.03	3
Leaf weight	131	66.6	27.5	100	26.7	0.6	0.004	0.1	28.7	3.4	11.7	3	9.55	3
Pod No.	28													
Pod No.	47													
Pod No.	61													
Pod No.	75	1.1	6.5	1.5	8.5	0.05	0.7	0.76	2.89	5.2	3.7	3	3.03	3
Pod No.	89	9.5	21.5	4.2	9.8	0.11	0.14	0.5	5.8	5.9	6.7	3	5.4	3
Pod No.	103	26.3	22.1	4.4	13.4	0.016	0.52	0.29	6.12	4.8	8.16	3	6.6	3
Pod No.	117	27.2	23.1	10.3	15.5	0.03	0.82	0.5	7.03	7.5	9.6	3	7.8	3
Pod No.	131	28	27.1	9.3	15.2	0.053	0.43	0.41	6.1	5.5	5.6	3	4.5	3

Table 1.7

Variable	DAS	UN 23	S19-323	UN 33	S19-333	Temperature P	Landrace P	Temperature. Landrace	sed1	df1	sed2	df2	sed3	df3
Pod weight	28													
Pod weight	47													
Pod weight	61													
Pod weight	75	0.8	6.9	1.2	12.1	0.3	0.05	0.48	3.7	5.6	4.6	3	3.7	3
Pod weight	89	33.8	46.5	13	32.3	0.16	0.22	0.78	14.7	5.8	17.2	3	14	3
Pod weight	103	80.9	87	11.6	58	0.06	0.14	0.46	26.4	5.6	32.4	3	26.4	3
Pod weight	117	114	129	35	70.4	0.01	0.3	0.6	25.8	4.7	34.7	3	28.3	3
Pod weight	131	150.8	158.6	32.5	64.7	0.06	0.3	0.5	41.9	4.5	29.9	3	24.4	3
TDM	28	4.85	7.6	16.8	17.7	0.003	0.67	0.81	3.79	3.6	5.56	3	4.5	3
TDM	47	17.6	26.6	58.2	75.5	0.01	0.2	0.67	11.7	5.84	13.8	3	11.2	3
TDM	61	37	67	146.7	145.9	0.02	0.3	0.02	23.9	4.1	14.8	3	12.16	3
TDM	75	77.5	99.6	212.2	205.8	0.01	0.69	0.31	24.3	4.7	18.36	3	14.9	3
TDM	89	145	159.5	241.4	225.5	0.03	0.84	0.46	27.6	5.89	28.2	3	23	3
TDM	103	228	201	274	227	0.53	0.44	0.83	68.5	5.8	68.6	3	56	3
TDM	117	239.7	210.5	264.6	184.9	0.98	0.22	0.56	48.3	5.37	61.2	3	50	3
TDM	131	262.6	231.4	222.2	154	0.28	0.13	0.53	52.7	4.8	41.18	3	33.6	3

Table 1.8

Variable	DAS	UN 23	S19-3 23	UN 33	S19-3 33	Temperature P	Landrace P	Temperature. Landrace	sed1	df1	sed2	df2	sed3	df3
SLA	28	219.	192.	193	210.	0.910	0.967	0.218	33.9	4.13	21.3	3	17.4	3
SLA	47	268..	237	294..	289.	0.041	0.610	0.671	29.8	4	42.6	3	34.8	3
SLA	61	338.	245	264.	253	0.174	0.521	0.549	64.1	3.55	95.0	3	77.5	3
SLA	75	281.	180.	218.	196.	0.236	0.018	0.043	19.6	5.52	18.0	3	14.7	3
SLA	89	154.	217.	201.	182.	0.777	0.187	0.016	22.2	3.96	12.9	3	10.6	3
SLA	103	155.4	135.0	185.6	183.2	0.021	0.596	0.626	18.81	4.57	25.73	3	21.01	3
SLA	117	224.	265	178.	173.	0.003	0.677	0.511	31.4	3.37	47.2	3	38.5	3
SLA	131	261.	101.	229.	133	1.000	0.138	0.639	81.4	5.87	95.6	3	78.1	3

