COMPARING THE PRECIPITATION USE EFFICIENCY OF MAIZE-BEAN INTERCROPPING WITH SOLE CROPPING IN A SEMI-ARID ECOTOPE

by

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Declaration

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

Harun Okello Ogindo

Signature

Date: May 2003

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  > ***"Humble yourself therefore under the mighty hand of God, that He may exalt you in due time: casting all your cares upon Him; for He cares for you."*** **(1 Peter 5:6)**.

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List of Symbols and Abbreviation

AGDM	Above-ground dry matter
AI	Aridity Index (rainfall/evaporation)
ANOVA	Analysis of variance
AWC	Available water capacity (mm water/mm soil depth)
BD	Bulk density (g cm^3)
CLL	Crop determined lower limit of plant available water (mm water/mm soil depth
C_{pa}	Ambient partial pressure of CO_2
C_{pi}	Intercellular partial pressure of CO_2
CR	Neutron meter count ratio (count readings/standard reading)
D	Vapour pressure deficit (kPa)
DAS	Days after sowing
Dd	Mean daytime vapour pressure deficit (kPa)
D_{rg}	Drainage during the current growing period (mm)
DTF	Days to flowering
DUL	Drained upper limit of available water (the value obtained with the soil surface covered with a plastic, i.e zero evaporation) .
$e^0(T)$	saturation vapour pressure deficit (kPa)
$e^0(T_{wet})$	saturation vapour pressure at wet bulb temperature (kPa)
e_a	Ambient partial pressure of H_2O
EF	depth of the extraction front (cm)
EFV	extraction front velocity (cm d^{-1})
e_i	Internal partial pressure of H_2O within the leaf stomatal cavity
Es_g	Evaporation from the soil surface
ET	Evapotranspiration (ET)
E_t	Transpiration (mm)
E_{tg}	Transpiration during the growing season (mm)
EV	Energy value
FI	Fractional interception of PAR by canopy
GV	Glucose value

IER	The conversion of the LER to economic terms and is the ratio of the area needed under sole cropping to produce the same gross income as one hectare of intercropping at the same management level
IMB	Intercrop of maize and beans
k	Extinction coefficient for PAR
kl	rate of soil water extraction (d^{-1})
kPa	kilopascals – unit for pressure
LAI	Leaf area index
LER	Land equivalent ratio
LER_B	Partial land equivalent ratio for bean
LER_M	Partial land equivalent ratio for maize
LER_T	The sum of the fractions of the yields of the intercrops relative to their sole crops and is defined as the ratio of the area needed under sole cropping to the area of intercropping at the same management level to obtain equal amount of yield.
LL-IMB	Crop lower limit for the soil water measurement for the intercrop maize-bean crop.
LL-SB	Crop lower limit for the soil water measurement for the sole bean crop.
LL-SM	Crop lower limit for the soil water measurement for the sole maize crop.
MCWE	Maximum cumulative water extraction (mm)
MV	Monetary value
mV	milliVolt
NWM	Neutron water meter
P	Precipitation (mm)
PAR	Photosynthetically active radiation
PAWC	Plant available water capacity (mm water/ mm soil depth)
P_g	Precipitation during the growing season (mm)
PUE_{ET}	Precipitation use efficiency based on evapotranspiration during the growing season

PUE_g	Precipitation use efficiency (kg $ha^{-1}mm^{-1}$)
PUE_T	Precipitation use efficiency based on transpiration
R_g	Run – off (on) during the current growing season (mm)
RGR	relative growth rate (d^{-1})
RUE	Radiation use efficiency
SAST	South African Standard Time
SB	Sole bean
SLA	Specific leaf area
SM	Sole maize
T	Temperature (°C)
t	Time
t_c	start of the decline of root extraction front (days)
T_{dry}	dry bulb temperature (°C)
t_o	start of extraction (DAS)
T_{wet}	wet bulb temperature (°C)
W	Plant dry matter weight
WUE_T	Water use efficiency at the leaf level (mg CO_2/g H_2O)
Y_{IB}	Yield of intercrop bean
Y_{IM}	Yield of intercrop maize
Y_{SB}	Yield of sole bean
Y_{SM}	Yield of sole maize
ZAR	South African Rands (currency unit)
B	
β	A constant expressing the ratio of the diffusion resistances for CO_2 and H_2O.
γ	Relates to the rate at which the growth response changes from its initial value
γ_{psy}	Pyschrometric constant for the wet bulb pyschrometer
δ	Flexibility parameter in the Richards model

ΔS_g	Change in water storage within the rootzone during the current cropping season (mm)
$\varepsilon_w D$	Dry matter: transpired water ratio, multiplied by the mean daytime saturation deficit
$\varepsilon_w D_b$	Dry matter: transpired water ratio for beans, multiplied by the mean daytime saturation deficit
$\varepsilon_w D_m$	Dry matter: transpired water ratio for maize, multiplied by the mean daytime saturation deficit
θ_{CLL}	Soil water content at the crop determined lower limit (mm water/mm soil depth)
θ_{DUL}	Soil water content at the drained upper limit (mm water/mm soil depth)
$\theta_{h(n)}$	Soil water content of the rootzone for the current at harvest (mm water/mm soil depth)
Θ_m	Mass soil water content
$\theta_{p(n)}$	Soil water content of rootzone for the current season at planting (mm water/mm soil depth)
Θ_{sat}	Soil water content at saturation
θ_v	Soil water content (mm water/mm soil depth)
θ_v	Volumetric soil water content
λ	Parameter relating to the to the intercept on the Y-axis
φ	Asymptote parameter in the Richards model
Γ	Describes the total trend of growth response of the modelled parameter.
Φ	Radiant flux density (subscripts PAR for incident PAR; PAR^i for intercepted PAR)

Abstract

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The study had a major aim of comparing precipitation use by a maize-bean intercrop (IMB) and its component sole crops. In doing so the important variables within the soil-crop system-atmosphere were quantified. The specific ecotope on which the experiment was conducted is Tempe/Valsrivier located at Bloemfontein, South Africa and experiences low and variable rainfall not exceeding 600 mm per annum. The soil was a duplex type with a slowly permeable layer at a depth of about 900-1000 mm depth. The summers are generally very hot with high vapour pressure deficit, and high evaporative demand making it particularly hostile for crop production.

The technical problem concerned comparing the cropping systems by quantifying their use of the water resource as well as determining the intervening weather and crop variables influencing water use. The hypothesis was that the intercrop had the potential benefits for water conservation within the ecotope compared to its sole crop components. This property was inferred from past studies which have shown that the intercrop cropping system has a superior water use efficiency. Field experiments were conducted over two summer growing seasons on the ecotope using an additive intercrop of maize and beans to test the hypothesis. Two sowing dates were adopted during each summer of 2000/01 and 2001/02, consequently, four cropping seasons were done. A randomized complete block design was used, with three treatments being intercrop, sole maize and sole bean (IMB, SM and SB) each with three replications. An experiment to determine the transpiration efficiency coefficient was conducted on an adjacent field with a weighing lysimeter and ran parallel to the first planting during both years. Detailed soil water content measurements were made on the ecotope including drained upper limit (DUL – 262 mm), crop determined lower limit (CLL: SM – 114 mm, SB - 103 mm and IMB – 121 mm) and soil bulk density. Similarly, measurements were made of crop growth and biomass accumulation and weather variables both within the canopy and at an automatic weather station at the experimental site. The measurements made

it possible to characterize the precipitation use for the cropping systems within the ecotope. Measurement of soil water content enabled the quantification of the water balance for each season while the component crop transpiration efficiency coefficient made it possible to partition water use between transpiration and soil evaporation. The lysimeter determined transpiration efficiency coefficient for the dry bean was 3.26 ± 0.25 $gkPakg^{-1}$ which was within range of those found for other legumes.

Analysis of the crop extraction limits and soil water balance components revealed that the intercrop had higher plant available water capacity (PAWC) indicating that it extracted more water than the sole crops. It had 7% and 18% more PAWC than SM and SB respectively. Findings from the soil water balance components showed that the IMB conserved water by losing less through soil evaporation. This attribute was conferred on it by the relatively high leaf area index which reduced the energy flux to the evapotranspiring soil surface. The canopy of the intercrop was more humid decreasing the vapour gradient between the canopy elements and the atmosphere within the canopy. Measured wet and dry bulb air temperatures attest to the presence of relatively higher humidity within the intercrop compared to the other sole maize and bean crops. It is probable that this property made the intercrop conserve more water that was then available for plant use. It can therefore be concluded that the microclimate of the intercrop is favourably modified to conserve water. The estimated soil surface evaporation indicated that the IMB had the lowest soil surface evaporation (Es_g) compared to the other crops. Consequently, the IMB had the highest transpiration meaning that it was able to produce more biomass than the sole crops as transpiration has a linear relationship to biomass accumulation. An analysis of the total water use did not reveal any significant differences between the cropping systems, with the SM having a slightly higher water use than the IMB and SB the lowest. These were significant findings as the plant populations were quite different between the cropping systems. The additive intercrop had a plant population of 120,000, sole bean 80, 000 and sole maize crop 40, 000 plants per hectare.

Another important product was the quantification of radiation interception and use by the cropping systems within the ecotope. The intercrop intercepted and used more PAR than each of the sole crops.

An attempt has been made to mathematically quantify water extraction by the cropping systems using the measured pattern of soil water contents in each cropping systems. This has revealed important possibilities for modeling water extraction by the intercrop.

Adopting a particular cropping enterprise, such as intercropping, involves choice among various alternatives that may be available to the farmer. The choices are both economic and financial and involve foregoing alternative employment of resources. The concept of "more crop per drop" should appropriately be "more cash per drop" of water. Water and therefore any form of precipitation should be allocated to the next best alternative in terms of financial returns. It is the contention that even the small scale farming sector to which this study is aimed has to a large extent been sucked into the economic and financial mainstream in many developing countries. The analysis for PUE was therefore done based on monetary value. It showed that sole beans had the best gross returns per drop of water (37 ± 6 ZAR ha^{-1} mm^{-1}), the intercrop had the second highest value at 32 ± 14 ZAR ha^{-1} mm^{-1} and sole maize 14 ± 5 ZAR ha^{-1} mm^{-1}. The difference between sole bean and the intercrop was not statistically significant.

The intercrop therefore exhibited no statistical difference in total water use despite the relatively higher plant population compared to the other cropping systems within the ecotope. At the same time it had yield advantage over the component sole crops. It can therefore be concluded that within similar ecotopes, where the preferred choice is one of producing the cereal maize, as it usually is in most small scale farming communities, it would be profitable and nutritionally more advisable to grow the intercrop.

Keywords: Semi-arid ecotope, transpiration efficiency coefficient, water extraction, radiation interception, radiation use efficiency, soil evaporation, water use, precipitation use efficiency.

UITTREKSEL

VERGELYING TUSSEN DIE REëNVALVERBRUIKSDOELTREFFENDHEID VAN 'n MIELIE-BOON TUSSEN- EN ENKELVERBOUING IN 'n SEMI-ARIEDE EKOTOOP

Deur

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Die hoofdoel van die studie was die vergelyking tussen die reënvalverbruik van 'n mielie-boon tussenverbouing (IMB) en sy enkelgewas komponente. Die belangrike veranderlikes binne die grond-gewas-atmosfeer sisteem is gekwantifiseer. Die ekotoop waarin die eksperiment uitgevoer is, is by Tempe/ Valsrivier naby Bloemfontein, Suid-Afrika, geleë. Die jaarlikse reënval in hierdie gebied is laag en veranderlik, en oorskry nie 600 mm per jaar nie. Die grond is 'n dupleks tipe met 'n stadig deurlaatbare laag van 900 - 1000 mm diep. Die somers is normaalweg baie warm met 'n lae dampdruktekort en hoë verdampingsaanvraag, wat beteken dat die gebied besonders vyandig teenoor gewasprodusie is.

Die tegniese probleem het gewasverbouingstelsels met mekaar vergelyk deur hul waterverbruik te kwantifiseer en was ook bemoei met die bepaling van die ingrypende weers- en gewasveranderlikes wat waterverbruik beïnvloed. Die hipotese was dat tussenverbouing, in teenstelling met sy enkelgewas komponente, oor potensiële voordele beskik vir waterbewaring binne die ekotoop. Hierdie eienskap is uit vorige studies afgelei wat getoon het dat die tussenverbouingstelsel oor 'n veel beter waterverbruiksdoeltreffendheid beskik. Terrein eksperimente was oor twee somer groeiseisoene uitgevoer deur gebruik te maak van 'n bykomstge tussenverbouing van mielies en bone om die hipotese te toets. Vier groeiseisoene is geskep deur gebruik te maak van twee plantdatums gedurende die somerseisoene van 2000/01 en 2001/02. 'n Volledig ewekansige blokpatroon met drie behandelings, nl. Mielie-boon tussenverbouing, slegs mielies en slegs bone (IMB, SM en SB) is gebruik. Elke behandeling is drie keer herhaal. Terselfdertyd is 'n eksperiment in 'n weeglisimeter op 'n aangrensende terrein uitgevoer om die transpirasie doeltreffendheidskoëffisient te bereken. Dit het saam met die eerste plantdatum eksperiment gedurende beide seisoene geloop. Gedetaileerde grondwater inhoudslesings, insluitende gedreineerde boonste limiet (DUL), gewas laagste limiet (CLL) en grondmassadigtheid is op die ekotoop gedoen. Op soortgelyke wyse is lesings van gewasgroei, biomassa-akkumulasie en weersveranderlikes in beide die blaardak asook by 'n outomatiese weerstasie by die eksperimentele terrein geneem. Dié lesings het dit moonlik gemaak om die reënvalverbruik vir die gewasstelsel binne die ekotoop te karakteriseer. Die kwantifisering van die waterbalans vir elke seisoen is moontlik gemaak deur meeting van grondwaterinhoud, terwyl enkelgewaskomponent gewastranspirasie effektiwiteitskoëffisiente dit moontlik gemaak het om waterverbruik tussen transpirasie en grondverdamping te verdeel. Die lisimeter het die transpirasie

doeltreffendheidskoëffisient vir droë bone gemeet as 3.26± 0.25 $gkPakg^{-1}$, wat binne die waardegebied vir ander peulgewasse is.

Ontleding van die gewasontginningsperke en grondwaterbalans komponente het laat blyk dat die tussenverbouing oor hoër plant beskikbare waterkapasiteit (PAWC) beskik, wat aandui dat dit meer water as die enkelgewasse ontgin het. IMB het 7 % en 18 % meer PAWC as SM en SB respektiewelik getoon. Grondwaterbalans komponente het ook getoon dat die IMB minder water d.m.v. verdamping vanuit die grond verloor het en dus water bewaar het. Dit kan verklaar word aan die hand van die relatiewe hoë blaaroppervlakte-indeks wat energievloei na die evapotranspirerende grondoppervlak verminder het. Die blaardak van die tussenverbouing was meer vogtig, wat gelei het tot 'n afname in die dampdruk gradient tussen die elemente van die blaardak en die atmosfeer binne die blaardak. Gemete nat- en droëbol lugtemperature getuig van die teenwoordigheid van relatief hoër humiditeit binne die tussenverbouing in vergelyking met die enkelgewas mielies en bone. Hierdie eienskap het waarskynlik veroorsaak dat die tussenverbouing meer water bewaar het en dit gevolglik beskikbaar gestel het vir plantverbruik. Die gevolgtrekking kan dus gemaak word dat die mikroklimaat van die tussenverbouing gunstig gemodifiëer is om water te bewaar. Die beraamde grondoppervlakverdamping het getoon dat die tussenverbouing die laagste Es_g (grondoppervlakverdaming) in vergelyking met die enkelgewasse besit. Gevolglik het die IMB die hoogste transpirasie wat beteken dat dit in staat was om meer biomassa as die enkelgewasse te produseer, aangesien tranpsirasie 'n linieëre verwantsap tot biomassa-akkumlasie toon. 'n Ontleding van die totale waterverbruik het geen noemenswaardige verskille tussen gewasverbouingstelsels aan die lig gebring nie, maar die SM het wel 'n effens hoër waterverbruik as die IMB getoon, met dié van SB die laagste. Omdat die plantbevolkings heelwat tussen die verskeie gewasverbouingstelsels verskil het, kan hierdie bevindings as betekenisvol beskou word. Die bykomstige tussenverbouing het 'n plantestand van 120 000 plante per hektaar gehad, terwyl dié van die enkelgewas bone 80 000 en enkelgewas mielies 40 000 was.

'n Ander belangrike produk van die navorsing was die kwantifisering van stralingsonderskepping en verbruik deur die gewasverbouingstelsels binne die ekotoop. Die tussenverbouing het meer fotosinteties-aktiewe straling (PAR) onderskep en gebruik as elkeen van die enkelgewasse.

Daar is gepoog om die water-ontginning deur gewasverbouingstelsels wiskundig te kwantifiseer deur van die gemete patroon van die grondwaterinhoud in elke stelsel gebruik te maak. Hierdie prosedure het belangrike moontlikhede vir die modellering van water-ontginning in die tussenverbouing aan die lig gebring.

Die toepassing van 'n spesifieke gewasonderneming, soos tussenverbouing, bring mee dat keuses gemaak moet word tussen die verskeie alternatiewe wat tot die boer se beskikking is. Hierdie keuses is beide ekonomies en finansiëel van aard en behels die voorafgaande alternatiewe inspanning van hulpbronne. Die konsep van "meer gewas per druppel" behoort paslik "meer kontant per druppel" te word. Water en derhalwe enige vorm van neerslag behoort aan die naasbeste alternatief - in terme van finansiële opbrengs - toegeken te word. Die

klein-skaalse boerderysektor, wat die eintlike teiken van hierdie studie is, is reeds tot 'n groot mate ingetrek deur die ekonomiese en finansiële hoofstroom in baie ontwikkelende lande. Die analise vir PUE is gevolglik op finansiële waarde gebaseer. Dit het getoon dat enkelgewas bone die hoogste bruto-opbrengste per druppel water (37 ± 6 ZAR $ha^{-1}mm^{-1}$) besit - die tussengewas het die tweede hoogste waarde van 32 ± 14 ZAR $ha^{-1}mm^{-1}$ gehad, en die enkelgewas mielies 'n waarde van 14 ± 5 ZAR $ha^{-1}mm^{-1}$. Die verskil tussen enkelgewas bone en die tussenverbouing was nie statisties betekenisvol nie.

Ten spyte van die relatief hoër plantbevolking in teenstelling met die ander gewasverbouingstelsels binne die ekotoop, het die tussenverbouin dus geen statistiese verskil in die totale waterverbruik vertoon nie. Terselfdertyd, het dit 'n opbrengsvoordeel bo die enkelgewas komponente vertoon. Die gevolgtrekking kan dus gemaak word dat binne soortgelyke ekotope, waar die produksie van graanmielies voorkeur geniet, soos die geval mag wees in meeste klein-skaalse boerderygemeenskappe, dit winsgewend en meer raadsaam sal wees uit 'n voedingsoogpunt om tussenverbouing toe te pas.

Sleutelwoorde: *Semi-ariede ekotoop, transpirasiedoeltreffendheidskoëffisient, water-ontginning, stralingsonderskepping, stralingsverbruiksdoeltreffendheid, grondverdamping, waterverbruik, presipitasieverbruiksdoeltreffendheid.*

Chapter 1

Introduction and Literature Review

" We need a Blue Revolution in agriculture that focuses on an increasing productivity per unit of water – more crop per drop." (Dr.Kofi Annan, Secretary General of the United Nations, Report to the Millennium Conference, October 2000)

1.1. Introduction

In developing countries rainfed agriculture on about 80% of arable land accounts for 60% of food production. Only about 20% of the arable land in developing countries is irrigated, but it produces 40% of all crops and close to 60% of cereal crop production (FAO, 2000). It is projected that the world population will grow from 6 billion to 8.3 billion by the year 2030, hence an additional 2 billion people need to be fed in the next 30 years. Food and Agriculture Organization (FAO) projects that world food production needs to increase by 60% to feed the growing world population. Agricultural water use is key to meeting this projection, especially in many developing countries, where water is often so scarce. Presently 800 million people in developing countries are chronically undernourished and therefore cannot sustain healthy active lives (FAO, 2000). The result is illness and death, as well as incalculable loss of human potential and social development. Women and children often bear the brunt of undernutrition. Traditional agriculture has evolved low cost cropping systems that strive to bridge nutrition shortfalls within the household. Intercropping of cereals and legumes is one of these cropping systems.