Tables 1.9 Summary of analysis of variance (ANOVA) results from gas exchange in TCRU experiments in 2007

Variable	DAS	UN 23	S19-323	UN 33	S19-333	Temperature P	Landrace P	Temperature.Landrace	sed1	df1	sed2	df2	sed3	df3
A	56	17.45	19.33	26.45	28.66	0.51	<.001	0.41	2.7	3.02	0.261	2	0.213	2
A	63	9.64	10.64	10.31	10.49	0.877	0.587	0.663	1.7	4.36	1.253	2	1.02	2
A	81	15.79	18.58	14.21	14.51	0.722	0.319	0.342	7.29	3.12	1.557	2	1.272	2
A	89	14.16	20.57	17.88	24.33	0.143	0.073	0.992	2.666	4.82	2.907	2	2.374	2
A	98	10.37	14.42	16.09	20.23	0.268	0.337	0.99	5.4	4.99	5.188	2	4.236	2
A	105	12.29	14.12	13.41	21.06	0.254	0.349	0.583	5.317	3.57	6.945	2	5.67	2
A	110	5.5	10.98	6.99	13.39	0.519	0.241	0.914	4.6	3.9	5.791	2	4.728	2
A	117	5.09	11.96	3.33	9.37	0.365	0.27	0.91	3.576	2.04	4.549	1	3.714	1
A	124	2.6	2.54	2.98	5.91	0.157	0.628	0.677	3.139	1.29	4.161	1	3.398	1
A	131	5.61	4.3	4.81	8.11	0.421	0.328	0.185	1.9	4.92	1.795	2	1.465	2
A	138	3.62	2.43	1.3	4.26	0.77	0.289	0.155	1.192	4.24	1.439	2	1.175	2
A	144	2.67	2.98	2.84	4.54	0.447	0.638	0.776	2.341	2.88	3.284	2	2.681	2
g_s	56	365	1069	647	1503	0.337	0.032	0.661	380.7	4.2	232	2	189.4	2
g_s	63	375	599	1723	1286	0.574	0.75	0.564	1688.2	3.52	748	2	610.7	2
g_s	81	653	3011	670	1058	0.455	0.01	0.028	781	4.99	788.2	2	643.5	2
g_s	89	293	984	575	1465	0.084	0.125	0.786	356	2.86	500.6	2	408.8	2
g_s	98	1015	1553	3528	1164	0.765	0.47	0.406	3527.3	4	2149.8	2	1755.3	2
g_s	105	550	756	482	2060	0.176	0.043	0.092	262.9	4.76	346.6	2	283	2
g_s	110	125	354	242	770	0.195	0.108	0.421	219.3	4.91	231.7	2	189.2	2
g_s	117	222	364	59	259	0.3	0.357	0.841	156	2.84	175.4	1	143.2	1
g_s	124	43	123	32	204	0.4	0.364	0.7	98.4	1.46	138	1	112.7	2
g_s	131	120	75	79	442	0.153	0.238	0.238	149.8	3.82	190.3	2	155.4	2
g_s	138	67.8	55.6	21.6	80.2	0.421	0.098	0.078	15.67	4.95	16.23	2	13.25	2
g_s	144	85	66	40	203	0.499	0.419	0.422	109.2	3.68	140.8	2	115	2

Table 1.10 Summary of analysis of variance (ANOVA) results from gas exchange in TCRU experiments in 2008

Variable	DAS	UN 23	S19-3 23	UN 33	S19-3 33	Temperature P	Landrace P	Temperature. Landrace	sed1	df1	sed2	df2	sed3	df3
A	38	17.46	20.44	22.88	23.87	0.218	0.49	0.698	3.671	5.77	3.594	3	2.934	3
A	42	18.89	23.64	20.48	21.51	0.897	0.242	0.37	2.61	5.96	2.742	3	2.239	3
A	48	14.61	18.85	18.36	17.86	0.677	0.561	0.357	3.702	5.49	3.381	3	2.761	3
A	55	13.68	14	16.47	18.77	0.189	0.4	0.576	2.7	5.38	2.434	3	1.987	3
A	62	16.62	17.46	14.17	17.32	0.63	0.215	0.483	2.836	4.89	2.246	3	1.834	3
A	69	14.86	13.32	12.71	12.4	0.717	0.773	0.804	4.479	5.12	3.757	3	3.067	3
A	83	7.72	11.6	8.36	8.42	0.042	0.469	0.401	1.992	3.22	3.03	3	2.475	3
A	90	12.44	13.02	7.6	4.48	0.056	0.516	0.475	3.173	5.99	3.529	3	2.8	3
A	97	11.09	11.6	6.47	5.49	0.03	0.865	0.745	2.506	5.21	3.235	3	2.642	3
A	104	9.74	8.38	7.09	3.4	0.147	0.197	0.546	2.5	5.88	2.613	3	2.134	3
A	111	10.26	4.64	3.61	2	0.064	0.09	0.228	1.324	5.78	2.059	3	1.681	3
A	118	9.96	6.66	4.39	2.82	0.102	0.458	0.772	3.3	5.54	4.211	3	3.439	3
A	125	10.69	9.1	2.83	0.97	0.018	0.236	0.91	1.988	4.76	1.656	2	1.352	2
g_s	38	132.4	168.2	240.4	243.7	0.099	0.278	0.285	40.81	3.62	19.48	3	15.91	3
g_s	42	120.5	148.2	267.2	256.4	0.002	0.87	0.523	29.4	4.22	41.4	3	33.8	3
g_s	48	117	126	226	203	0.222	0.628	0.462	63.3	3.58	29.3	3	23.9	3
g_s	55	119.4	92	176.1	175.5	0.252	0.757	0.721	60.13	5.32	52.8	3	43.11	3
g_s	62	172.4	136.9	205.2	183.4	0.446	0.48	0.855	57.01	5.61	53.55	3	43.72	3
g_s	83	114.5	74	100.8	124.9	0.698	0.952	0.313	51.02	4.98	41.38	3	33.79	3
g_s	90	62.2	60.9	59	53.5	0.519	0.844	0.918	19.75	3.93	28.43	3	23.21	3
g_s	97	85.2	61.5	56.8	28.5	0.194	0.273	0.918	27.33	5.95	31.23	3	25.5	3
g_s	104	36.5	52	49.1	44	0.744	0.891	0.666	22.48	3.52	33.39	3	27.27	3
g_s	111	24.8	11.9	38.1	16.8	0.245	0.063	0.555	8.95	6	9.78	3	7.99	3
g_s	118	96.4	24.8	33.7	24.7	0.129	0.088	0.11	20.5	5.96	21.55	3	17.6	3
g_s	125	99.2	58.9	28.4	12.9	0.021	0.385	0.65	26.94	3.23	36.45	2	29.76	2

Appendix 2 . Summary of analysis of variance (ANOVA) results from growth analysis in Field experiments

Table A. An example of the structure of ANOVA tables for analysis of treatment effects in the experiments conducted in the field. The ANOVA table presented below is for leaf weight g m^{-2} at 89 DAS in 2008-09.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
BLOCK stratum	3	32474.	10825.	1.34	
BLOCK.LANDRACE stratum					
LANDRACE	1	18259.	18259.	2.25	0.230
Residual	3	24316.	8105.	0.81	
BLOCK.LANDRACE.STRIP stratum					
SWNG_DATE	2	540901.	270451.	27.18	<.001
TREAT	1	4194.	4194.	0.42	0.521
LANDRACE.SWNG_DATE	2	9112.	4556.	0.46	0.637
LANDRACE.TREAT	1	2078.	2078.	0.21	0.651
SWNG_DATE.TREAT	2	14576.	7288.	0.73	0.489
LANDRACE.SWNG_DATE.TREAT	2	7807.	3903.	0.39	0.679
Residual	30	298540.	9951.	3.12	