Cereal-legume intercrops are preferred in many different parts of the tropics and maize is grown in association with pigeon pea (Sivakumar and Virmani, 1980), or maize and cowpea (Wahua *et al.*, 1981; Watiki *et al.*, 1993), or maize and beans (Ayisi and Poswall, 1997; Siame *et al.*, 1997) or maize and groundnuts (Liphadzi *et al.*, 1997). The persistence of intercropping over the years has been due to its stability and resilience under variable growing conditions (Trenbath, 1999; Francis *et al.*, 1978; Willey, 1979a). Recent research has shown that intercropping can produce higher yields than its component sole systems. Several mechanisms make this cropping system attractive, among which, is the important aspect of better utilization of environmental resources. The advantage associated with this superior use of resources has been well explored in the last two to three decades (Willey, 1979a; Francis, 1986; Fukai, 1993; Willey, 1990). Willey (1990) in his review of resource use by this cropping system attributed the yield advantage of intercrops to temporal and spatial complementarity in the use of resources. Beets (1982) observed that multiple cropping allowed for better utilization of atmospheric and soil environmental factors. He further noted that plants of different growth habits have different environmental requirements.

Maize and bean intercropping is preferred in many parts of tropical Africa due to the ability of the secondary crop, beans, to provide additional source of food without substantially jeopardizing the yield of maize which is the primary crop. Further, under small-scale farming conditions the objective is to enrich the often-starchy diets with a cheap protein source.

Climate especially, precipitation plays a fundamental role in successful farming in semi-arid environments. Naturally, the decisions to adopt particular farming systems are not only based on the assessment of the adequacy of precipitation, but also on soil and socio-economic factors. An analysis of the cropping system is incomplete without consideration of the soil-plant-atmosphere system. Such treatment is critical in the evaluation of cropping systems use of natural resources.

The technical concepts relating to "more crop per drop" have advanced a great deal and have been used to evaluate agricultural systems ability to make efficient use of scarce water resources (Rockstrom, 2000). New concepts in the area of rainfall use efficiency have been formulated from this general efficiency concept. Precipitation use efficiency (PUE) is now commonly used to assess the efficiency of rainfall use. This concept has been adopted in the evaluation of rainfall use mainly by sole crops and or under conservation techniques (Hensley *et al.*, 2000), but can also be used to evaluate intercrop systems. The ability to further disaggregate the evapotranspiration terms of the seasonal water balance has the beauty of estimating the actual amounts of water contributing to transpiration and therefore biomass production, and losses due to soil surface evaporation. Such analysis of precipitation use efficiency for the cropping system vis-a-vis its sole crop components is critical in unraveling the often mentioned intercrop advantages as well as isolating parameters of use in modelling the cropping system.

1.2. Motivation

The challenge facing third world agricultural researchers, especially is sub-Saharan Africa, is the dire need to increase food production. The food security situation is burdened by the progressively limited resources at national and household level, and inadequate strategies at policy level. The majority of households within the region are of the small-holder type with production being targeted at meeting consumption needs of the household. Strategies aimed at reducing the worsening food security situation by governments in the region should target production systems implemented at household level.

Intercropping as practiced in the region is a low external input farming system. It is dependent on rainfall which is seasonal, variable and erratic. Many countries within the southern Africa development region presently face food deficits due to poor rains. The mean annual rainfall is between 400 and 600 mm in most of the countries (SADC, 1995). The low mean annual rainfall is associated with very high mean annual potential evapotranspiration of about 2000-2500 mm (Bennie *et al.*, 1995). This results in severe crop water stress. Intercropping, which is an integral part of the smallholder traditional farming system has gone through decades of testing and has attained a reasonable level of stability and resilience under such conditions. However, with increasing rainfall variability, both in amount and time of occurrence, there is sufficient justification to quantify and evaluate this cropping system within the region vis-à-vis its sole crop components.

It has been argued that sustainable crop production in the Southern African region can be attained through techniques that make effective and efficient use of the erratic rainfall resource (Bennie *et al.*, 1995; Bennie & Hensley, 2001). These studies have concentrated on soil tillage and other conservation techniques. Intercropping presents a viable option in conjunction with these techniques in making effective use of rain while at the same time providing additional quality food for small scale farmers within the region.

A substantial number of studies on intercropping have observed yield advantage of the maize and bean intercrop over its sole crop components within this semi-arid region of southern Africa (Francis *et al.*, 1978; Pilbeam *et al.*, 1995; Siddons *et al.*, 1994; Mukhala, 1998; Tsubo *et al.*, 2001). This study is the third of a series of studies involving the maize and bean intercrop at this location (Mukhala, 1998; Tsubo, 2000). Its main purpose is to compare the efficiency with which the intercrop and its sole components make use of the limited rainfall within this semi-arid region of South Africa. This will provide the necessary output required to make informed decisions on the adoption and possible manipulation of the cropping system to make better use of rainfall on similar ecotopes.

1.3. Precipitation use efficiency

Bennie and Hensley (2001) observed that rainfall utilization is concerned with maximizing the soil-plant-atmosphere system. They noted that precipitation during the growing period can be separated into a number of components, thus:-

$$P_g = Et_g \pm R_g \pm D_{rg} + Es_g \pm \Delta S_g \qquad (1.1)$$

where P_g is the precipitation during the growing season (mm); Et_g is water uptake by plant roots which is equal to transpiration loss through the plant canopy during growing season (mm); R_g is run-off (+) from, or run-on (-) on to the experimental area during the growing season (mm); D_{rg} is deep drainage below the root zone (+) or upward flux into the root zone during the growing (-) (mm); Es_g is the amount of water evaporated from the soil surface during the growing season (mm) and ΔS_g is the seasonal change in soil water content of the root zone between the onset and end of the growing season (mm). When water content at harvesting is less than at sowing the value of ΔS_g will be negative.

Hensley *et al.* (2000) observed that precipitation use efficiency (PUE) is not the same as water use efficiency, a commonly used term in water use studies. It is crucial to note that PUE takes account of all water loses which distinguish it from water use efficiency (WUE) which ignores some water losses such as deep drainage, run-off and includes soil surface evaporation. Bennie and Hensley (2001) in their review of precipitation use efficiency of soil water conservation techniques provided a definition for PUE as follows:-

$$PUE_g = \frac{Y}{P_g + (\theta_{p(n)} - \theta_{h(n)})} \qquad (\text{kg ha}^{-1}\,\text{mm}^{-1}) \qquad (1.2)$$

where: Y is crop yield in (kg ha^{-1}), but can also be presented in other forms such as monetary value (ZAR ha^{-1}), P_g is the precipitation during the growing season (mm) (see equation 1.1), $\theta_{p(n)}$ is water content of the root zone at planting for the current season (mm), and $\theta_{h(n)}$ is water content of the root zone at harvest for the current season (mm). The ΔS_g specified in equation 1.1 is the same as $\theta_{p(n)}-\theta_{h(n)}$.

Water use efficiency refers to the total dry matter or grain yield produced per unit of evapotranspiration (Boyer, 1996; Hillel, 1972; Tanner and Sinclair, 1983):

$$WUE = \frac{Y}{ET} \qquad (kg\ mm^{-1} ha^{-1}) \qquad (1.3)$$

where: Y is crop yield in (kg ha^{-1}), ET is the evapotranspiration during the growing season (mm) and is the sum of Es_g and E_{tg} defined in equation 1.1. Water use efficiency measures the efficiency with which a particular crop can convert the water available to it during a particular growing season into yield. It does not measure the efficiency with which the total amount of rainfall falling during the season becomes available to the crop (Hensley *et al.*, 2000).

The separation of evapotranspiration into transpiration and soil evaporation enables a more accurate determination of dry matter/water ratio, since it quantifies the physiological ability of the crop to convert water into yield. The precipitation use efficiency (PUE) should preferably be based on transpired water rather than evapotranspiration for it to be more meaningful and reflect the true efficiency of a cropping system (Hensley *et al.*, 2000).

Productivity on a piece of land essentially depends on three natural resource factors: topography, soil and climate. Each homogenous piece of land with a unique combination of climate, topography and soil characteristic is described as an ecotope (MacVicar *et al.*, 1974; Hensley, 1984). Productivity of a cropping system significantly changes when there is a substantial variation in any of the three resource factors. The quantification of factors influencing PUE is therefore an exercise in the determination of the interactions within the soil – cropping system - atmospheric continuum. The accurate determination of these parameters under conditions of similar topographical, soil and climate is crucial in transfer of such technical information for such cropping systems to other areas with similar topography-soil-climate attributes.

1.4. Soil water aspects

The soil profile water content can be envisaged as a bank account with deposits and withdrawals from the system. The "deposits" consist of precipitation, irrigation and run-on, while the "withdrawals" are evapotranspiration, deep drainage and run-off from the system. Using this analogy, the dryland water balance can be expressed as:

$$Es_g + Et_g = ET = (P_g + \Delta S_g) - (D_g + R_g) \qquad (1.4)$$

Where ET is the evapotranspiration and is the sum of E_g and E_{tg} during the cropping season (mm). The loss of water directly from the soil surface by evaporation beneath crops (Es_g) has been shown to be critical in influencing both biomass and grain yield. It has been observed that up to 30-60% of seasonal evapotranspiration (ET) can be lost as evaporation (Perry, 1987; Siddique *et al.*, 1990). Wallace (2000) observed that 13-18% of the water resource in irrigated agriculture is used as transpiration, while 8-13% is used as evaporation from the soil or water surface and the rest as other losses. Quantifying these losses is fundamental to understanding the influence of cropping systems on water use and eventual yield, especially where water is limiting. Evaporation within crop canopies is influenced by the interactions between the atmospheric evaporative demand, canopy cover and soil water content. Rainfed crops tend to have sparser cover and therefore their soil surface evaporation losses are higher. Soil evaporation losses equivalent to 30-35% of rainfall have been reported by Wallace and Batchelor (1997) under a millet crop grown at a research station in Niger. They observed from these analyses that water used as transpiration was as low as 15-30% of rainfall under these conditions and could be much lower under farmers' fields. Other soil evaporation estimates of 30-60% of seasonal rainfall under semi-arid conditions have been reported in literature (Wallace *et al.*, 1995; Lascano *et al.*, 1987; Daamen *et al.*, 1995).

What the above information shows is that there is substantial scope in improving water use by minimizing losses by evaporation and concomitantly increasing transpiration. The problem of increasing food production therefore becomes one of increasing rain water used via transpiration rather than evaporation and other losses.

Soil evaporation can be reduced by minimizing the amount of energy reaching the soil surface under various cropping systems by stimulating a denser crop canopy. Wallace *et al.* (1999) have demonstrated the potential for using canopy shade to reduce soil evaporation under a *Gravillea robusta* agroforestry system with about 50% ground cover in Kenya. They demonstrated that without the canopy approximately 59% of the rainfall was lost as evaporation, while 41% of rainfall was lost as evaporation within the canopy. Under semi-arid climatic conditions of southern Africa, Bennie *et al.* (1994) found that bare soil evaporation amounted to 60-75 % of the rainfall in the driest summer cropping areas. They noted that substantial evaporation losses could be reduced in the short term (less than 14 days after wetting), with a ground cover of 70% and more in the form of a mulch.

Drainage can amount to a substantial loss of the incoming water, especially in high rainfall environments. Contrary to expectations, drainage can also be high in deep sandy soils under semi-arid environments as was found in Mali (Bley *et al.*, 1991). The factor of soil depth and rooting systems has been noted to be important in determining the extent of deep drainage. Rapidly developing root systems can capture most of the water which could otherwise be lost as deep drainage (Gregory and Reddy, 1982). Similarly, soils with slowly permeable profile layers at certain depth can reduce drainage losses substantially.

How does the foregoing relate to intercropping and precipitation use efficiency? Willey (1990) used the concept of resource capture and conversion efficiency to explain ways in which intercropping could improve water use compared to sole crops. He cited increased plant available water, evapotranspiration, proportion of evapotranspiration which is transpiration, conversion efficiency and harvest index as beneficial services that could be offered by intercropping systems.

The advantages associated with higher plant available water under intercrops has been attributed to a greater canopy cover which protects the soil from run-off and therefore improves soil infiltration (Lal, 1974). Reddy and Willey (1981), Natarajan and Willey (1980a, b) and Rogers (1987) have noted that early and increased canopy closure increases the proportion of seasonal water use that is transpiration, especially when there are frequent wetting events that keep the soil surface wet. Stoop (1986) observed that additive intercrops have a higher canopy cover or leaf area index and therefore have less soil erosion and better soil fertility. Further, it is noted that dry matter increase without an increased water input is possible. The development of higher leaf area under intercropping may in some instances contribute to reduced water availability at greater depths due to the increased leaf transpiration surface.

The fact that the two root systems complement each other in distribution in the soil profile has been proposed as one way of making water more available to intercrops (Fisher, 1977). Consequently, additive intercrops should have a higher total seasonal evapotranspiration than a sole crop with similar density as the components. This has been amply documented for some intercrops (Lakhani, 1976 - sunflower/fodder; Mazaheri, 1979 – maize/kale; Reddy & Willey, 1981 - millet/groundnut, Midmore *et al.*, 1988 - maize/potato; Ikeorgu *et al.*, 1989 - multicropping). The spatial exploration of different soil horizons has been cited as the reason for this greater evapotranspiration. Willey (1990) suggests that greater withdrawal of water may be due to greater root concentrations i.e higher soil volume occupancy. Baker (1974) has also observed that temporal differences in rooting patterns may confer greater withdrawal during the season.

A higher conversion efficiency for water based on transpiration may occur under intercropping systems, especially where the combination comprises a taller cereal (C4) and a shorter legume (C3) through reduction of wind speed or turbulence. C3 species reach radiation saturation at relatively lower intensities; hence, some radiation reduction at high radiation intensities may increase conversion efficiency without accompanied reduction in photosynthesis.

1.5. Soil water extraction

Accurate estimation and knowledge of plant water uptake is crucial in analyzing agricultural productivity. The extent to which water availability limits crop production depends on the balance between supply to the root system and demand by the atmosphere. Where water is relatively ample the supply to the crop becomes largely dependent on demand. However, when the water supply is limited the degree of root extension and ramification within the soil profile and soil physical and chemical characteristics determine the rate of water extraction.

Monteith (1986) developed a mathematical framework that has been adopted extensively to describe root water extraction under water limited conditions. This framework has been used as a basis for simulating water extraction in crop models (Robertson *et al.*, 1993a, 1993b; Robertson *et al.*, 1989; Fukai and Hammer, 1995; Singh *et al.*, 1998; Meinke *et al.*, 1993).

Water uptake by roots at various depths within the soil profile is a requirement in computing water depletion. Water uptake is a function of rooting density distribution, conductivities between the soil and root system and the availability of soil water. Rooting is a function of cropping system adopted, crop species, and genotype and soil physical and chemical parameters. Several intercrops have been documented to withdraw more water than sole crops (Lakhani, 1976; Mazaheri, 1979; Reddy and Willey, 1981) Consideration of atmospheric evaporative demand and soil root exploration is important when examining plant water uptake on a particular soil-plant-atmosphere system (Monteith, 1986)

Little is known of the root water extraction behavior of intercrop systems involving more than one genotype. Most studies conducted to date, have in almost all cases considered sole crops rather than intercrops to analyze soil water extraction. This study provides an idea of the water extraction characteristics of the intercrop and attempts to provide empirical parameters that may be used in modeling the water extraction within the ecotope.

1.6. Transpiration efficiency coefficient

The ratio of dry matter production to water transpired, expressed on unit land area or leaf area, is known as the water use ratio. The quantity of dry matter produced is linearly related to the quantity of water transpired, denoting the conservativeness of the relationship (de Wit, 1958; Azam-Ali, 1984; Cooper *et al.*, 1987). These relationships can be explained at leaf stomatal level. Transpiration efficiency (ε_w) at the leaf level has been expressed by Farquhar and Richards (1984) as:-

$$\varepsilon_w = \frac{\left(c_{pa} - c_{pi}\right)}{\left[\beta\left(e_i - e_a\right)\right]} \qquad (1.5)$$

where ε_w is the transpiration efficiency in mg CO_2 to g H_2O at leaf level, c_{pa} is the partial pressure of carbon dioxide in the air surrounding the leaf, c_{pi} is the concentration of carbon dioxide in the intercellular spaces, β is a constant expressing the ratio of the diffusion resistances in air for carbon dioxide and water vapour and e_i and e_a are the concentration of water vapour in the intercellular spaces of the leaf and in the surrounding air respectively. The (e_i-e_a) is proportional to the vapour pressure deficit (D) of the atmosphere. The atmospheric concentrations of carbon dioxide is fairly constant while that of water vapour differs considerably with temperature and humidity of ambient air surrounding crop canopy. The internal concentration of carbon dioxide although not absolutely constant is much less variable than the internal concentration of water vapour which is controlled by leaf temperature and water status. The ε_w should therefore be inversely proportional to vapour pressure deficit. Observations on many species have shown that the dry matter to transpired water ratio is inversely proportional to the vapour pressure deficit, such that the product of the two is often conservative (Bierhuizen and Slatyer, 1965; Monteith, 1986; Tanner and Sinclair, 1983; Cooper *et al.*, 1987; Goudriaan and Van Laar, 1978; Ramos and Hall, 1982). It has therefore been suggested that this constancy of transpiration efficiency accounts for the usually strong and consistent relationship between biomass production and soil water depletion in a given climatic regime.

Tanner and Sinclair (1983) demonstrated how this pathway determines the observed efficiency of water use by field grown crops. The importance of vapour pressure deficit in determining the variation in water use efficiency has been demonstrated in a number of crop cultivars (Tanner, 1981; Walker, 1986; Azam-Ali *et al.*, 1989; Squire *et al.*, 1984).

The use of the transpiration efficiency coefficient, $\varepsilon_w D$, provides a simple way of partitioning soil evaporation from transpiration. The value $\varepsilon_w D$ is the product of transpiration efficiency (total biomass/transpiration) and the mean daytime saturation deficit over the growing season (Tanner & Sinclair, 1983; Chapman *et al.*, 1993). Hattingh (1993) reported a value of 8.2 g m^{-2} mm^{-1} for maize above ground dry matter in South Africa. Tanner and Sinclair (1983) reported a value of 9.5 g m^{-2} mm^{-1}, while Walker (1986) reported a value of 7.4 g m^{-2} mm^{-1} for maize in the United States and Canada respectively. Hensley *et al.* (2000) adopted a value of 9.4 g m^{-2} mm^{-1} after correcting for root biomass using Tanner and Sinclair's value of 1.2 (assumed root biomass to be 20% of above ground dry matter). A transpiration efficiency coefficient for dry beans could not be found in the literature and had to be determined at the site over two growing seasons. Past studies show that the $\varepsilon_w D$ value for C4 species is a little more than double those for C3 species. Squire *et al.* (1984) reported values of 3.9 g kPa kg^{-1} and 4.6 g kPa kg^{-1} for millet in India with D ranging between 2-2.5 kPa. Ong *et al.* (1987), Azam-Ali *et al.* (1989) and Mathews *et al.* (1988) found values of 1.50 to 5.20 g kPa kg^{-1} for groundnut under varying conditions of D. Pilbeam *et al* (1995) in a study conducted in Kenya found a value of 2.2 to 3.7 g kPa kg^{-1} for beans. Lawn (1982) found a value of 1.15 g kPa kg^{-1} for green gram, cowpea and soybean. Barnard *et al.* (1998) working on legumes found values ranging between 2 and 2.5 g kPa kg^{-1} for lucerne, soybean, sorghum and cowpeas. The values mentioned were in all cases computed for above-ground dry matter.