2007-08 Leaf number

45 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		17	14.35	18.95	18	37.75	31.95
2		12.25	13.1	17.05	14.05	35.3	42.6
	D	T	D.T	L	L.D	L.T	L.D.T
F P	<0.001	0.683	0.808	0.697	0.132	0.124	2.08
df	15	15	15	18	31.8	31.8	31.8
SED	2.084	1.702	2.948	1.535	2.292	2.807	3.97

60DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		42.5	36.5	41.9	47	43.7	64.5
2		33.9	32.6	37.4	34.6	51.4	43
	D	T	D.T	L	L.D	L.T	L.D.T
F P	0.033	0.769	0.624	0.005	0.919	0.027	4.79
df	15	15	15	18	23.64	23.64	23.64
SED	5.02	4.1	7.09	2.25	5.73	4.67	8.1

105DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		78.6	106.9	67.5	71.8	37.7	55.2
2		66.3	56.9	65.5	56.5	39	47.3
	D	T	D.T	L	L.D	L.T	L.D.T
F P	0.001	0.266	0.543	0.014	0.101	0.075	0.7
df	18	15	15	31.95	31.95	15	31.95
SED	5.29	7.08	5.78	9.59	7.83	10.01	13.57

112 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		86	83.2	83	70.9	42.1	51.5
2		60.3	61.6	62.4	65.2	48	37.8
	D	T	D.T	L	L.D	L.T	L.D.T
F P	0.669	<0.001	0.91	0.01	0.983	0.258	1.16
df	15	15	15	18	32.99	32.99	32.99
SED	4.4	5.39	7.62	4.72	6.45	7.9	11.17

D *Sowing date*
T *Treatment*
L *Landrace*

2007-08 TDM
45 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		47.5	35.3	39.6	38.1	59.5	47.5
2		31	32.7	40.3	33.9	59.7	84.6
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.846	0.536	0.541	0.025	0.067	2.37	0.122
df	15	15	31.12	18	31.12	15	31.12
SED	5.62	4.59	7.39	3.93	6.04	7.94	10.46

60 Das

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		123.8	95.3	93	126.5	81.7	125.3
2		112.6	100.9	123	107.5	117.5	91.1
	D	T	D.T	L	L.D	L.T	L.D.T
	F pr.	0.89	0.953	0.651	0.9	0.93	0.073
	df	15	15	15	18	25.52	25.52
	SED	17.75	14.49	25.1	8.95	20.85	17.03

105 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		414.5	471.5	224.9	221.6	89.2	124.7
2		357.6	300.4	236.3	212	87.2	122.6
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.821	0.805	0.193	0.198	0.438	0.38
df	15	15	15	18	31.86	31.86	31.86
SED	38.33	31.29	54.2	28.38	51.74	42.25	73.17

12 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	
1		463.2	488.8	382.1	286.7	102.8	I
2		379.9	291.9	366.4	317.6	129.5	123.6
	D	T	D.T	L	L.D	L.T	116.6
F pr.	<0.001	0.26	0.561	0.17	0.074	0.564	L.D.T
df	15	15	15	18	32.78	32.78	0.65
SED	34.7	28.33	49.08	28.59	49.3	40.25	32.78

2007-08 Leaf dry matter

45 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		30.64	22.7	26.76	27.51	40.64	31.94
2		20.08	21.94	27.22	22.04	41.1	58.14
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.91	0.599	0.508	0.015	0.069	3.22
df	15	15	15	18	30.37	30.37	30.37
SED	3.831	3.128	5.418	2.548	4.941	4.034	6.988

60DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		78.8	61.9	58.9	76.8	51	74.2
2		70.3	64.5	75	64.3	74.8	57.1
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.902	0.864	0.769	0.896	0.893	0.098	1.97
df	15	15	15	18	24.88	24.88	24.88
SED	11.52	9.41	16.3	5.59	13.4	10.94	18.96

105DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		238.2	265.2	124.1	131.7	52.6	73.5
2		210.5	175.7	140.3	121	51.9	75.2
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.821	0.78	0.268	0.238	0.384	0.33
df	15	15	15	18	31.74	31.74	31.74
SED	21.99	17.95	31.09	16.12	29.55	24.13	41.79

112 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		228.3	231.3	175.3	158.7	61.1	73.1
2		198	165	180.3	172.4	76.7	69.1
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.479	0.808	0.477	0.247	0.613	0.19
df	15	15	15	18	31.95	31.95	31.95
SED	14.07	11.49	19.89	15.17	23.31	19.03	32.96

2007-08 Pod number

105 DAS

	Sowing date	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		11.16	12.29	14.52	4.34	0.9	6.1
2		17.86	6	16.82	4.99	10.56	3.35
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.016	0.033	0.126	0.181	0.002	0.515	1.8
df	15	15	31.96	18	14	31.96	31.96
SED	1.481	2.472	3.067	2.019	2.504	3.497	4.337

112 DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		17.25	17.55	13.95	4.95	0.6	0.9
2		11.35	3.74	10.55	6.45	0.7	0.95
	D	T	D.T	L	L.D	L.T	L.D.T
df	15	15	15	18	26.38	26.38	26.38
SED	4.422	3.61	6.253	2.341	5.27	4.303	7.453
F pr.	0.05	0.374	0.745	0.144	0.192	0.83	0.63

2007-08 Pod weight

105 DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		39.3	64.3	0.9	61.7	12.5	1.4
2		71	95.1	6.2	27	6.7	2
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.089	0.044	0.171	0.682	0.124	0.872	0.64
df	18	15	15	28.61	28.61	15	28.61
SED	11.14	15.17	18.58	18.82	23.05	26.27	32.59

112 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		64.3	70.4	77.5	12.1	1.1	1.5
2		49	17.5	68.1	20.1	0.7	1.6
	D	T	D.T	L	L.D	L.T	L.D.T
df	18	15	15	19.76	19.76	15	19.76
SED	8.96	27.42	22.39	29.53	24.11	38.78	41.77
F pr.	0.182	0.322	0.562	0.211	0.234	0.719	0.82

2008-09 Leaf No.

45 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		40.59	30.1	29.25	24.2	21.3	16
2		32.25	26.55	22.6	21.65	19.25	16.7
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.002	0.075	0.704	0.059	0.499	0.311	0.974
df	15	15	15	18	28.03	28.03	28.03
SED	3.203	2.615	4.529	1.859	3.929	3.208	5.557

60 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		66.9	55	52.9	58.6	32.8	25.7
2		71.7	70.2	41.9	42.6	29.4	22.1
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.299	0.376	0.501	0.039	0.805	0.657
df	15	15	15	18	32.92	32.92	32.92
SED	4.06	3.31	5.74	3.45	5.86	4.78	8.28

89 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		73.1	68.7	69.7	71.2	45.6	46.2
2		67.2	81	57.3	50	60	48.7
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.02	0.838	0.762	0.68	0.047	0.919	0.272
df	15	15	15	18	27.88	27.88	27.88
SED	7.01	5.72	9.91	4.04	8.58	7	12.13

105 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		69.1	65.5	59.2	60	48.4	42.7
2		72.5	56.6	59.1	50.6	44.8	42.8
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.024	0.497	0.319	0.915	0.334	0.52
df	15	15	15	16	29.51	29.51	29.51
SED	2.83	2.31	4.01	3.01	4.65	3.79	6.57