It has been reported that one way of increasing the transpiration ratio is by reducing vapour pressure deficit by some type of manipulation of the crop microclimate (Wallace, 2000). Data from an agroforestry trial in Kenya has shown that the air under agroforestry trees is more humid than the free atmosphere above the crop (Wallace *et al.*, 1995). Chastian and Grabe (1989) observed that growing a taller stature crop with one of a shorter stature may significantly affect the microclimate hence influencing WUE positively. The altered microclimate condition improves the transpiration/water ratio so long as there is water in the soil profile. Hence cropping systems such as intercrops that provide a shelter belt effect have potential beneficial effects with respect to transpiration/water use ratio.

1.7. Biomass growth and yield

In assessments of crop yields of sole cropping systems, a useful expression is mass yield per unit area. However, in intercropping systems, direct comparison is difficult because products are different for the different plant species growing on the same piece of land (Beets, 1982). Crop species grown together as intercrops need to be evaluated using a common unit. Beets (1982) and Willey (1985) introduced quantitative methods for evaluating intercrop productivity based on intensity of land use, production of constituents (energy, protein, carbohydrate, fat, etc.), and capital return.

A widely used indicator for productivity is the land equivalent ratio (LER) (Willey and Osiru, 1972; Mead and Willey, 1980; Beets, 1982; Willey, 1985). LER_T is defined as the ratio of the area needed under sole cropping to area of intercropping at the same management level to obtain an equal amount of yield (Mead and Willey, 1980). Osiru and Willey (1972) and Willey and Osiru (1972) first used LER to explain the yield advantage of cereal-legume intercropping in Kampala, Uganda. Since then, LER has been widely accepted in the evaluation of intercrop yield advantages (Fisher, 1977; Rees, 1986; Lightfoot and Tayler, 1987; Pilbeam *et al.*, 1994; Mukhala *et al.*, 1999; Tsubo, 2000). When LER is less than 1.0, there is no intercropping advantage and this indicates that the interspecific competition is stronger than interspecific facilitation (or complementarity) in the intercropping system (Vandermeer, 1989). The partial LER gives an indication of the relative competitive abilities of the components of intercrop systems. The species with the higher partial LER is the more competitive for growth limiting factors than the one with the lower partial LER. Income equivalent ratio (IER) is the conversion of LER into economic terms and is the ratio of the area needed under sole cropping to produce the same gross income as one hectare of intercropping at the same management level (Mullen, 1996).

Observations from past research indicate that intercrops produce higher yield than when the component crops are grown as sole crops. It has been mentioned that this is due to the more efficient utilization of environmental resources (Willey and Osiru, 1972). Incidences of yield decreases due to adverse competitive effects have also been reported. Fisher (1977a) found that the normal benefits of intercropping, namely, increased yield and greater yield stability, are not found in drier conditions within some environments and noted that availability of water appears to influence the LER_T, such that LER_T values may be low and variable with water limitation. Siddons *et al.* (1994) found values of $LER_T < 1$ in a determinate type I common bean-maize intercrop grown in short rainy season and an advantage of 9% in the long rainy season. Enyi (1973) documented a decrease in yield of cereal-legume intercrop when the reproductive stages coincided, introducing severe competition for radiation and soil water resources. Enyi (1973) also reported a reduction of about 50% in maize grain yield when it was intercropped with cowpea, however, sorghum had a lower yield reduction of only 23% when intercropped with cowpea. Santalla *et al.* (1999) similarly showed that the contemporaneous development of a maize and bean intercrop in a dry environment may result in simultaneous extraction of water resulting in no complementary water use. They noted reduction in maize yields by up to 45% due to the association with beans. Pilbeam *et al.* (1994) conducting experiments on maize-bean intercrop in the dry parts of Eastern

Kenya showed that the presence of maize decreased the yield of bush beans by 59%; while the presence of bush beans reduced the yield of maize by 44%, indicating that there was intense competition for resources. Other studies of maize-bean intercrops have noted various degrees of yield decrease by both species, with maize yields being affected much less than bean yields (Francis *et al.*, 1978; Mukhala, 1998; Tsubo, 2000).

Growth and development influence crop yield with slower growth and/or poor development resulting in lower crop yield. As reviewed by Hunt (1982, 1990), growth analysis and curves are used as a tool for monitoring crop growth and development. Many such analyses have been applied for evaluating individual crop and canopy growth in mono-cropping systems, however, intercropping has not received similar treatment. Growth analysis forms a crucial part of investigations into the influence of environmental factors on growth and development. Basic growth analyses include the determination of absolute crop growth rate (CGR), relative growth rate (RGR) and net assimilation rate (NAR) among others. In intercropping studies, growth analysis can be made either on the basis of dry matter accumulation or energy value. Growth curves are often applied in the quantitative analysis of plant growth, such as the logistic, the Gompertz, the Chanter and the Richards growth curves. These curves are fitted to biomass production over time (Hunt, 1982).

The Richards function proposed by Richards (1959) has often been applied to functional growth analysis (Hunt, 1982; Ramachandra Prasad *et al.*, 1992, Aikman and Benjamin, 1994). The function has four parameters and therefore provides greater flexibility and superiority in application where three parameter functions such as the logistic model will not provide an adequate fit for data. The Richards function or model is represented by the following relationship:

$$\Gamma = \frac{\varphi}{\left[1 + \exp(\lambda - \gamma t)\right]^{1/\delta}} \qquad (1.6)$$

where φ is the parameter relating to the asymptote, the parameter λ relates to the intercept on the Y-axis (i.e the Γ value corresponding to t = 0), the parameter γ relates to the rate at which the response changes from its initial value (determined by the magnitude of λ) to its final value (determined by the magnitude of the φ), and the parameter δ is present in the four parameter model to provide increased flexibility for data fitting. The parameter δ controls the point of inflexion in asymptotic growth functions.

The greater flexibility exhibited by the function, is however, combined with disadvantages as well. The parameters λ, γ, and δ have a high covariance which can produce problems during non-linear regressions. Davis and Ku (1977) found that the three parameters were poorly estimated by least squares, there being a very wide range for each of these parameters, covering several orders of magnitude, which gave almost identical minimum sum of squares. The Richards model has been found to provide biologically more sensitive growth trend description and has therefore been recommended for use by Venus and Causton (1979). It accounts for growth rates during all the stages of plant development.

1.8. Intercrop environmental modification

The growth environment encountered by intercrop components is strikingly different from that in the sole crops. The nature and the degree of environmental modification depend on a number of factors. Studies have shown that intercrop environments composed of two crops of differing stature and growth dynamics, may create characteristics that convey favorable direct effect on transpiration efficiency (biomass produced per unit of water transpired). Fischer and Turner (1978) suggest that an examination of the physical parameters indicate that water use efficiency at the leaf level is dependent on the leaf to air water vapour pressure deficit, the leaf boundary layer, stomatal and leaf internal resistances to diffusion of water vapour and carbon dioxide respectively (Fischer and Turner, 1978). Within a crop canopy the resistances are to be found within the leaf and the laminar layer of air surrounding a leaf. The thickness of the laminar layer mainly depends on the windspeed, crop height and temperature. At high windspeeds the thickness of the laminar layer becomes small and therefore the aerial resistance to vapour diffusion from the leaves to the ambient air becomes low. An increase in the stomatal resistance will then be effected to reduce evapotranspiration. The evapotranspiration is therefore directly proportional to the vapour pressure gradient and inversely proportional to the magnitude of the aerial and stomatal resistance to vapour exchange. These biophysical aspects of the crop and its canopy condition are critically influenced by availability of soil water and have serious implications for water use and production. Intercropping a taller stature crop with one of shorter stature may significantly affect the biophysical factors within the canopy that influence water use efficiency by the crop. Such influences have been noted within agroforestry systems (Wallace *et al.*, 1995).

Where a short stature species is shaded by a taller one there is a reduction of photosynthetically active radiation resulting in reduced growth and yield of the shorter crop. Shading can also lead to increased plant height, which encourages lodging (Trenbath and Harper, 1973; Chui and Shibles, 1984). There is also a reduction in air temperature, which may favour understorey growth, particularly when the ambient temperature in a sole crop of it is supra-optimal (Midmore *et al.*, 1988) or when the sole crop is water stressed (Harris and Natarajan, 1987). The windbreak effect by the taller canopy component tends to elevate the relative humidity in the vicinity of the shorter crop component and the partial shading effect tends to reduce the air temperature, these both tend to reduce Δe (IRRI, 1978 in Morris and Garrity, 1993). It has been suggested from studies of other ecological systems such as agro-forestry that there is more penetration of air in the interiors of intercrops due to the non-uniform canopy compared to the sole crops. Intercrop canopies are generally rough due to the differences in plant height and architecture among the components. Water use efficiency in the C4 plants is therefore thought to be favoured by the reduced boundary layer (r_a) of the open canopy (Jones, 1976).

Stomatal resistance is suspected to increase in the dominated species in the intercrop, particularly with water stress (Chastian and Grabe, 1989). Water use efficiency tends to increase as the stomatal resistance increases as less water is transpired, especially in the dominated C3 species (Jones, 1976).

Radiant energy loads on the dominated crop is reduced but this crop is usually a C3 species with low light saturated photosynthetic rates. The dominated crop will still produce an appreciable biomass and hence does not seriously affect the total yield of the intercrops.

A taller canopy cover in an intercrop has an effect on soil temperature. This is more so where we have an additive intercrop, which contributes to reduced soil erosion and hence better soil fertility (Stoop, 1986). The reduced spatial exposure leads to less water being lost by way of evaporation under intercropping (Midmore *et al.*, 1988; Ikeorgu *et al.*, 1989). Run-off is normally reduced and therefore infiltration increased (Olasantan, 1988). On the other hand the development of higher leaf area under intercropping may contribute to reduced water availability at greater depths within the soil profile due to the increased transpiration. Cover during the early season leaf development is greater than in sole crops and it has been shown that increased water use efficiency is accounted for by greater proportion of evapotranspiration which is transpiration (Reddy and Willey, 1981).

In additive intercrops higher root soil volume occupation density is common and results in greater below- and above-ground competition. The effect on the dominated crop in most cases the shorter species is more than the dominant crop such as in cereal-legume intercrop (Francis *et al.*, 1982 in Baldy and Stigter, 1997). Trenbath (1974, 1976) suggested that the water supply to each component of an intercrop can vary greatly with the different development of the root system resulting in effects compensating for a difference in water supply. Reddy and Willey (1981) and Hullugalle and Lal (1986) demonstrated that the growth of roots of each species differs and at certain periods can become more important than that of the best sole crop. In this way they noted, maize-cowpea intercrop of alternate rows in conditions of limited water supply can attain higher yield than their sole crops.

1.9. Study Rationale

Field studies have shown that the benefit of intercropping can in most cases be attributed to increased water use efficiency and not to greater water use. A number of suspect mechanisms at the plant physiological level have been mentioned by a number of studies and reviews (Morris and Garrity, 1993). This review observed that the mechanisms that influence water and carbon dioxide fluxes may account for the higher WUE. Morris and Garrity (1993) point to the absence of literature on physiological mechanisms determining water use efficiency among intercrops. Whatever, mechanisms associated with performance of intercrops has been inferred mainly from agroforestry systems.

Jones (1976) suggested that the dominant crops higher water use efficiency is favoured by the reduced boundary layer resistance of its rough canopy as a result of plants of differing heights. These suggestions stemmed from earlier studies conducted with agroforestry systems. Fischer and Turner (1978) proposed that the intercrop environment composed of two crops of different stature and growth dynamics may create characteristics that convey favorable direct effects on transpiration efficiency. Few studies have been conducted to confirm these suggestions. It has also been suggested that a crop component that combines a physically dominating architecture that interferes with the growth of the dominated species, captures a large proportion of seasonal available water, and possesses inherently greater water use efficiency and affects the change in water use efficiency of the intercrop as a whole (Morris and Garrity, 1993).

Mukhala (1998) did a study on the water use efficiency for maize and bean intercrop. He evaluated the biomass production against the seasonal soil water balance at field level under both full and supplementary irrigation. This study confirmed that intercrops have a WUE advantage over sole crops. However, the factors contributing to this advantage were not the subject of the study. Few studies have been conducted to evaluate the water use efficiency of rainfed intercrops under semi-arid conditions. Small-scale farmers practice intercropping system under variable rainfall, therefore appropriate research to benefit them, must provide solutions to the prevailing environmental conditions. This study attempts to provide answers to some of the possible mechanisms that may be at the core of soil-cropping system-atmosphere interactions for this particular cropping system under variable weather conditions.

The purpose of this study is to compare the precipitation use efficiency (PUE) of the maize-bean intercrop with its sole crop components under the semi-arid conditions of Bloemfontein, South Africa. It will strive to provide answers to the question: does intercrop maize-bean give more yield, cash or alternative values per drop of water compared to the sole crop maize and beans. At the same time it will address some of the factors determining an advantage if any.

1.10. Study Objectives

1.10.1. General objectives

i) To compare the precipitation use efficiency for maize and bean intercropping and sole cropping in the semi-arid ecotope.

ii) To generate data from the intercropping field experiment to be used in crop growth modelling.

1.10.2. Specific aims

i) To conduct a field experiment at the University of the Free State, West Campus site and quantify the water balance and growth of the maize and bean intercrop, and simultaneously the sole maize and bean crops under rainfed conditions.

ii) To determine the dry bean transpiration efficiency coefficient and use it to separate the water use to determine the physiological basis of water use by the cropping systems.

Chapter 2

Materials and Methods

2.1. Field Experiments

The field experiments were conducted during the summer months of 2000/01 and 2001/02. The experiment was conducted at the Agrometeorology site located at the West Campus of the University of the Free State (latitude: 29° 01' S, longitude: 26°1' E, altitude 1354 meters above sea level).

A site map showing the position for the experimental plots is provided in the Appendix 1. It shows the location of the plots, irrigation system, weather station, lysimeter, crop lower limit (CLL) plot and drained upper limit determination (DUL) area. The soil at the site is described as fine sandy loam Bloemdal Vrede (3100) (Soil Classification Working Group, 1991). The experimental blocks were located in the southern part with plots having soils with more or less similar textural composition. de Jager *et al.* (1987) and Mukhala (1998) found that the clay content in the upper A-horizon for the experimental location varied from 8-22%. The textural composition of the topsoil can be considered to be predominantly sand. The northern part of the site has higher clay content in the A-horizon.

The topography of the site can be described as flat to a gentle slope from south to north and east to west, with micro-relief being the dominant landform. It was therefore possible to modify the slope substantially through cultivation practice. Run-off from the site was negligible during the two cropping seasons. No surface crusting was noted during the experiments.

The site had been fallow since 1997/1998 summer season. An automatic weather station, a lysimeter and a center pivot irrigation facility at the site were used during the experiment. They facilitated weather data collection and irrigation application to start the crops after sowing.

2.2. Experimental design

The trials were conducted during the summer season beginning mid-November 2000 and December 2001 and ending March 2001 and April 2002. Each experimental season had two sowing dates (see Table 2.1) to expose the experiments to a wide range of weather elements at the different growth stages of the crops. Each sowing date was planted in a completely randomized block. Each block occupied an area of 1620 m^2, each plot being 18 m x 12 m. There were three treatments within each block: sole bean (SB), sole maize (SM) and intercrop maize and bean (IMB). Each treatment had three replications.

Table 2.1 Planting and harvest dates during (2000/01) and (2001/02) cropping seasons.

Year	Planting 1		Planting 2	
	Sowing date	Harvest date	Sowing date	Harvest date
2000/01	23/11/2000	30/03/2001	11/01/2001	30/04/2001
2001/02	10/12/2001	23/03/2002	08/01/2002	30/04/2002

The intercrop components were sown simultaneously using an additive scheme (Willey, 1979; Connolly *et al.*, 2001) with full maize and bean sole crop population (Figures 2.1, 2.2 and 2.3). The plots were planted by hand. The intercrop had a double row of bean between every row of maize. Each planting hole had two seeds for both sole and intercrops. The row spacing for maize was 1.00 m, while that for beans was 0.40 m.

Figure 2.1. Sole maize (SM) crop at the West campus experimental site (6-7 weeks old during the 2001/02 cropping season)

Figure 2.2. Additive Maize-bean intercrop (IMB) at the West campus experimental site (6-7 weeks after sowing during the 2001/02 season)

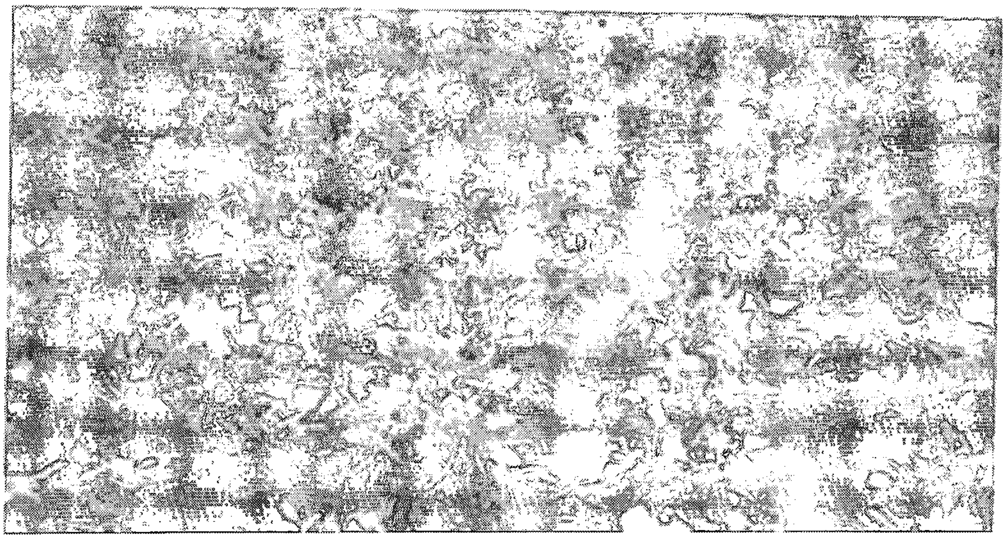


Figure 2.3. Sole bean crop at the West campus experimental site (8 weeks after sowing during the season 2001/02).

Figure 2.4 is a schematic representation of the planting arrangement for the intercrop. The row orientation during both seasons was east-west.

A weighing lysimeter at the site was used to determine the bean crop transpiration coefficient during the two cropping seasons. In the 2000/2001season the bean crop spacing and density in the experimental plots was adopted on the lysimeter. In the

2001/2002 season a higher density with a spacing of 0.20 m by 0.40 m was adopted (Chapter 2, section 2.7).

Table 2.2 Cropping system, spacing and densities adopted during the experimental seasons (2000/2001 and 2001/2002) for the two sowing dates.

Cropping system	Crop	Spacing	Plant density (plants m^{-2})
Sole cropping	Maize	1 m x 0.5 m	4
	Beans	0.4 m x 0.5 m	8
Intercropping	Maize	1 m x 0.5 m	4
	Beans	0.4 m x 0.5 m	8

2.3. Agronomy

The planting material was an ultra short season cultivar of maize (*Zea mays* L cv. PAN 6804) and indeterminate bean cultivar (*Phaseolus vulgaris* L cv. PAN 148). The maturity period for both species was 120 days. Both were planted as sole crops and intercrops. The intercrop components were sown simultaneous and an additive design was adopted during both seasons. The plant densities and row spacing are shown on Table 2.2.

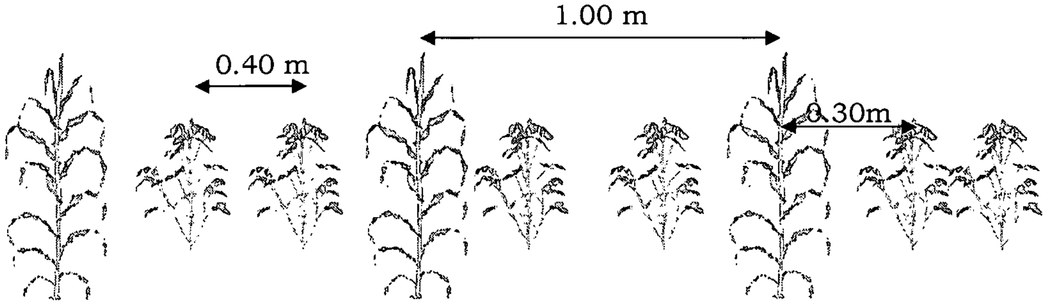


Figure 2.4. The planting arrangement in the intercrop during both seasons 2000/01 and 2001/02.

The seeding rate for the sole maize was 40,000 plants per ha^{-1} and for the sole bean 80,000 plants per ha^{-1}. Due to the additive sowing scheme for the intercrop its density was 120,000 plants per ha^{-1} (beans and maize). The fertilizer application, sowing, weeding and harvesting was done by hand. Fertilizer was applied single dose at sowing (basal) at the rate of 240 kg N, 96 kg P and 48 kg K per ha^{-1}. Weeding was done on a regular basis to ensure a weed free crop.

Irrigation was applied using the center pivot system to start the crops off at sowing when rainfall was inadequate after which the crops grew on natural precipitation from rainfall. At least four rain gauges were placed within the blocks to catch the precipitation which was measured and used as input into the water balance equation

2.4. Atmospheric variables

2.4.1. Long term climatic variables

According to the Koppen climate classification the Bloemfontein area is categorized as BSk (arid steppe) with winter drought, with a mean annual temperature below 18 ^{o}C. The Thornwaite climate classification categorizes the area as a semi-arid warm climate (Schulze, 1947; Schulze and McGee, 1978). Mean monthly weather data (South African Weather Service) for Bloemfontein Airport for 34 years ending 1992, (latitude 29^{0} 06' S, longitude 26^{0} 18' E, altitude 1351 m above sea level) is shown in Table 2.3. The mean annual temperature is 15.9 ^{o}C, the annual rainfall is 559 mm, and the mean global solar radiation is 244 Wm^{-2}. Eighty percent of the rainfall occurs between November and April during the summer growing months. Rainfall during February forms 44% of the evapotranspiration (Penman-Monteith), making this month the most favourable period for plant growth.

Table 2.3 Long term mean monthly climate data for Bloemfontein Airport, South Africa (latitude 29^{0} 06' S, longitude 26^{0} 18' E, altitude 1351 m above sea level; for 34 years to 1992)

Month	Average Max Temp (^{o}C)	Average Min Temp (^{o}C)	Average Temp (^{o}C)	Monthly Rainfall (mm)	Average ETo-PM (mm d^{-1})	Global Radiation (Wm^{-2})
Jan	30.8	15.4	23.1	81.4	9.6	311
Feb	29.0	14.7	21.9	99.9	8.3	285
Mar	27.0	12.4	19.7	74.2	6.1	244
Apr	23.3	7.7	15.5	56.3	6.2	204
May	20.3	2.4	11.3	18.0	3.7	175
Jun	16.9	-1.5	7.7	12.6	2.6	156
Jul	17.5	-1.9	7.8	8.9	4.0	168
Aug	20.0	0.5	10.3	14.1	4.7	201
Sep	24.0	5.3	14.7	21.7	6.0	246
Oct	26.0	9.1	17.6	46.7	7.3	285
Nov	28.1	11.7	19.9	61.2	8.5	320
Dec	30.1	13.8	22.0	61.1	9.4	337

2.4.2. Seasonal climatic variables

During the two seasons meteorological weather variables were recorded at an automatic weather station situated at the West Campus experimental site. The data was averaged over hourly intervals and stored in a datalogger. The data included rainfall, solar radiation, photosynthetically active radiation (PAR), wind speed, dry and wet bulb temperatures. Rainfall was also recorded within the blocks by using at least four rain gauges per block.

The monthly meteorological variable means and rainfall and evapotranspiration sums are shown for the period of the experiments during the two seasons (see Table 2.4). Derived variables including reference evapotranspiration (Penman-Monteith) (Allen *et al.*, 1998) and vapour pressure deficits are also indicated to provide an overview of the atmospheric demand during the period of cropping.

Table 2.4 Summary of the monthly mean meteorological variables during the season (2000/01 and 2001/02) and the sowing dates.

Variable	Season	Nov	Dec	Jan	Feb	Mar	Apr
T_{max}	2000/01	26.2	28.9	30.4	28.9	27.5	21.0
(°C)	2001/02		27.1	27.8	28.5	27.6	25.6
T_{min}	2000/01	14.1	15.4	15.8	15.9	15.6	11.1
(°C)	2001/02		14.8	15.1	15.8	14.5	10.7
T_{mean}	2000/01	20.2	22.2	23.1	22.4	21.6	16.3
(C)	2001/02		20.9	21.3	21.9	20.7	18.0
Rain+Irrig.	2000/01*	12.8	82.8	80.0	79.1	68.6	
(mm)	2000/01♣			56.0	97.1	76.8	30.0
	2001/02†	26.2	88.0	168	42.4	33.0	
	2001/02‡			161	35.4	33.0	26.0
Solar Rad	2000/01	311	320	335	299	234	159
(W m^{-2})	2001/02		331	308	297	241	196
D	2000/01	1.3	1.8	2.1	1.8	1.7	0.6
(kPa)	2001/02		1.6	1.2	1.3	1.6	1.3
Windspeed	2000/01	2.0	2.2	2.2	2.1	1.5	1.4
(m s^{-1})	2001/02		1.9	2.2	1.6	1.3	1.3
ETo	2000/01	43.9	204.1	206.4	170.3	144.8	69.1
(mm)	2001/02		142.0	202.8	173.7	156.1	125.5

* Season 1, sowing date 1; ♣Season 1, sowing date 2; †Season 2, sowing date 1 and ‡Season 2, sowing date 2

2.4.3. Canopy vapour pressure

Dry and wet resistance thermometers were used to record canopy wet and dry temperature. Half hourly data was recorded from the sensors and datalogged. The sensors were housed at the most actively transpiring part of the canopy within mini-shelters located for protection against direct exposure to radiative heating and other weather elements. The purpose was to identify differences in the atmospheric evaporative demand of the sole crop and intercrop systems. The sensors were calibrated using a thermostatically controlled waterbath at different temperatures. The data from the wet and dry resistance thermometers were used to calculate the vapour pressure deficits (D).

2.4.4. Photosynthetically active radiation

In the first planting for both cropping seasons (2000/01 and 2001/02) Li-Cor line quantum sensor (LI-191SA Line Quantum) were used to measure transmitted PAR below the crop canopy within the three different treatments. The sensors were placed perpendicular to the row, which were 1.00 m wide in the sole maize crop and the intercrop. In the beans the sensor was placed perpendicular to the row and was astride two rows. The measurements were logged by a CR10 datalogger over hourly intervals continuously during the seasons.

In the second planting for both seasons the SunScan canopy analyzer (Delta-T, Cambridge, UK) was used to measure both the incoming and transmitted PAR. The system has a single quantum sensor (Beam Fraction Sensor-BFS) and a linear quantum sensor 1 m long with 64 photodiodes equally spaced along its length for measuring PAR above and beneath plant canopies, respectively. The single quantum sensor is placed at the top of the canopy to measure incoming PAR while the linear one is placed beneath the canopy perpendicular to the crop row. A quantum sensor (type LI-COR 190SA) was use at the automatic weather station and recorded hourly incoming PAR.

During the season data on biomass, leaf area and plant height were collected. Three above ground plant samples per plot were harvested at a seven to ten day interval. The plant samples were separated into leaves, stems, cobs and pods. The harvested samples were dried in the oven at 80 °C for 72 hours. The measurements were used to determine radiation interception (FI) and radiation use efficiency (RUE).

2.5. Crop variables

2.5.1. Plant dry matter and yield

Shoot biomass measurements were done at seven to ten day intervals. Plants were cut at the soil surface and separated into leaves, stems, pods (beans) and cobs (maize). Tassels were included with the stems. Flowers on bean plants were included with the pods. The separated plant parts were put in brown paper bags oven dried at 80 °C for 72 hours after which they were weighed for dry mass.

The above ground biomass measurements started at about 30 days after sowing (DAS) for all the sowing dates. The final harvest was done from an area of 12 m^2 for each treatment, separated into cobs and stems and leaves, and weighed. After drying the stems and leaves were weighed together. The grains were removed from the cobs by hand and weighed to get the final seed yield. The grain was at 12.5% moisture content at the time of hand shelling.

2.5.2. Leaf area index

Leaf area measurement was crucial in this study as leaf area is indicative of light interception and plant growth (Burstall and Harris, 1983), photosynthesis (Monteith, 1977; Heilman *et al.*, 1977), transpiration (Enoch and Hurd, 1979) and growth rate (Lieth *et al.*, 1986). The progression of leaf area development was measured using a digital electronic area meter (LI-COR 3100) at 7-10 day intervals. Areas of leaves with irregular margins or those with holes can be measured with these devices. Three plants were sampled from each plot i.e nine plants per treatment. The plants were cut at the soil surface. The leaves were stripped off each plant and fed into the leaf area meter. The sample means from each plot and treatment were calculated. Leaf dry mass was also determined to calculate specific leaf area (SLA) which is the ratio of leaf area per unit leaf dry mass.

2.5.3. Plant height

Plant heights were monitored at 7 to 10 day intervals during season 2000/01, however, in season 2001/02 measurement were taken at maturity. The height of plant sample was measured from soil surface level to the top of the canopy for both maize and beans. Tassels were included in plant height measurements for maize.

2.6. Soil water variables

2.6.1. Experimental plots water measurement

Measurement of soil water content was done using the neutron water meter (NWM) (Campbell Pacific Nuclear (CPN), model 503DR). Table 2.5 shows the number of access tubes installed per treatment. The tubes were installed to a depth of 1200 mm. They were installed both within and between the rows and for the intercrop an additional one was installed between the bean and maize plant rows. Readings were taken in counts at intervals of 32 seconds and converted into count ratios using standard readings taken at the beginning and end of each measurement. Measurements were made on a 7 to 10 day interval except at a time when the neutron water meter had a problem and was taken for repairs. A second NWM was borrowed and used during the time of repair. Later cross calibration was done by taking count readings from three standard PVC pipes of different diameters using the two NWM's. The calibration regression equation was then used to convert readings from the soil science NWM readings to the other NWM (Appendix 2).

Measurement was conducted from steel access tubes installed to a depth of 1200 mm at the beginning of the cropping seasons. Gravimetric samples were taken at each depth (150, 450, 750 and 1050 mm) during installation. The samples were weighed before and after oven drying.

Table 2.5 Number of access tubes in each replicate and treatment during the 2000/01 and 2001/02 growing season.

Cropping system	Replications	Planting 1	Planting 2
SM	I	2	2
	II	2	2
	III	2	2
SB	I	2	2
	II	2	2
	III	2	2
IMB	I	3	3
	II	3	3
	III	3	3

The access tubes were located both within and between the row for the sole maize and beans. For the intercrop maize-bean they were located within the maize row (between two maize plants), between the maize and bean rows and between the bean to bean rows. The soil water content measurement was done at sowing to determine the initial soil water status. Subsequently, 7 to 10 day measurements were done until harvest time when the final measurement was taken.

2.6.2. Drained upper limit determination

The drained upper limit (DUL) is the highest field measured water content of a soil after it has been wetted thoroughly and allowed to drain until the drainage became practically negligible. This was when the measured soil water content decline in the profile was 0.1 - 0.2 % water content per day (Ratliff *et al.*, 1983). The DUL depends solely on the properties of the soil as the effect of vegetation and climates are excluded.

To determine the DUL, a dam measuring 3 m x 3 m was made with earthen bunds along its perimeter (Hensley, 1984; Hensley *et al.*, 2000; Mukhala, 1998). Two access tubes were installed at the site to a depth of 1310 mm at a distance of 1.00 m from each other (Mukhala, 1998). The area was leveled to ensure uniform water infiltration. The dam was wetted for a period of two weeks after which it was covered by a polythene sheet. Care was taken to ensure that there was a good seal around the protruding Neutron probe access tubes to prevent wetting by subsequent rain storms. Figure 2.5 shows the site for the DUL determination at the West campus site.

Measurement of water content for the whole profile was performed at depths of 150, 450, 750, 1050 and 1310 mm and the time of measurement recorded. The water content of the profile plotted against time after saturation described the drainage curve (see Chapter 7, Figure 7.1). The water content for each soil layer at that stage provided the DUL for the individual layer within the soil profile (Hensley, 1984; Hensley *et al*, 2000; Mukhala, 1998). The water content above DUL is important in determination of drainage. Drainage only occurs when the water content of a layer of the root zone exceeds DUL assuming there is no water table.

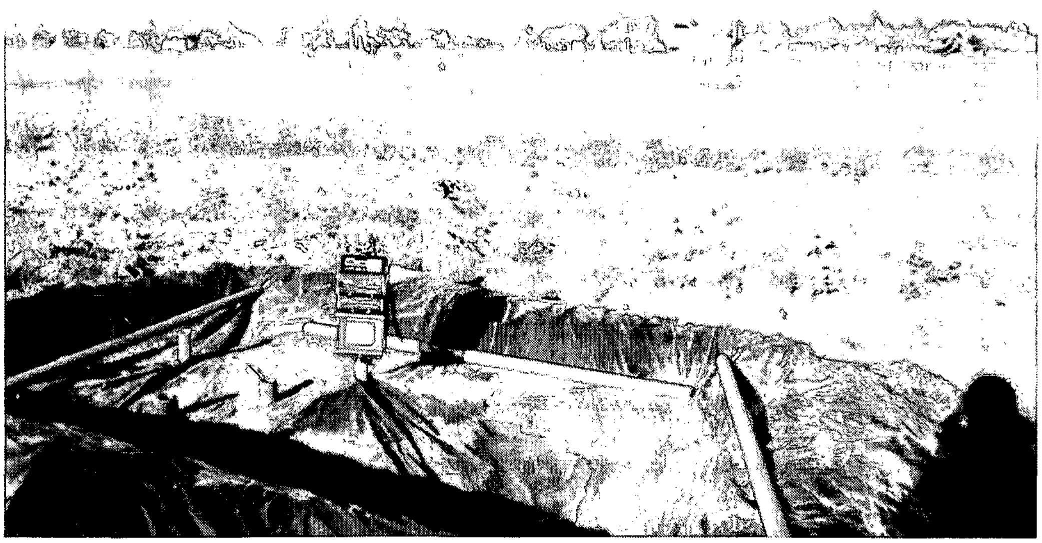


Figure 2.5. Site for drainage curve determination at a representative location at the West Campus experimental site during the 2000/01cropping season.

It was noted that after the two weeks of wetting there was a perched water table at about 600-700 mm depth. The layers below this depth showed gradual change in water content as measurement progressed. This indicated that the layer below the perched water table was very slowly permeable. A number of auger and all access tube installation sites indicated a highly compacted layer at about 900-1200 mm depth.

2.6.3. Crop lower limit determination

The lower limit is defined as the lowest field measured soil water content after plants have stopped extracting water and are near premature death and have become dormant due to water stress (Ratliff *et al.*, 1983). Three plots of 4m by 4m protected from run-on and run-off were prepared at a representative site at West Campus. Two access tubes were installed in the sole bean and maize plots, while three were installed in the intercrop at a representative location at the site. The plots were watered until the crops reached a stage of maximum root development i.e. two weeks before flowering. The soil surface was then completely sealed with plastic sheeting to stop further direct water inputs from rain. Soil water was measured by a NWM on a weekly basis until wilting beyond recovery point was reached. The soil water measurement was done at 150, 450, 750, and 1050 mm depths. The final and lowest NWM reading for each layer gave the lowest limit of crop water extraction for each cropping system at the respective depths (0-300; 300-600; 600-900). These limits were compared to the soil water readings at harvest for the crops in the experimental plots. If the experimental field readings were lower, they were used instead of the crop lower limit plot reading.

2.6.4. Neutron water meter calibration

A separate calibration regression line was constructed for each 300mm layer. This was done to avoid error due to the substantial differences in texture and bulk densities between the layers. The Bloemfontein area falls within a semi-arid zone and hence most of the readings taken at the installation of the access tubes fell below the DUL. The dry end calibration line was therefore the main one under these conditions. Samples for gravimetric water content determinations were taken during the installation of the access tubes before the beginning of season 2000/01. A total of twenty eight samples were taken at each depth. NWM readings were taken at the same gravimetric sampling depths. The samples were weighed at sampling and after oven drying to constant mass at 105°C.

Bulk density values were determined using the core method. Two test pits were dug to a depth of 1500 mm at representative sites on the eastern and western parts of the experimental site. Three replicate core samples were taken at depths of 0-300 mm, 400-700 mm, 700-900 mm and 900-1200 mm depth. These depths represented layers within the soil profile that were reasonably homogenous. Bulk density values (see Appendix 3) for the same depths were used to convert mass water content (θ_m) to volumetric water content (θ_v). Linear regressions of volumetric water content (%) values against NWM count ratios for the corresponding depths provide the calibration regression line for each depth.

The volumetric water content of the gravimetric samples often differed considerably. The samples with volumetric water content values falling above porosity were excluded from the calibration. The equations obtained from regressions are presented in Table 2.6:

Table 2.6. Results of linear regression of volumetric water content (%) for each depth on count ratio (see Appendix 2 data). WC – soil water content; CR – neutron water meter count ratios.

Profile Depth (mm)	Calibration equation	R^2	S.E
0-300	% WC = (21.34 x CR) - 0.69	0.86	2.93
400-700	%WC = (28.89 x CR) - 13.02	0.96	1.41
700-900	%WC = (38.97 x CR) - 25.76	0.80	3.99
900-1200	%WC = (31.88 x CR) - 17.72	0.87	2.62

2.7. Lysimetry

The weighing lysimeter located at the experimental site was used to determine the sole bean transpiration efficiency coefficient, $\varepsilon_w D$. The bean cultivar was the same as in the main trial plots (*Phaseolus vulgaris* L cv. PAN 148; indeterminate growth habit). This crop was planted by hand on 23rd November 2000 and harvested on 30th March 2001 during the first cropping season. A second crop was planted on the 27th December 2001 and harvested on the 23rd March 2002. The lysimeter crop was situated in the middle of a bean plot of 18 m by 18 m. The lysimeter and the surrounding crop received similar irrigation and management treatment during its development. The weighing lysimeter dimensions was 3.1 m by 3.1 m by 2.1 m depth. The mass of the lysimeter was counterbalanced on a weighing system equivalent to less than its total weight to enable changes in weight during the growing season to be monitored to the nearest 100 grams. A commercial precision strain gauge load cell (Load Cell Services (PTY) Ltd) was used to translate lysimeter weight changes to voltage changes. The tension type load cell had a capacity of 200 kg and an excitation voltage of 10 volts. Mass measurements were translated into loadcell measurements and logged on a CR10X datalogger. The readings were recorded as electrical voltage outputs on hourly basis. The lysimeter was calibrated before sowing and after the harvest and the calibration regression equation used to convert the loadcell voltage (V) readings to transpiration (T) readings (mm). The regression equation used was:

$$T = 1.0025 \times V \qquad R^2 = 0.99 \qquad (2.1)$$

The transpiration calculation was done for daylight hours only (07:00-17:00 hours). This was then integrated over each day and the season. Transpiration measurement commenced on 1st January 2001 and ended on 30th March 2001 during which period the lysimeter plot was covered by a black polyethylene sheet. During the second season the measurement was done throughout the season, but only the measurement during the period of cover (2nd February 2002 - end of season) was used. There were four rows of beans at 0.5 m by 0.4 m spacing on the lysimeter during the 2000/01 season. In the second season the planting density was increased to 0.2 m by 0.4 m. The polyethylene completely covered the soil surface of the lysimeter. Three pipes of 100-mm diameter each and 3 meter lengths covered at one end were placed between the rows of beans. Holes were drilled along the pipes to allow irrigation and escape of gases from under the polyethylene sheet. The top of the polyethylene was covered lightly by soil to a depth of about 3 mm to minimize adverse radiative effects on the crop (Figure 2.6).