2008-09
Leaf No.
112
DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		73.7	71.5	57.7	66.7	42.4	30.7
2		57.5	81.2	63.4	51.8	46.2	43.2
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.873	0.276	0.983	0.397	0.579	0.094
df	15	15	15	18	32	32	32
SED	5.5	4.49	7.78	4.12	7.47	6.1	10.57

120
DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		74.2	84.3	58.6	68.2	38.6	39.7
2		78.3	64.7	48.4	53.6	35	38.5
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.428	0.529	0.033	0.206	0.473	0.267
df	15	15	15	18	32.74	32.74	32.74
SED	4	3.26	5.65	3.27	5.66	4.62	8

2008-09 **TDM**
45 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		75.36	58.75	45	29.83	22.75	12.89
2		65.97	59.03	27.7	31.82	22.19	15.37
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.167	0.911	0.427	0.745	0.263	0.773
df	15	15	15	18	29.72	29.72	29.72
SED	7.211	5.888	10.198	4.611	9.159	7.478	12.952

60 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		91.3	79.9	66	62.9	29.2	21.6
2		151.8	138.9	64.5	62.5	30.5	17.3
	D	T	D.T	L	L.D	L.T	L.D.T
FP	<0.001	0.266	0.851	0.012	0.002	0.886	0.98
df	15	15	15	18	32.32	32.32	32.32
SED	8.87	7.24	12.54	6.86	12.22	9.98	17.28

2008-09
TDM
89 DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		300.1	297.1	165.9	154.2	69.5	45.8
2		313.9	405.2	199.8	163	93.7	91.2
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.942	0.624	0.112	0.783	0.527	0.584
df	15	15	15	18	29.43	29.43	29.43
SED	37.17	30.35	52.57	23.36	46.9	38.3	66.33

105
DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		383.4	364	196.5	185.5	75.2	35.8
2		370.2	364.5	228.3	185.5	78.1	58.7
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.159	0.893	0.554	0.733	0.979	0.656
df	15	15	15	16	29.13	29.13	29.13
SED	18.98	15.49	26.84	12.37	24.28	19.83	34.34

112
DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		363.2	405.8	202.9	225.9	55.8	41.1
2		349.3	598.3	293.4	182.2	53	62.9
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.291	0.052	0.025	0.142	0.345	0.002
df	15	15	15	18	23.64	23.64	23.64
SED	37.06	30.26	52.41	16.64	42.3	34.53	59.82

120
DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		387.4	418.7	229.4	238.6	54.7	44.9
2		520.4	530	195.3	247	47.8	51.6
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.57	0.879	0.046	0.008	0.739	0.744
df	15	15	15	18	25.5	25.5	25.5
SED	33.68	27.5	47.63	16.96	39.57	32.31	55.96

2008-09 SLA

45 DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		227.9	188.9	200.4	224.1	143.6	156.8
2		231.2	229.8	207	220.7	151.2	168.9
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.617	0.82	0.809	0.037	0.929	0.688	0.903
df	15	15	15	18	33	33	33
SED	24.63	20.11	34.83	21.9	36.42	29.74	51.5

60 DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		333	365	213	222	149	134
2		374	380	203	203	167	130
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.069	0.415	0.267	0.244	0.412	0.541	0.487
df	15	15	15	18	33	33	33
SED	24.8	20.2	35.07	23.8	38.3	31.3	35.07

89 DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		165	165.8	167.3	164.3	107.2	
2		156.1	258.2	162.5	160.7	120.7	
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.311	0.061	0.303	0.202	0.301	0.07
df	15	15	15	17	31.94	31.94	31.94
SED	13.47	11	19.05	11.23	19.25	15.72	27.23

105 DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		239.7	251.8	150.3	159.5	108	108.3
2		190.9	199.5	143.3	152.4	79.1	95.6
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.406	0.998	0.095	0.484	0.889	0.95
df	15	15	15	16	29.02	29.02	29.02
SED	13.33	10.89	18.86	14.73	22.43	18.32	31.72