Figure 2.6. Transpiration measurement on a weighing lysimeter to determine transpiration efficiency coefficient during the 2001/02 growing seasons at the West Campus UFS.

Wet and dry bulb air temperature measurements was carried out at half hourly interval using resistance thermometers housed in mini-shelters. The units were placed at a canopy height of 200-400 mm from the surface of the lysimeter. This was the most actively transpiring part of the canopy (see Figure 2.6).

At harvest the crop was separated into stems, leaves, pods and seeds. These were then dried for 72 hours in a forced circulation oven at 80 °C. The weights of the various components were summed up to get the total above ground dry mass (see Chapter 3, section 3.3.1, Table 3.1).

2.8. Data analysis

2.8.1. Biomass and yield

The biomass and yield data from the different cropping systems and planting dates was analyzed using a statistical package NCSS 2000 (Hintze, 1997). The treatments means within and between single planting dates were tested for statistical difference. The effect of precipitation variability on cropping system performance was tested using ANOVA and other statistical tests.

2.8.2. Land and income equivalent ratios

LER_T was initially used by Osiru and Willey (1972) to explain yield advantage in cereal-legume intercropping system. LER of less than 1.0, indicates that there is no intercropping advantage and it further shows that the interspecific competition is stronger than interspecific facilitation (or complementarity) in the intercropping system (Vandermeer, 1989). The partial LER gives an indication of the relative competitive abilities of the components of intercrop systems. The species with the higher partial LER is the more competitive for growth limiting factors than the one with the lower LER. The following relationships were used:

$$LER_M=Y_{IM}/Y_{SM} \quad (2.2a)$$

$$LER_B=Y_{IB}/Y_{SB} \quad (2.2b)$$

$$LER_T=LER_M+LER_B \quad (2.2c)$$

Where subscripts B, M, T, IM, IB, SM and SB stand for beans, maize, total, intercrop maize, intercrop bean, sole maize and sole bean respectively. LER_M, LER_B and LER_T are the partial maize, bean and the total LER. Income equivalent ratio (IER_T) is the conversion of LER_T into economic terms and is the area needed under sole cropping to produce the same gross income as one hectare of intercropping at the same management level (Mullen, 1996).

2.8.3. Seasonal water balance

The seasonal field water balance relationship for dryland crop production (Hensley *et al.*, 1997) was adopted in the computation of water balance components.

$$Et_g = (P_g + \Delta S_g) - (R_g + Es_s + D_{rg}) \quad (2.3)$$

where Et_g is the transpiration from the crop canopy (mm), P_g the precipitation (mm), ΔS_g is the water extracted from the rootzone (mm), R_g is the run-off from or run -on to the field during the growing season (mm), Es_g is the amount of evaporation from the soil surface (mm), D_{rg} is the drainage beyond the root zone of the crop during the season (mm).

The product of dry matter/water and the mean daytime seasonal saturation deficit ($\varepsilon_w D$) was used to estimate the Et_g using the final harvest biomass for crop components. The Et_g was then deducted from the total water use for each cropping systems determined from the field water balance for the season. For the intercrop the sum of the component crop Et_g was deducted from the ET calculated from the seasonal water balance to provide the value of Es_g. The $\varepsilon_w D$ for dry beans used was 3.4 g kPa kg^{-1}. Similarly, a mean transpiration efficiency coefficient ($\varepsilon_w D$) for maize of 9.5 g kPa kg^{-1}, widely used within South Africa, was adopted in this study (Hensley *et al.*, 2000).

2.8.4. Precipitation use efficiency

PUE for the growing seasons was determined using the definition (Hensley *et al.*, 2000):-

$$PUE_g = \frac{Y}{P_g + (\theta_{p(n)} - \theta_{h(n)})} \quad (\text{kg ha}^{-1}\,\text{mm}^{-1}) \qquad (2.4)$$

where: Y is crop yield in (kg ha^{-1}) or it can be expressed in terms of monetary value (MV) or energy value (EV) or glucose value (GV), P_g is the precipitation during the growing season (mm), $\theta_{p(n)}$ is water content of the root zone at planting for the current season (mm), and $\theta_{h(n)}$ is water content of the root zone at harvest for the current season (mm).

The PUE is similar to WUE when drainage and run-off and run-on are negligible and therefore considered zero. This was the actual situation during the two summer growing seasons. The experimental site was fairly flat, rainfall amounts low and far apart to necessitate any run-off or deep drainage.

The PUE was determined on the basis of MV, EV and GV. This is because it is not possible to add the biomass and grain yields for the intercrop components as they are different species and therefore of different biological constituents.

The long-term price ratio between maize and beans was calculated using data from 1966 to 2002 (National Department of Agriculture, 2002). The trend for the price ratios are shown in the Figure 2.7 and confirms that beans had a better price during all years with the ratios higher for years when production for both crops was lower i.e 1975 and 1995. The average long term price ratio between beans and maize of 5.5:1 was used to convert grain yield to monetary value (MV) in ZAR values. Precipitation use efficiency was calculated in ZAR ha^{-1}mm^{-1} terms. Variable costs for cropping systems were not available and therefore gross earnings have been used.

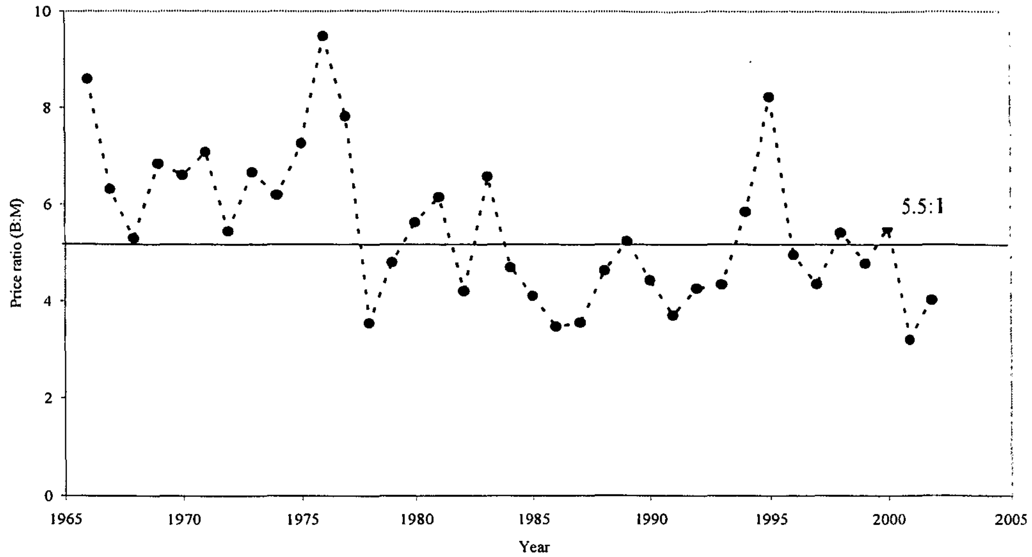


Figure 2.7. Long-term bean: maize price ratio within the Republic of South Africa (National Department of Agriculture, 2002).

One gram of primary assimilate converts to about 0.83 g of carbohydrate, 0.40 g of protein and 0.33 g of lipid (Penning de Vries *et al.*, 1989; Gregory, 1989). The gross chemical composition of maize and beans has been widely documented. The variability of each major component is great. The major component starch provides 72-73% of kernel weight, protein 8-11% of kernel weight and lipids 3-18% of kernel weight. Common bean seed on the other hand has about 35.5 % starch, 22.3 % protein and 30 % lipid by composition. The seeds were dried to a moisture content of 12.5%.

PUE was also calculated on the basis of transpiration component of the water balance. This was done as it was possible to partition the ET among the crop components for the intercrop using the transpiration efficiency coefficient ($\varepsilon_w D$).

Chapter 3

Transpiration Efficiency Coefficient for Dry Beans

3.1. Introduction

Dry bean (*Phaseoulus vulgaris L.*) is an important food crop in most parts of sub-Saharan Africa. It is grown either as sole crop or in combination with cereal crops (Siame *et al.*, 1997; Ayisi and Poswall, 1997; Osiru and Willey, 1972; Mukhala, 1998). In either cropping system it is important to determine resource capture and use. The concept of resource capture and utilization is important when we are considering either radiation or water use in crops. Black and Ong (2000) provide an in-depth review of the concept in relation to radiation and water use in tropical agriculture. Water resources are particularly limiting in tropical regions compared to radiation which is almost always abundant and therefore research into its use is of direct benefit to understand crop productivity.

The link between the amount of carbon dioxide entering the crop and the amount of water leaving via the stomata means that in principle seasonal transpiration can be used to estimate the carbon assimilation of a crop. These relationships can be explained at leaf stomatal level and were expressed by Farquhar and Richards (1984) as:

$$\varepsilon_w = \frac{\left(c_{p_a} - c_{p_i}\right)}{\left[\beta\left(e_i - e_a\right)\right]} \qquad (3.1)$$

where ε_w is the transpiration efficiency in mg CO_2 to g H_2O at leaf lavel, c_{pa} is the partial pressure of carbon dioxide in the air surrounding the leaf, c_{pi} is the concentration of carbon dioxide in the intercellular spaces, β is a constant expressing the ratio of the diffusion resistances in air for carbon dioxide and water vapour and e_i and e_a are the concentration of water vapour in the intercellular spaces of the leaf and in the surrounding air respectively. The $(e_i$-$e_a)$ is proportional to the vapour pressure deficit (D) of the atmosphere. The atmospheric concentrations of carbon dioxide are fairly constant while that of water vapour differs considerably with temperature and humidity of ambient air surrounding crop canopy. The internal concentration of carbon dioxide although not absolutely constant is much less variable than the internal concentration of water vapour which is controlled by leaf temperature and water status. The ε_w should therefore be inversely proportional to vapour pressure deficit. Observations on many species have shown that the dry matter to transpired water ratio is inversely proportional to the vapour pressure deficit, such that the product of the two is often conservative (Bierhuizen and Slatyer, 1965; Monteith, 1986; Tanner and Sinclair, 1983; Cooper *et al.*, 1987; Goudriaan and Van Laar, 1978; Ramos and Hall, 1982). It has therefore been suggested that this constancy of transpiration efficiency accounts for the usually strong and consistent relationship between biomass production and soil water depletion in a given climatic regime. This concept is of great value in tropical environments where water is more limiting to crop productivity compared to solar radiation. The transpiration process essentially contributes to the construction of plant biomass, therefore the relationship between total dry matter and seasonal transpiration is often linear with a slope known as dry matter/transpired water ratio, ε_w (Squire, 1990). Past studies have observed that soil fertility (de Wit, 1958; Wong *et al.*, 1979; Tanner and Sinclair, 1983), or water stress (Azam-Ali *et al.*, 1994) variations do not adversely affect the relationship. However, the value has been shown to vary with location and/or seasons with such variations being attributed mainly two factors, exclusion of root biomass in calculations and influence of vapour pressure deficit (Simmonds and Azam-Ali, 1989; Azam-Ali *et al.*, 1989). The product of dry matter/transpired water ratio and mean saturation deficit calculated for daytime hours appears to remain conservative both spatially and temporally. This value has been given different names such as transpiration equivalent (Azam-Ali and Squire, 2002) or transpiration efficiency coefficient, $\varepsilon_w D$ (Tanner and Sinclair, 1983). The transpiration efficiency coefficient has found wide application in modelling (Adiku *et al.*, 1995; Howard *et al.*, 1995; Chapman *et al.*, 1993).

The aim of this experiment was to quantify the amount of water required to produce a unit mass of dry matter for dry beans. To do so measurements were made of wet and dry bulb air temperatures within the canopy and at the weather station height; water loss by the crop from a weighing lysimeter; and final above-ground dry biomass and seed yield for the bean crop at harvest.

3.2. Definitions and calculations

The vapour pressure deficit, which is the difference between, saturated and ambient vapour pressure is a measure of the evaporative demand of the atmosphere as a partial pressure (units in kPa). The mean vapour pressure deficit was calculated as the mean of this difference for the period during which the crop was actively transpiring (07:00-17:00 - South African Standard Time - SAST). Vapour pressure deficit was calculated at two vertical positions, the standard weather station and at canopy height (200-400 mm). The saturation vapour pressure was calculated using the relationship outlined in FAO 56 (Allen *et al.*, 1998):

$$e^{o}(T) = 0.6108\exp\left(\frac{17.27T}{T + 237.3}\right) \qquad \text{(kPa)} \qquad (3.2)$$

where $e^{o}(T)$ is saturation vapour pressure at air temperature T (kPa), T is air temperature (°C), exp[..] is 2.7183 (base of natural logarithm) raised to the power [...]

The ambient vapour pressure was determined from the dry and wet bulb temperatures using the relationship expressed by the following equation:

$$e_a = e^{o}(T_{wet}) - \gamma_{psy}(T_{dry} - T_{wet}) \qquad (3.3)$$

where e_a is the ambient vapour pressure [kPa], e^{o} (T_{wet}) is the saturation vapour pressure at wet bulb temperature [kPa], γ_{psy} is the pyschrometric constant of the instrument [kPa $^{o}C^{-1}$], T_{dry}-T_{wet} is the wet bulb depression, with T_{dry} the dry bulb and T_{wet} the wet bulb temperature [°C].

The pyschrometric constant for the instrument was calculated from the equation:

$$a_{psy}P = \gamma_{psy} \qquad (3.4)$$

where a_{psy} is a coefficient depending on the type of ventilation of the wet bulb [$^{o}C^{-1}$], and P is the atmospheric pressure [kPa]. A γ-value of 0.000800 was used for natural ventilated psychrometer at canopy height of 200-400 mm and 0.000662 for a fan ventilated pyschrometer at screen height (Allen *et al.*, 1998).

Weight changes due to transpiration losses from the lysimeter were monitored via a loadcell connected electronically to a datalogger. Hourly weight changes were transformed into millivolt readings and recorded by the datalogger using this system. The lysimeter was calibrated using known weights at the beginning and end the season. The calibration coefficient was used to change the hourly millivolt readings into depth of transpired water. Calculation was done for the period of active transpiration (07:00 – 17:00 SAST). The transpiration values were integrated over the daytime and season.

At the end of the season the above-ground dry biomass was harvested and separated into various components including leaves and stems, pods and seeds. The lysimeter yield was calculated on grams per square metre basis.

Variation in transpiration efficiency may be attributed to seasonal differences in the vapour pressure deficit of the air (Bierhuizen and Slatyer, 1965) where $\varepsilon_w D$ is a crop specific coefficient (Sinclair *et al.*, 1984). The coefficient was computed using the relationship:

$$\varepsilon_w D = \left(\frac{\text{AGDM}}{\text{Et}}\right) \times (D_d) \qquad (\text{g kPa kg}^{-1}) \qquad (3.5)$$

where $\varepsilon_w D$ is the transpiration efficiency coefficient, AGDM is seasonal above-ground dry matter production (g m^{-2}), Et is transpiration (kg) and D_d mean daytime vapour pressure deficit (kPa). The D for the canopy is assumed to be closer to the e_i-e_a at stomatal site, however, weather station vapour pressure deficit (D) values are mostly used as they are readily available. To calculate the transpiration efficiency coefficient the transpiration efficiency had to be normalized using D calculated at either canopy (200-400 mm) or weather station height (2m).

Daily reference evapotranspiration rates (ETo) were calculated for the same period as the D using the Penman-Monteith equation (Allen *et al.*, 1998). This was with a view to compare the evapotranspiration and transpiration values over the same period.

3.3. Results and Discussion

3.3.1. Dry matter production and saturation deficit

The components of the above ground dry matter (AGDM) during the two seasons are shown in the Table 3.1. The dry mass components were very different during the two seasons due to the higher plant population adopted during the second season 2001/02.

Table 3.1. Components of above-ground dry biomass during the 2000/01 and 2001/02 seasons after oven drying at 80 °C for 72 hours.

Above- ground biomass (AGDM) g m^{-2}		
Components	Season 2000/01	Season 2001/02
Stems and leaves	108.9	260.5
Pods and seed	184.3	313.1
Seed	136.4	227.2
Above ground biomass	293.2	573.5
Adjusted for root biomass*	351.8	688.2

* The above ground biomass to root mass ratio was assumed 5:1

The mean daytime vapour pressure deficit, D during the season 2000/01 and 2001/02 at both Stevenson screen and canopy heights are shown on Figure 3.1 and 3.2. The mean daytime vapour pressure deficit, D for the season 2000/01 during the period of plastic cover (01/01 - 30/03) was 2.26 ± 0.98 kPa and 1.80 ± 0.78 kPa, while that for season 2001/02 (02/02 - 30/04) were 1.79 ± 0.80 kPa and 1.03 ± 0.52 kPa at the weather station and canopy heights respectively. The vapour pressure deficit for weather station height during the two seasons was obviously higher than those of the canopy height. The vapour pressure was lower for the canopy height due to transpiration at that height and therefore more humid conditions than at weather station height in an open grass field with free air movement.

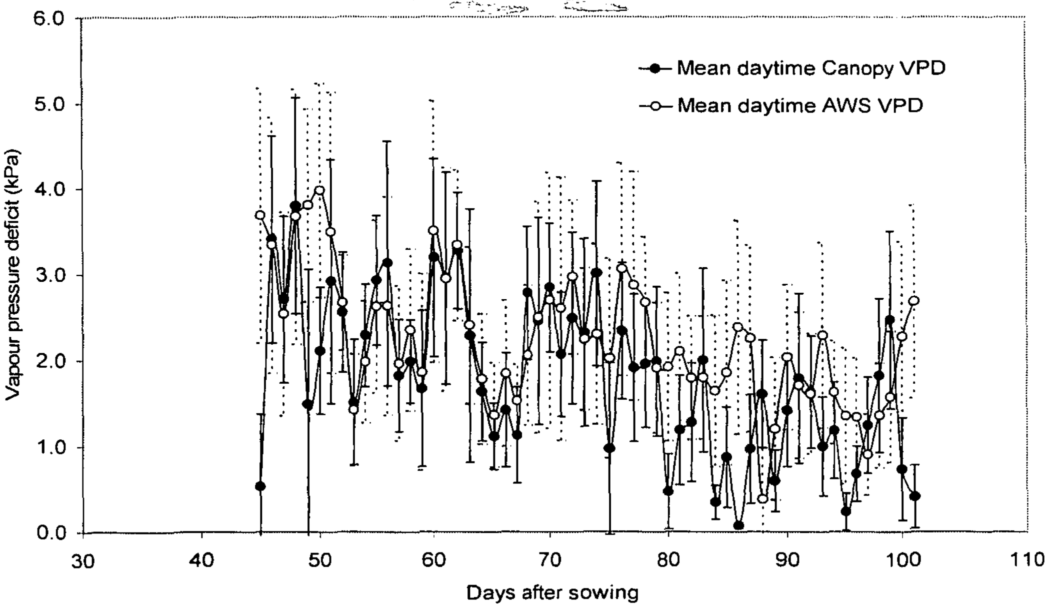


Figure 3.1. Season 2000/01 variation in canopy height (200-400 mm) and weather station (AWS) (1500 mm) mean daytime vapour pressure deficits (7:00-17:00 hours) during periods of polyethylene cover over the lysimeter.

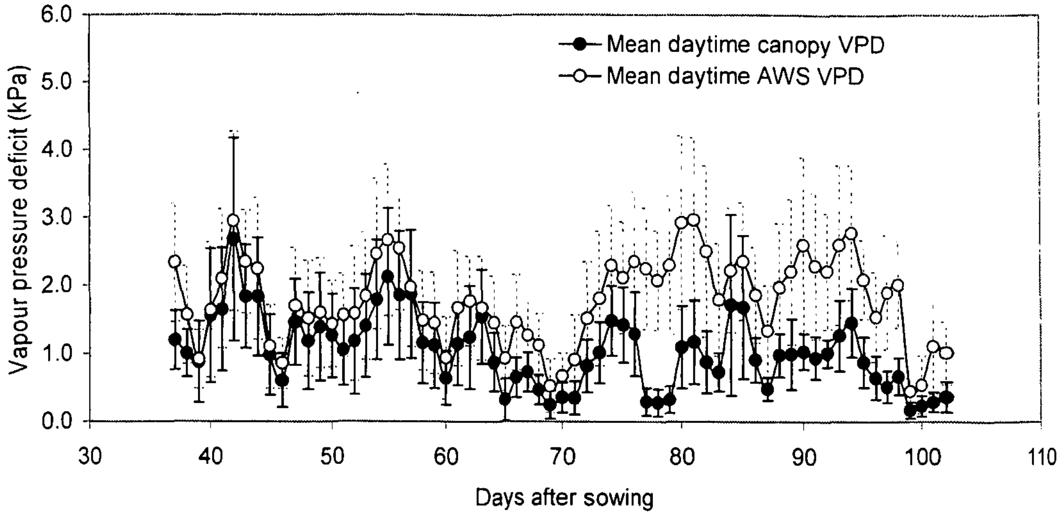


Figure 3.2. Season 2001/02 variation in canopy height (200-400 mm) and weather station (AWS) (1500 mm) mean daytime vapour pressure deficits (7:00-17:00 hours) during periods of polyethylene cover over the lysimeter.

3.3.2. Transpiration

The daily transpiration rates for the two seasons are shown in the Figure. 3.3. These were calculated from the hourly values using the calibration constant from the lysimeter. The mean transpiration rate for season 2000/01 and 2001/02 was 3.6 ± 1.2 and 4.9 ± 2.5 mm d^{-1} respectively. The total amount of water transpired during the period of lysimeter cover for the 2000/01 and 2001/02 seasons were 263.7 mm and 351.5 mm respectively. Season 2001/02 had a higher transpiration and therefore a higher cumulative transpiration than season 2000/01. This could be explained by the higher plant density adopted for the second season.

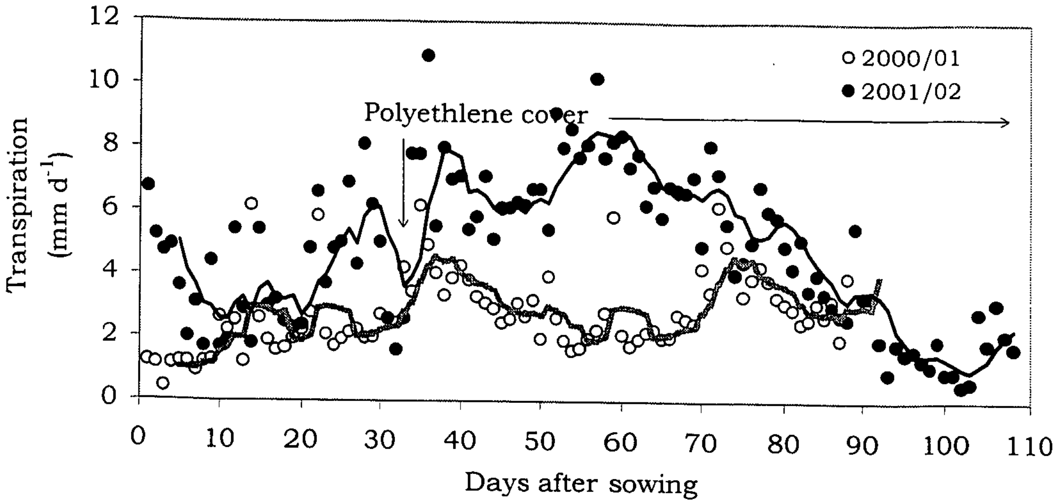


Figure 3.3. Daily totals of transpiration for the cropping seasons 2000/01 (open symbols) and 2001/02 (closed symbols).

The mean reference evapotranspiration (ETo) value for seasons 2000/01 and 2001/02 seasons were 7.7 ± 1.6 and 5.4 ± 1.7 mm d^{-1} respectively. The ratios of the transpiration to evapotranspiration were 0.46 and 0.91 for each season respectively. This confirms that during season 2000/01 the evaporative demand was higher than season 2001/02.

The polyethylene cover over the lysimeter during the two seasons could have slightly modified the surface energy balance, generating sensible heat and augmenting the transpiration. This can lead to an underestimation of the soil evaporation component, however, the precautionary measure was taken by placing a thin film of soil of 3 cm over the surface of the polyethylene to minimize the reflected radiation effect on the bean crop canopy.

3.3.3. Transpiration efficiency

Transpiration efficiency was calculated as mass of above-ground biomass per unit transpiration, (gkg^{-1}). The calculation was done for both AGDM and seed mass. The transpiration efficiency during season 2001/02 was higher than 2000/01 as exhibited in the Table 3.2. This was due to the relatively lower vapour pressure deficits and the higher plant density during season 2001/02.

Table 3.2. Transpiration efficiencies for above ground biomass, total biomass and seed yield for season 2000/01 and 2001/02 .

Crop Components	ε_w (gkg^{-1})	
	Season 2000/01	Season 20001/02
Above ground dry matter	1.11	1.63
Root mass adjusted AGDM	1.33	1.96
Seed	0.52	0.65

3.3.4. Transpiration efficiency coefficient

The transpiration efficiencies were normalized for the season using the mean daytime value of the vapour pressure deficit at canopy (200-400mm) and Stevenson screen height (2m) to obtain transpiration efficiency coefficient ($\varepsilon_w D$). The normalized values for both seasons are shown in Table 3.3.

Table 3.3. Transpiration efficiency coefficient values for season 2000/01 and 2001/02 at both canopy (200-400 mm) and weather station (1500 mm) heights (Normalized and corrected for root biomass).

Crop Components	$\varepsilon_w D$ ($gkPakg^{-1}$)			
	Season 2000/01		Season 2001/02	
	Canopy	AWS	Canopy	AWS
Above ground dry matter	2.00	2.51	1.68	2.92
Root mass adjusted AGDM	2.40	3.02	2.02	3.51
Seed	0.93	1.16	0.67	1.16

The values of transpiration efficiency coefficient (using weather station vapour pressure deficit) calculated for the two seasons were reasonably close, showing that the value is fairly conservative and can provide a good estimate of transpiration for dry beans grown within the same climatic zone (Table 3.3). Whereas canopy vapour pressure deficit, D provides better estimates of the physiological behavior of the crop in relation to vapour and gaseous exchange at leaf level, but the use of weather station vapour pressure deficit, D remains the more commonly applied value since data is more readily available.

The top growth/root ratio data was not available for this study, however, estimates from Soybean (*Glycine max*) at 5:1 was used to estimate total biomass for both seasons as shown in Table 3.1. (Barnard *et al.*, 1998). The estimated transpiration efficiency using the total biomass was 1.33 and 1.96 g kg^{-1} for 2000/01 and 2001/02 seasons respectively. These values were normalized using AWS, D to get the transpiration efficiency coefficient for the seasons as 3.02 and 3.51 g kPa kg^{-1}. A value of 3.26 ± 0.25 g kPa kg^{-1} can be adopted as an average transpiration efficiency coefficient for the two cropping seasons for the dry bean crop. Similarly, normalization of the transpiration efficiency using canopy height vapour pressure deficit values gave transpiration efficiency coefficients of 2.40 and 2.02 g kPa kg^{-1} for 2000/01 and 2001/02 respectively.

Past studies show that the $\varepsilon_w D$ value for C4 species is a little more than double those for C3 species. Squire *et al.* (1984) reported values of 3.9 g kPa kg^{-1} and 4.6 g kPa kg^{-1} for millet in India with vapour pressure deficit ranging between 2-2.5 kPa. Ong *et al.*, (1987), Azam-Ali *et al.* (1989) and Mathews *et al.* (1988) found values of 1.50 to 5.20 g kPa kg^{-1} for groundnut under varying conditions of vapour pressure deficit. Pilbeam *et al.* (1995) in a study conducted in Kenya found a value of 2.2 to 3.7 g kPa kg^{-1} for beans. Lawn (1982) found a value of 1.15 g kPa kg^{-1} for green gram, cowpea and soybean. Barnard *et al.* (1998) working on legumes found values ranging between 2 and 2.5 g kPa kg^{-1} for lucerne, soybean, sorghum and cowpeas. The values mentioned were in all cases computed for above - ground dry matter. The values for $\varepsilon_w D$ found in this study is therefore consistent with those found elsewhere and within an acceptable range for C3 species.

The transpiration values measured at hourly intervals using weighing lysimeter show a mean value of 3.3 ± 1.2 mm d^{-1} for the 2001/02 season. Squire (1990) reported transpiration rates for groundnut and millet (growing on drying soil) of 2 to 4 mm d^{-1} and for millet (growing on stored soil water) of 3.8 mm d^{-1}. The ratio of the hourly mean transpiration to mean potential evapotranspiration was 52%.

3.4. Conclusion and recommendations

The results from the study confirm that $\varepsilon_w D$ is conservative for a particular location as the values for two seasons were close. Correction for below ground biomass and normalization using the vapour pressure deficit has been noted to be major factors determining variations in $\varepsilon_w D$ value. Shoot/root ratio estimate should be approached with caution as root mass is dependent on a number of factors, which vary from location to location depending on the crop, soil and water stress conditions. The shoot/root ratio adopted from soybean therefore provides just a guide to possible ratios for similar species. Azam-Ali and Squire (2002) note that transpiration efficiency for groundnuts almost doubled when roots were included in the measurements of crop dry weight. Roots therefore form a very crucial part of the estimates of transpiration efficiency coefficient.

Similarly, vapour pressure deficit an indicator of atmospheric evaporative demand varies from location to location, therefore there is need to normalize the transpiration efficiency values for each location (Walker, 1986). It is therefore recommended that regionally based variations be determined before the values can be adopted for use at a specific locality. Vapour pressure deficit at canopy level represents a closer estimate of the $\varepsilon_w D$ value as it is closer to the canopy elements involved in photosynthesis and transpiration. However to conform to regional application of $\varepsilon_w D$ value, it is important to use weather station vapour pressure deficits rather than canopy height values.

Plastic covering over the lysimeter soil surface may have modified the energy balance. The amount of this modification was not assessed during either season. The transpiration efficiency coefficient found was however consistent with values found elsewhere hence can be adopted for use in separating the water use of the crop from the soil evaporation. This approach can be used in the tropical and sub-tropical semi-arid areas where water is limiting and can also be adopted in separating water use among intercrop components, when the transpiration efficiency coefficient for the each of the components is known. Therefore if a value of the biomass accumulation is available, the transpiration efficiency coefficient can be used to give an estimate of the water use of the crop. This methodology has been used in chapter 7 to separate the soil surface evaporation and the crop transpiration to obtain a detailed water balance for the maize-bean intercrop.

Chapter 4

Yield Evaluation between Cropping Systems

4.1. Introduction

In the on-going studies involving mixed cropping systems, maize and bean intercropping has received a substantial amount of attention (Gardiner and Craker, 1981; Clark and Francis, 1985; Francis *et al.*, 1982; Mukhala, 1998; Tsubo, 2000; Oljaca *et al.*, 2000). These studies form part of an attempt to understand this cropping system in an effort to improve food production within small holder farming systems in the developing world. Mixed cropping of two or more crops species is the most common form of production in areas where subsistence agriculture is practiced as it helps to spread the risk. Common bean (*Phaseolus vulgaris L.*) is an important legume grown for human consumption in traditional cropping systems in sub-Saharan Africa and it is commonly intercropped with Maize (*Zea mays L.*). Generally, in southern Africa, maize and beans are staple and supplementary crops respectively.

Intercrops have been observed to produce higher yield than when component crops are grown as sole crops. It has been mentioned that this is due to the more efficient utilization of the environmental resources (Willey and Osiru, 1972). It must also be appreciated that sometimes there can be yield decreases due to adverse competitive effects (Willey, 1979a). It has been found in past studies that in maize and bean intercropping, both species yield are negatively affected by intercropping, although maize yields are generally affected much less than bean yields (Francis *et al.*, 1978).

In assessments of crop yields of sole cropping systems, a useful expression is mass yield per unit area. However, in intercropping systems, direct comparison is difficult because products are different for the different plant species growing on one piece of land (Beets, 1982). Beets (1982) and Willey (1985) introduced quantitative methods for evaluating intercrop productivity including the use of (i) intensity of land use, (ii) energy value and (iii) capital return.

A measurement most widely used to assess the efficiency of intercrops is the land equivalent ratio (LER_T) (Mead and Willey, 1980; Vandermeer, 1989; Beets, 1982, Willey and Osiru, 1972). LER_T can be expressed as the ratio of land area required under mono-culture cropping to the area giving equal yield obtained in the poly-culture cropping system (Mead and Willey, 1980). Osiru and Willey (1972) and Willey and Osiru (1972) first used LER_T to explain the yield advantage of cereal-legume intercropping in Uganda. Since then, LER_T has been widely accepted in the evaluation of intercrop yield advantages (e.g., Fisher, 1977; Rees, 1986 a, b; Pilbeam *et al.*, 1994; Mukhala *et al.*, 1999; Tsubo, 2000). When LER_T is less than 1.0, there is no intercropping advantage and this indicates that the interspecific competition is stronger than interspecific facilitation (or complementarity) in the intercropping system (Vandermeer, 1989). The partial LER gives an indication of the relative competitive abilities of the components of intercrop systems.

Hunt (1982, 1990) reviewed growth analysis and curves used in the assessment and monitoring of crop growth and development. These analyses and monitoring have been applied to individual crop and canopy growth in mono-cropping systems. Few studies have been reported for intercrop systems. Basic growth analysis includes absolute growth rate (AGR), relative growth rate (RGR), net assimilation rate (NAR) and crop growth rate (CGR). In intercropping studies, growth analysis can be done either on the basis of dry matter accumulation or converted to an energy value.

A functional growth analysis approach has been used in many studies and calculates growth parameters from functions fitted to the time trends of biomass or their transformed values. A variety of functions have been adopted to describe time trends of biomass accumulation such as exponential, logistic and polynomial expressions. Hunt and Parsons (1974) list some of the functions that have been used. The results of functional analysis are sensitive to the choice of curve fitting procedure (Hunt and Parsons, 1974). The Richards function proposed by Richards (1959) has often been applied to functional growth analysis (Hunt, 1982; Ramachandra Prasad *et al.*, 1992, Aikman and Benjamin, 1994). The function has four parameters and therefore provides greater flexibility and superiority in application where three parameter functions such as the logistic model will not provide an adequate fit for data. The Richards function or model is represented by the following relationship:

$$\Gamma = \frac{\varphi}{[1+\exp(\lambda-\gamma t)]^{1/\delta}} \qquad (4.1)$$

where φ is the parameter relating to the asymptote, the parameter λ relates to the intercept on the Y-axis (i.e the Γ value corresponding to $t = 0$), the parameter γ relates to the rate at which the response changes from its initial value (determined by the magnitude of λ) to its final value (determined by the magnitude of the φ), and the parameter δ is present in the four parameter model to provide increased flexibility for data fitting. The parameter δ controls the point of inflexion in asymptotic growth functions.

The greater flexibility exhibited by the function, is however, combined with disadvantages as well. The parameters λ, γ, and δ have a high covariance which can produce problems during non-linear regressions. Davis and Ku (1977) found that the three parameters were poorly estimated by least squares, there being a very wide range for each of these parameters, covering several orders of magnitude, which gave almost identical minimum sum of squares. The Richards model has been found to provide biologically more sensitive growth trend description and has therefore been recommended for use by Venus and Causton (1979). It accounts for growth rates during all the stages of plant development.

The objectives of the chapter were as follows:

- To determine and compare the yield advantage of the cropping systems on a common scale using the land equivalent ratio (LER) given the variable weather during the various planting dates.
- To compare the yield variations over the two seasons and sowing dates.
- To determine empirical distribution of growth using function analysis in order to facilitate comparisons and clarify variability between the cropping systems

4.2. Calculations and data analysis

Primary production among plant communities result in accumulation of biomass with time, and the accumulation normally follows a sigmoid pattern. The primary data obtained from biomass accumulation was analyzed for its efficiency in producing new material. This measure of efficiency is called relative growth rate (RGR) normally represented by the letters RGR.

The RGR expresses the dry mass increase in a time interval in relation to the initial mass (Gardner *et al.*, 1985). Mean RGR is calculated from measurements taken at consecutive times t_1 and t_2. The relationship for calculation of RGR is derived from the standard compound interest equation (Blackman, 1919). Gardner *et al.* (1985) used the equation 4.2 to calculate instantaneous RGR:-

$$\mathrm{RGR} = \frac{1}{W} \times \frac{dW}{dt} \qquad [\mathrm{g\ g^{-1}\ d^{-1}}] \qquad (4.2)$$

where W is the initial dry mass, dW is the change in mass between two harvests while dt is the change in time. During the exponential phase of growth the RGR decreases at a declining rate with time afterwards it does not change much with time.

The software NCSS 2000 (Hintz, 1997) was used to fit the Richards function (see equation 4.1) to the primary dry matter data from sequential biomass harvests. To compare the Richards curve fits, the distance between the empirical distribution functions (EDF) of the fits was done using the Kolmogorov-Smirnov test. The test uses a D-statistic criterion value, which is the maximum difference between two empirical distributions. The Kolmogorov-Smirnov test involves pair wise comparison whereby the test statistic is applied to the maximum vertical distance between distributions. Two distributions are different if the maximum vertical distance between them exceeds the critical level of significance (e.g. alpha = 5%). Statistical software (Hintz, 2000) was used to perform the tests between the Richards curve fits for sole and intercropped crop bean and maize species. D-statistic is presented for intercropping and sole maize and beans grown in the same season and at different planting dates. The assumption is that the differences during a season are because of the cropping system adopted and those between planting dates due to both cropping system and different climatic conditions.

The empirical data generated from the fitted equation was used to derive relative growth rates, which enabled the comparison of the efficiency at which additional biomass growth occured during the seasons and sowing dates. The relative growth rate RGR as derived by Richards function is represented by the following relationship (4.3):

$$\mathrm{RGR} = \frac{\lambda}{(\delta-1)\left[1-\left(\frac{\Gamma}{\varphi}\right)^{\delta-1}\right]} \qquad (\mathrm{g\ g^{-1}\ d^{-1}}) \qquad (4.3)$$

The parameters in equation 4.3 were defined in the Richards function presented in equation 4.1 (see page 48).

4.3. Results

4.3.1 Growth analysis

Above ground dry matter accumulation

Assessment of growth over time was done by considering the growth of total above ground dry matter during the different seasons. Figure 4.1(a) and (b) exhibits the progress of dry matter accumulation during each growing season.

Experiment 1 (2000-2001), planting date 1 and 2

Maize crop

During season 2000/2001, planting 1, sole and intercrop maize showed a higher biomass accumulation than the sole and intercrop beans beyond 40 DAS (see Figure 4.1a). However, the sole maize had a higher biomass than intercrop maize from 40 DAS to the end of the season. The differences between the sequential harvests for all crops were not statistically significant at $p = 0.05$. During planting 2, the sole maize had a higher biomass than the intercrop maize from 55 DAS to the end of the season.