SLA
2008-09
112
DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		181.6	168.4	119.3	106.1	101	107.6
2		217.4	151.4	105.6	95.8	144.8	100.3
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.022	0.45	0.603	0.454	0.108	0.433
df	15	15	15	18	32.99	32.99	32.99
SED	11.22	9.16	15.87	9.87	16.5	13.47	23.33

120
DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		121.1	112.4	132.2	131.5	73.4	76.9
2		218.3	131.2	148.9	97.8	108	93.7
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.005	0.049	0.395	0.046	0.094	0.051	0.579
df	15	15	15	17	31.52	31.52	31.52
SED	15.12	12.34	21.38	11.62	20.76	16.95	29.36

2008-09 LDM
45 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		46.43	35.12	29.82	19.02	14.91	8.18
2		40.33	38.79	18.27	20.91	15.33	10.58
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.169	0.966	0.584	0.659	0.147	0.694
df	15	15	15	18	28.72	28.72	28.72
SED	4.59	3.748	6.491	2.77	5.708	4.66	8.072

60 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		51.5	39.3	41.4	37.9	19.2	14.2
2		91.8	82	40.2	39.3	20	11
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.148	0.724	0.021	0.006	0.974	0.96
df	15	15	15	18	32.74	32.74	32.74
SED	5.42	4.42	7.66	5.3	8.46	6.9	11.96

LDM 2008-09
89 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		137.2	149.2	83	90.5	39	26.9
2		149.5	198.2	93.2	82.3	51.3	56.1
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.545	0.528	0.167	0.633	0.605	0.649
df	15	15	15	18	31.75	31.75	31.75
SED	16.53	13.5	23.38	12.13	22.23	18.15	31.43

105 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		155	153.5	90.2	98.1	43.7	17.9
2		173.7	154.2	92.4	88.4	42.1	28.5
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.119	0.323	0.623	0.735	0.678	0.654
df	15	15	15	16	30.11	30.11	30.11
SED	6.95	5.68	9.83	6.98	11.02	9	15.59

112 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		159.4	166.9	93.9	108.9	28.8	19.1
2		156.2	227	126.1	84	26.1	28.9
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.545	0.192	0.134	0.686	0.324	0.015
df	15	15	15	18	26.06	26.06	26.06
SED	14.55	11.88	20.58	7.56	17.25	14.08	24.39

120 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		160.3	201.4	96.6	121.8	25.4	25.5
2		218.2	230.3	89.7	113.1	23.6	25.4
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.22	0.699	0.082	0.007	0.449	0.59
df	15	15	15	18	21.32	21.32	21.32
SED	16.54	13.51	23.39	6.26	18.23	14.89	25.79

2008-09
LAI

45 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		0.8	0.598	0.633	0.408	0.218	0.116
2		0.735	0.638	0.377	0.419	0.229	0.159
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.137	0.917	0.632	0.698	0.375	0.805
df	15	15	15	18	32.98	32.98	32.98
SED	0.0846	0.0691	0.1197	0.0739	0.1239	0.1012	0.1753

60 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		1.932	1.561	0.841	0.836	0.266	0.168
2		2.981	2.716	0.735	0.763	0.25	0.143
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.252	0.505	0.018	0.002	0.865	0.983
df	15	15	15	18	33	33	33
SED	0.14	0.1143	0.198	0.1265	0.2089	0.1705	0.2954

89 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		2.364	2.314	1.32	1.277	0.367	0.248
2		2.421	3.227	1.468	1.208	0.535	0.31
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.954	0.715	0.255	0.572	0.63	0.431
df	15	15	15	18	24.78	24.78	24.78
SED	0.3759	0.307	0.5317	0.1814	0.4367	0.3565	0.6175