Bean crop

Statistical test for differences on sequential harvests between the sole and intercrop bean did not show any statistically significant difference throughout the season during planting 1 at $p=0.05$.

The progression of dry matter accumulation for all the cropping systems is exhibited in Figure 4.1. The Appendix 4 shows the results of the t-tests performed on the sequential biomass harvests.

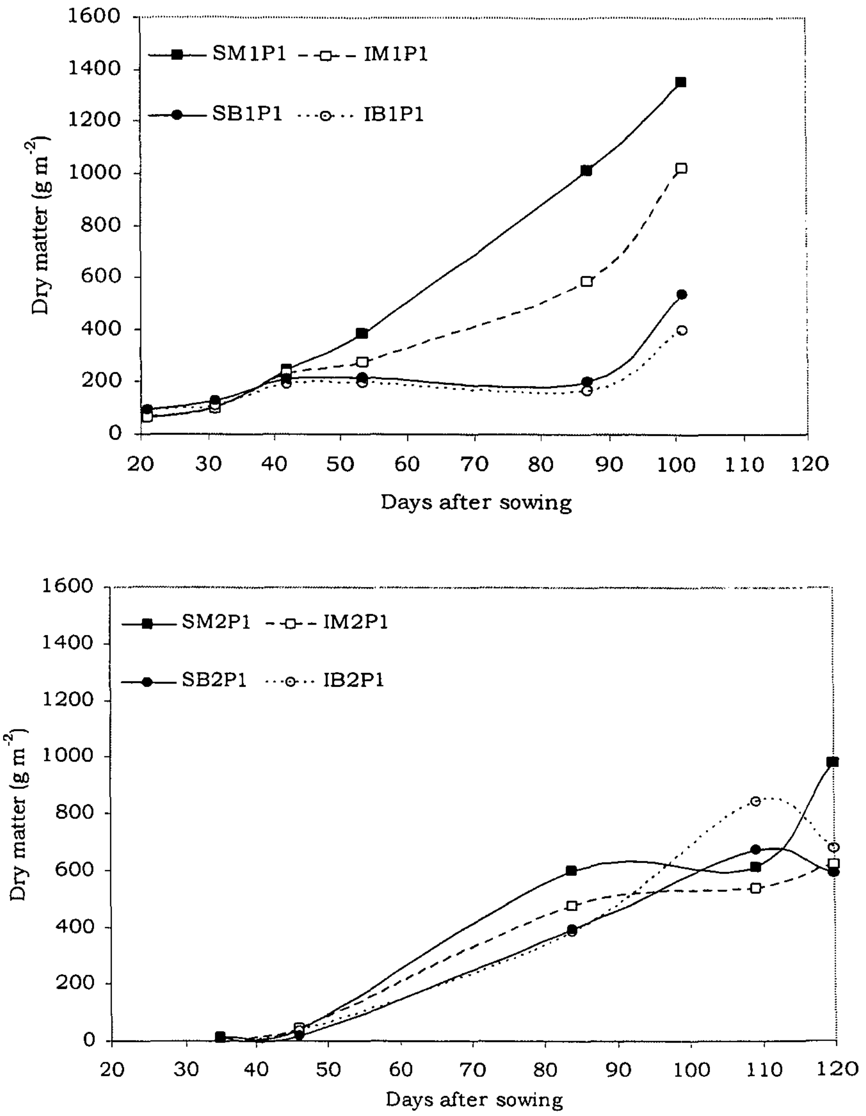


Figure 4.1. Above-ground biomass development for all the cropping systems during season 2000/01, planting 1 (above) and planting 2 (below). SM1P1, IM1P1, SB1P1, IB1P1 represent cropping systems, planting date (1), planting season (1) while SM2P1, IM2P1, SB2P1, IB2P1 cropping system, planting (2), planting season (1).

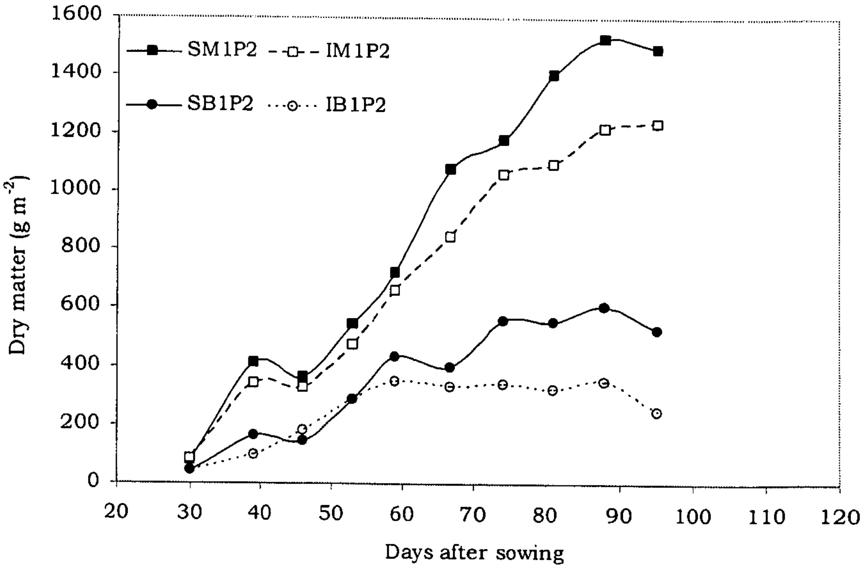
Experiment 2 (2001-2002), planting date 1 and 2

Maize crop

Statistical analysis between sole and intercrop maize for both plantings did not reveal much difference for most of the growing period. During planting 1, there was no significant difference at p=0.05 between 30-59 DAS (see Appendix 5). Also during planting 2, the biomass accumulation did not exhibit significant differences for the sole and intercrop maize from 39-87 DAS after which it showed divergence. These trends are shown on the figure 4.2 and the results for the t-test on sequential above ground biomass harvests are presented as Appendix 5.

Bean crop

Statistical test on sequential harvest data did not reveal significant differences at p=0.05 from 30-67 DAS for sole and intercrop beans during both planting dates. The biomass accumulation trends during both seasons are shown in Figure 4.2.



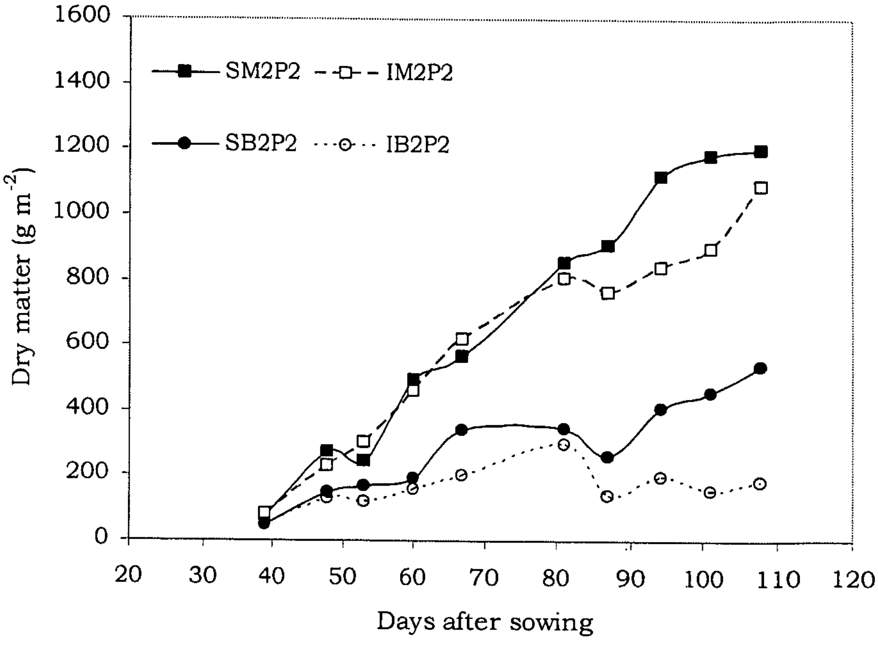


Figure 4.2. Above ground biomass development for the cropping systems during season 2001/02, planting 1 (previous page) and planting 2 (above).

Biomass relative growth rate

Biomass relative growth rate for the various treatments and planting dates were computed from the consecutive harvest data and are shown in Figure 4.3. The results are discussed according to the season and planting dates.

Experiment 1 (2000-2001), planting date 1

RGR which is the rate of growth per unit weight of plant is important in the analysis of biomass growth. RGR decreases as the plant matures, however, during the growing seasons fluctuations were at times occurring due to the irregular supply and limitation of growth resources and possible competition for the same resources. During season 2000/01, planting date 1 – SM and IM had more or less similar RGR trend until 40 DAS when there was a slight divergence with the SM relative growth rate surpassed by that of IM (see Figure 4.3).

IB had a lower RGR at the beginning of the season which by 32 DAS caught up with the SB and afterwards was more or less similar with no significant difference between them throughout the season. Overall, the cropping systems exhibited similar trends in RGR but with divergences noted most likely due to differences in resource availability especially soil water.

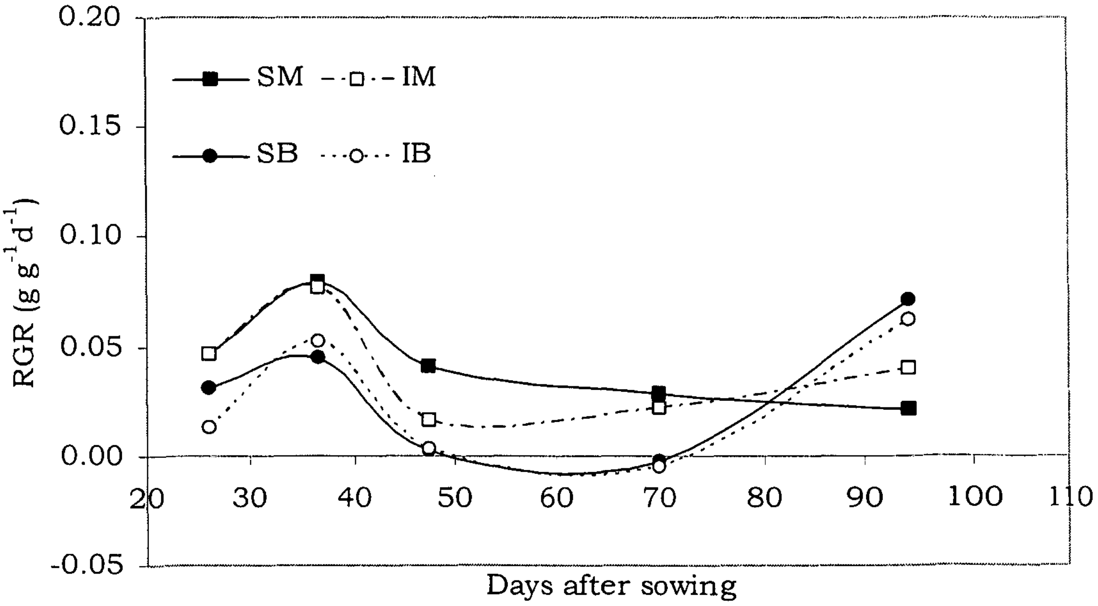


Figure 4.3. Relative growth rates for cropping systems based on actual above ground dry matter accumulation for season 2000/01, planting 1.

Experiment 1 (2000-2001), planting date 2

IM performed relatively better than at the beginning of the season compared to SM up to 60 DAS when there was a slight but insignificant decrease below the IM rate. This trend continued to the end of the season. IB performed better than the SB up to 55 DAS when SB had a higher R than IB. The differences in R were however not significant to the end of the season.

In general, the RGR during planting date 2 was at a higher level during the first half of the season compared to planting date 1, afterwards there was a sharper decline towards the end of the season compared to date 1. This may have been due to the lower temperatures as the season progressed towards winter season (see Figure 4.4).

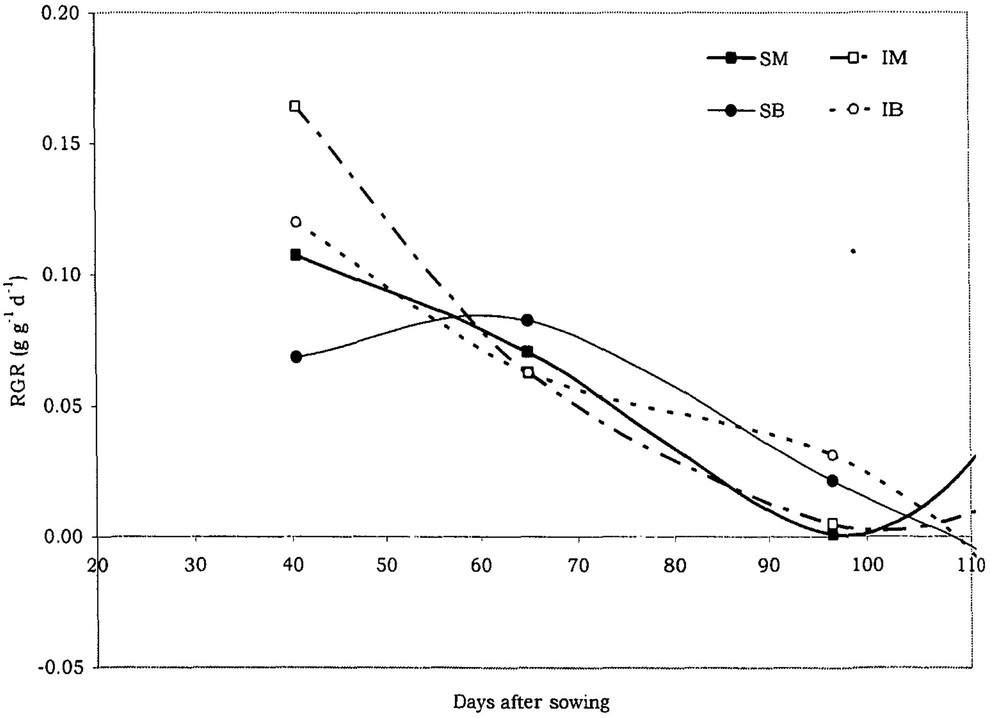


Figure 4.4. Relative growth rates for cropping systems based on actual above ground dry matter accumulation for season 2000/01, planting 2.

Experiment 2 (2001-2002), planting date 1

There was a sharper decline in RGR compared to the first experiment with a higher starting RGR at the beginning of measurement. There was insignificant difference between the SM and IM relative growth rate during the date 1 although fluctuations can be seen from the Figure 4.5. This was probably due to competition for resources in the IMB.

There was greater fluctuation in RGR for the bean crop compared to the maize. This can be attributed to the growth characteristics for above ground and below ground system. The bean roots are shallower and therefore are likely to be sensitive to changes in soil water and environmental changes. IB had a less drastic drop in RGR during the beginning of the season compared to the SB. IB also had less fluctuation but lower RGR towards the end of the season (see Figure 4.5).

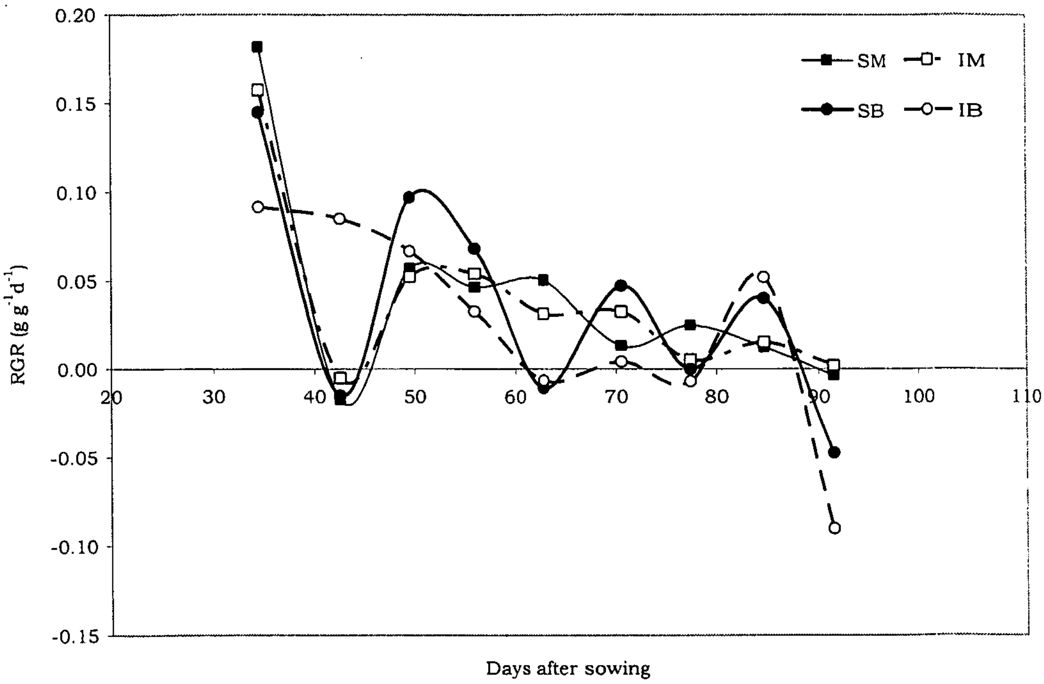


Figure 4.5. Relative growth rates for cropping systems based on actual above ground dry matter accumulation for season 2001/02, planting 1.

Experiment 2 (2001-2002), planting date 2

IM had a higher RGR than the SM up to 70 DAS after which the growth rate of the SM surpassed that of the IM up to end of the growing season. There was however no statistical difference between the SM and IM growth rates during the season.

SB had a higher RGR during 60-70 DAS and eventually from 76 to the end of the season. During the other periods the RGR for SB was slightly surpassed by IB except during 79-90 DAS when the IB had a negative and lower RGR than the SB crop (see Figure 4.6).

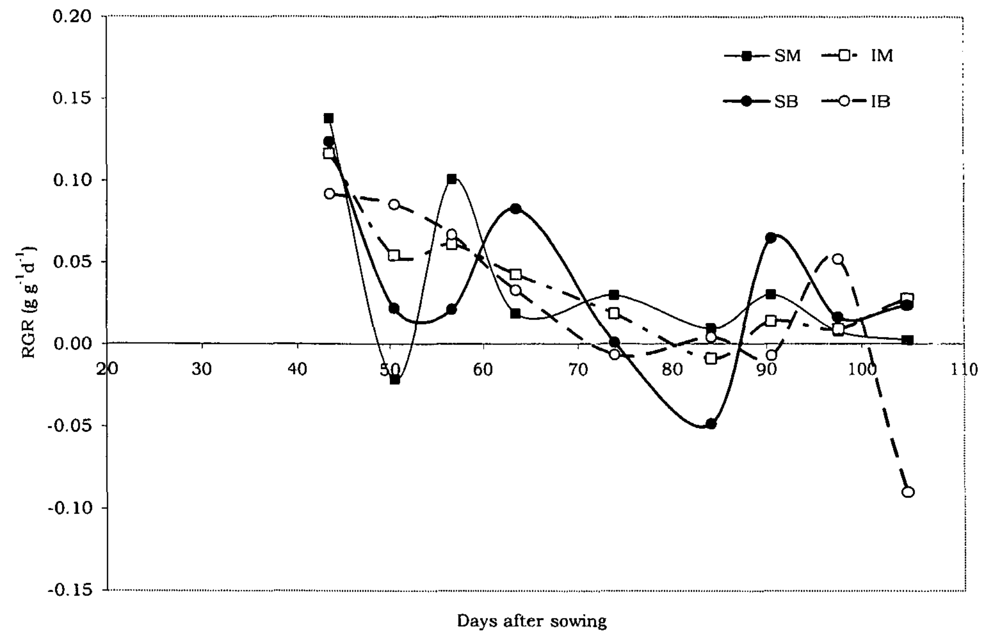


Figure 4.6. Relative growth rates for cropping systems based on actual above ground dry matter accumulation for season 2001/02, planting 2.