105 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		2.648	3.14	1.297	1.124	0.421	0.172
2		3.061	2.745	1.236	1.065	0.356	0.271
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<.001	0.535	0.663	0.946	0.978	0.522	0.447
df	15	15	15	16	30.05	30.05	30.05
SED	0.1616	0.132	0.2286	0.1634	0.2572	0.21	0.3637

LAI
2008-09
112 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		2.474	2.368	0.857	1.088	0.209	0.187
2		2.561	3.207	1.228	0.791	0.247	0.231
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.816	0.752	0.122	0.225	0.895	0.056
df	15	15	15	18	23.09	23.09	23.09
SED	0.2566	0.2095	0.3629	0.1111	0.2905	0.2372	0.4108

120 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		1.907	2.279	1.167	1.465	0.181	0.158
2		3.427	2.757	1.12	1.067	0.214	0.19
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	<0.001	0.929	0.837	0.164	0.036	0.227	0.52
df	15	15	15	18	32.77	32.77	32.77
SED	0.2261	0.1846	0.3197	0.1858	0.3208	0.2619	0.4536

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89 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		18.79	14.6	9	0.8	0.95	0.19
2		23.05	25.45	19.3	7.45	1.35	1.85
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.361	0.531	0.784	0.004	0.038	0.437	0.712
df	15	15	25.8	15	16	25.8	25.8
SED	3.911	6.773	4.647	4.789	2.51	5.691	8.048

105 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		24.9	22.1	7.07	2.7	4.58	4.03
2		11.15	16.55	17.8	5	0.99	3.04
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.442	0.288	0.876	0.001	0.479	0.057	0.404
df	14	14	27.72	14	14	27.72	27.72
SED	2.748	4.76	3.705	3.366	2.485	4.538	6.417

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112 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		5.55	16.2	9.2	5.4	1.35	1.6
2		12.5	21.4	17.05	2.05	1.6	2.3
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.982	0.018	0.314	0.002	0.069	0.505	0.264
df	15	15	27.46	15	17	27.46	27.46
SED	2.406	4.167	2.936	2.947	1.683	3.596	5.085

120 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		3.24	0.92	3.41	0.62	0.12	0.2
2		4.4	8.52	3.63	4.4	0.2	0.1
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.934	0.682	0.014	0.005	0.003	0.034	0.129
df	15	15	27.31	15	17	27.31	27.31
SED	0.879	1.523	1.07	1.077	0.61	1.311	1.853

2008-09 Pod wt

89 DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		19.2	18.6	16.9	0.6	0.8	0.7
2		28.2	39.2	39.4	14.9	1.1	2.1
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.405	0.188	0.859	0.009	0.015	0.228	0.636
df	15	15	28.58	15	18	28.58	28.58
SED	5.75	9.96	7.13	7.04	4.22	8.73	12.35

105 DAS

	SD	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		76	66.6	26.9	9.7	1.2	0.8
2		31.2	56.4	65.2	19	1.4	3
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.439	0.254	0.836	0.001	0.921	0.021	0.183
df	15	15	26.94	15	17	26.94	26.94
SED	9.88	17.1	11.93	12.09	6.7	14.61	20.67

Pod weight 2008-09

112 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		21.1	63.4	31.5	19.9	0.3	0.2
2		54.3	137.9	76.3	10.4	1.1	1.7
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.61	0.053	0.803	0.01	0.007	0.04	0.072
df	15	15	22.44	15	18	22.44	22.44
SED	15.65	27.11	17.54	19.17	7.92	21.49	30.39

120 DAS

	D	1		3		5	
Landrace	Treatment	RF	I	RF	I	RF	I
1		37	10.5	38.9	7.1	1.4	0.1
2		50.2	93.9	38.1	38.8	2.3	1.2
	D	T	D.T	L	L.D	L.T	L.D.T
F pr.	0.797	0.644	0.03	0.008	0.008	0.045	0.173
df	15	15	27.65	15	18	27.65	27.65
SED	10.43	18.06	12.7	12.77	7.26	15.56	22.01