4.3.2. Functional analysis

Dry matter accumulation

Richards function was fitted to the biomass accumulation data for above ground dry matter for all the seasons and planting dates. Most of the estimates of the Richard function parameters had coefficient of determination exceeding 70% (see Appendix 6, Table 1& 2). The results of the D-statistic performed between pairs of curve fits for the same species within and between the seasons are shown in Table 4.1.

Table 4.1. Results of the Kolmogorov-Smirnov test statistic pair wise comparisons between Richards curve fits for above ground biomass accumulation within the planting dates for same species 0.05 probability.

Alternative Hypotheses	D Statistic	Reject Ho if > than	Test alpha	Decision (α=0.05)	Prob. Level
IB <> SB, (2000/01, date 1)	0.65	0.1626	0.05	Reject Ho	0.0000
IM <> SM (2000/01, date 1)	0.57	0.1626	0.05	Reject Ho	0.0000
IB <> SB, (2000/01, date 2)	0.33	0.1626	0.05	Reject Ho	0.0000
IM <> SM (2000/01, date 2)	0.57	0.1877	0.05	Reject Ho	0.0000
IB <> SB, (2001/02, date 1)	0.79	0.1842	0.05	Reject Ho	0.0000
IM <> SM (2001/02, date 1)	0.48	0.1655	0.05	Reject Ho	0.0000
IB <> SB, (2001/02, date 2)	0.79	0.1737	0.05	Reject Ho	0.0000
IM <> SM (2001/02, date 2)	0.41	0.1877	0.05	Reject Ho	0.0001

Table 4.1 show that the value of the Kolmogorov-Smirnov D–test statistic for comparison between curve fit distribution was higher than the p-value which was p = 0.000 in all cases. The null hypotheses that the fits were similar was rejected at alpha = 0.05 in favour of alternative that the distributions are different. Table 4.1 only presents the comparisons within the season. The conclusion that can be drawn from this is that the curve fit data are drawn from different populations (i.e SB different from IB) and that the differences are due to possible competition between the crop components that participate in the intercrop.

Similar comparisons as in Table 4.1 were performed for different planting dates but same species (i.e all the bean and maize crop combinations). The results all showed that the distributions were different at alpha = 0.05, and therefore the null hypotheses was rejected in all the cases. The D-statistic indicates the magnitude of the vertical variation, which is the maximum difference in cumulative fraction between the two curves. The purpose of the analysis is to explain seasonal variation between the empirical distributions within the same species and be able to deduce possible reasons behind the variations.

Relative growth rate (functional approach)

Relative growth rates were computed from the curve fit parameters. This was with a view to estimate and compare RGR from the curve fits. The relative growth rate curves computed from the function are shown in Figure 4.7. The differences between the curve fits were analyzed using ANOVA. The results of the analysis are presented as Appendix 7.

Experiment 1 (2000-2001), planting date 1

SB had the highest RGR compared to SM, IM and IB up to 30 DAS. The RGR for SB was higher than that for IB up to 35 DAS after which the both RGR were almost similar until the end of the growing season (Figure 4.7). A comparison of RGR for the maize species show a higher relative growth for the SM up to 75 DAS after which the two RGR's converge towards end of the season (Figure 4.7).

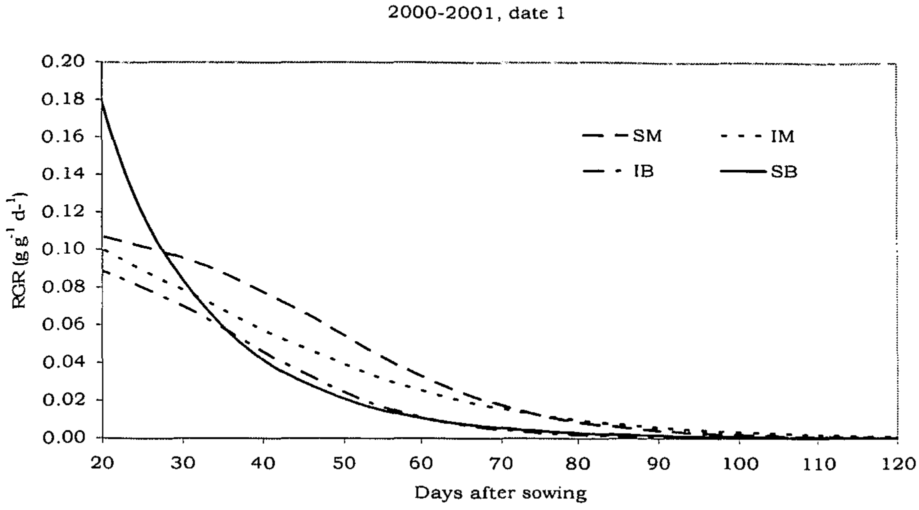


Figure 4.7. Relative growth rates calculated from Richards curve fits on above ground biomass for season 2000/01, planting 1.

Experiment 1 (2000-2001), planting date 2

The SM and IM had a higher relative growth compared to the bean crop. The trend of RGR for SM and IM were almost similar throughout the season (from 40 DAS) (Figure 4.8). The RGR for bean showed a similar pattern with the SB having a higher but constant RGR (~0.09 g g^{-1} d^{-1}) to 75 DAS, while the IB had a lower but constant growth (~0.07 g g^{-1} d^{-1}) up to 90 DAS after which it declined toward the end of the season (Figure 4.8).

The general trend of RGR during both seasons shows that the sole crops had higher RGR during the earlier growth. The bean crops (sole and intercrop), showed the largest differences in RGR, probably due to the shading and competition experienced by the understorey bean crop.

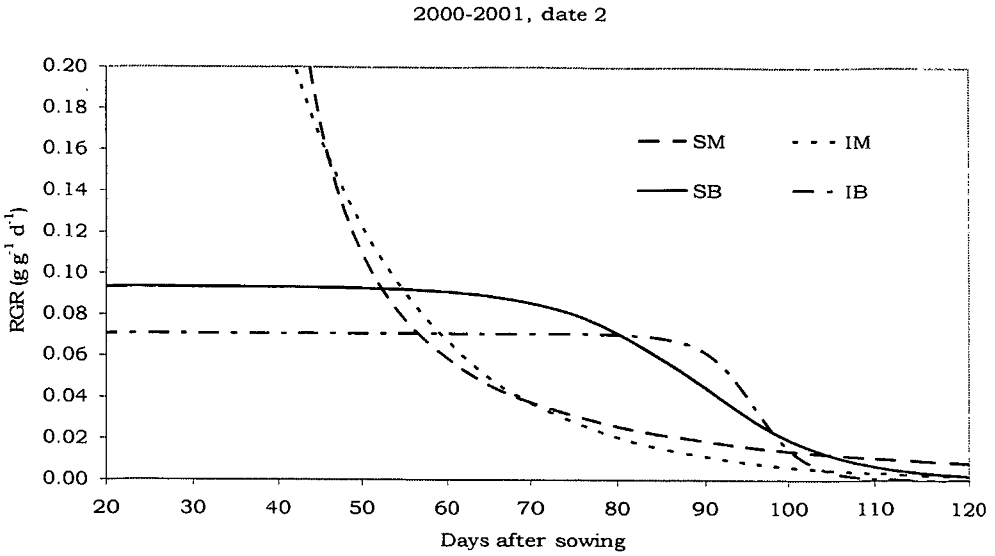


Figure 4.8. Relative growth rates calculated from Richards curve fits on above ground biomass for season 2000/01, planting 2.

Experiment 2 (2001-2002), planting date 1

The season had a more favorable resource availability compared to the first experiment and this can be seen from the generally higher growth rates attained by the estimates. The maize crop grew much taller and this had a marked effect on the growth of IB crop. IB had the highest RGR to 50 DAS after which it declined while the SB showed a gradual decline right from 20 DAS towards the end of the growing season. The SM and IM on the other hand showed a similar RGR throughout the season. The maize crop had a lower RGR compared to beans to 55 DAS after which the rates of increase were almost similar (see Figure 4.9).

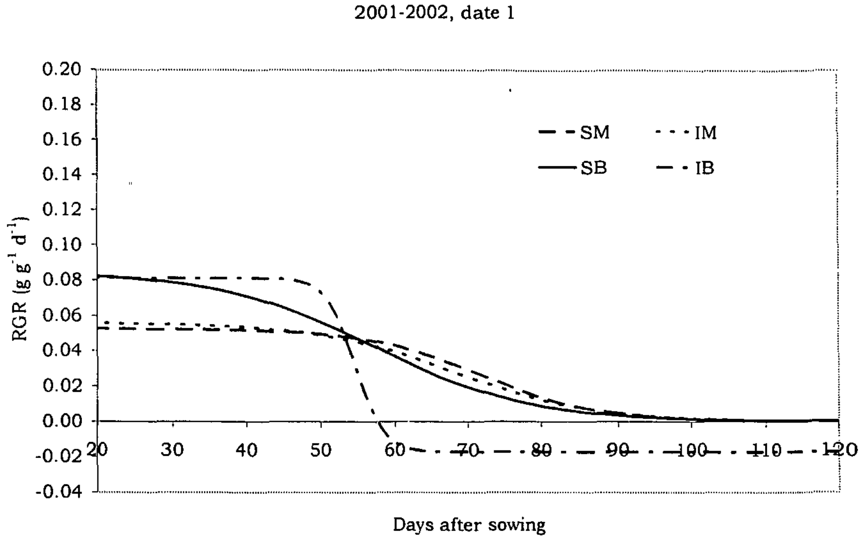


Figure 4.9. Relative growth rates calculated from Richards curve fits on above ground biomass for season 2001/02, planting 1.

Experiment 2 (2001-2002), date 2

SB and IM had a higher RGR, which declined sharply between 35-40 DAS and then gradually to end of the growing season. SM had a lower RGR, which converged with that of the IM and SB at 45 DAS and then was more or less similar towards the end of the season. The lowest growth rate was exhibited by the IB which had a constant relative growth rate from 20-60 DAS, declined sharply to 70 DAS, and remained constant at zero RGR to end of the season (Figure 4.10).

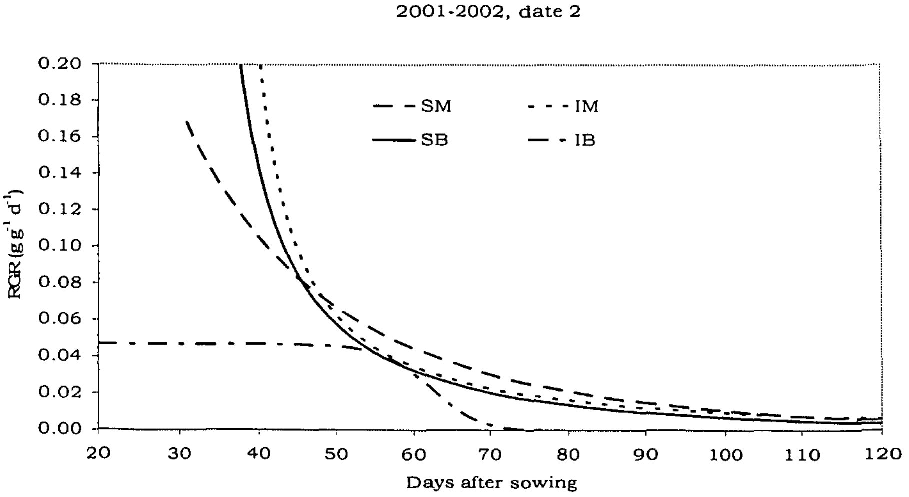


Figure 4.10. Relative growth rates calculated from Richards curve fits on above ground biomass for season 2001/02, planting 2.

4.4. Leaf area growth

Experiment 1 (2000/2001), planting date 1 and 2

Maize leaf area index (LAI) for sole and intercrop did not differ significantly during the first and the second planting dates (p-value > 0.05). The same was noted for the sole and intercrop beans during the two planting dates. Comparisons between the other leaf areas did not show significant statistical differences except for the combined intercrop maize and beans and sole beans during planting date 1 (p = 0.021). The combined leaf area development for the intercrop was higher compared to the sole crops during both planting dates. During the cooler part of the season during date 2, an even much higher LAI was exhibited compared to date 1 which experienced higher air temperatures (Fig. 4.11a & b).

Experiment 2 (2001/2002), planting date 1 and 2

The leaf area index development during the 2001/2002 season (planting 2) was analyzed for statistical differences during the various harvest dates. Leaf area development for maize during the first three harvests showed no statistical difference after which there was fluctuation in the LAI (53, 67, 74 DAS). The beans leaf area development showed no significant difference except for 53 DAS (4.11 c & d).

The combined intercrop leaf area index was higher than both of the sole crops. A leaf area index of 2 and even higher was achieved within 40 DAS. An earlier and higher leaf area index was therefore observed for the intercrop compared to the sole crops during both planting dates.

In general season 2 attained a higher LAI early in the season compared to season 1. This was because season 1 experienced water stress compared to season 2. This can also be seen in Figure 4.11b and 4.11c which had better rainfall amounts and distribution and therefore attained higher LAI, compared to Figures 4.11a and 4.11d. Figure 4.11 (a-d) provides a visual summary of the progress of leaf area growth during the seasons and planting dates.

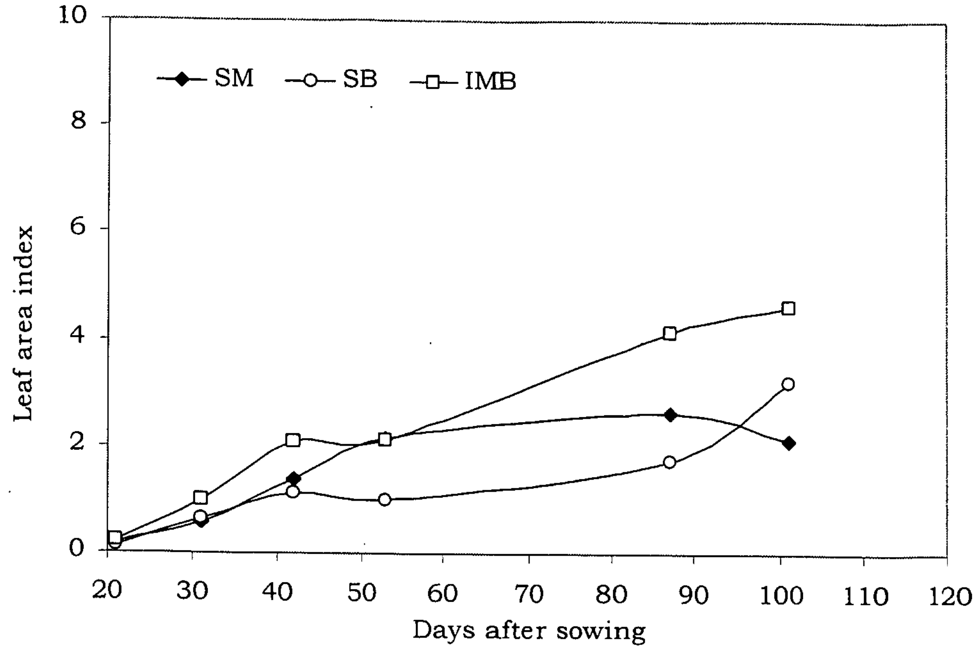


Figure 4.11a. Leaf area index for sole maize, sole bean and intercrop during the 2000/01, planting 1.

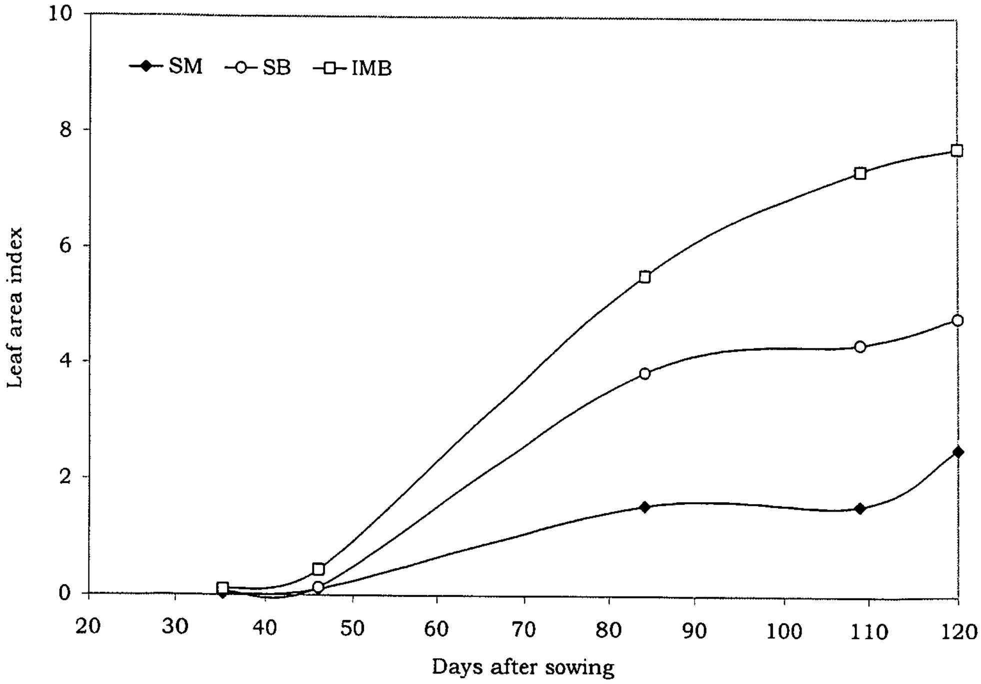


Figure 4.11b. Leaf area index for sole maize, sole bean and intercrop during the 2000/01, planting 2.

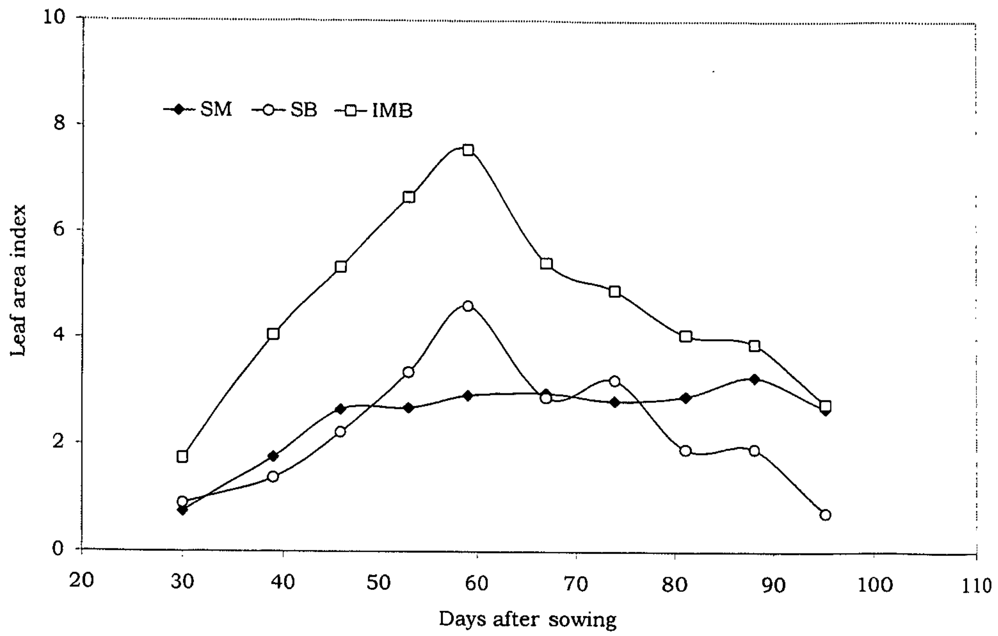


Figure 4.11c. Leaf area index for sole maize, sole bean and intercrop during the 2001/02, planting 1.

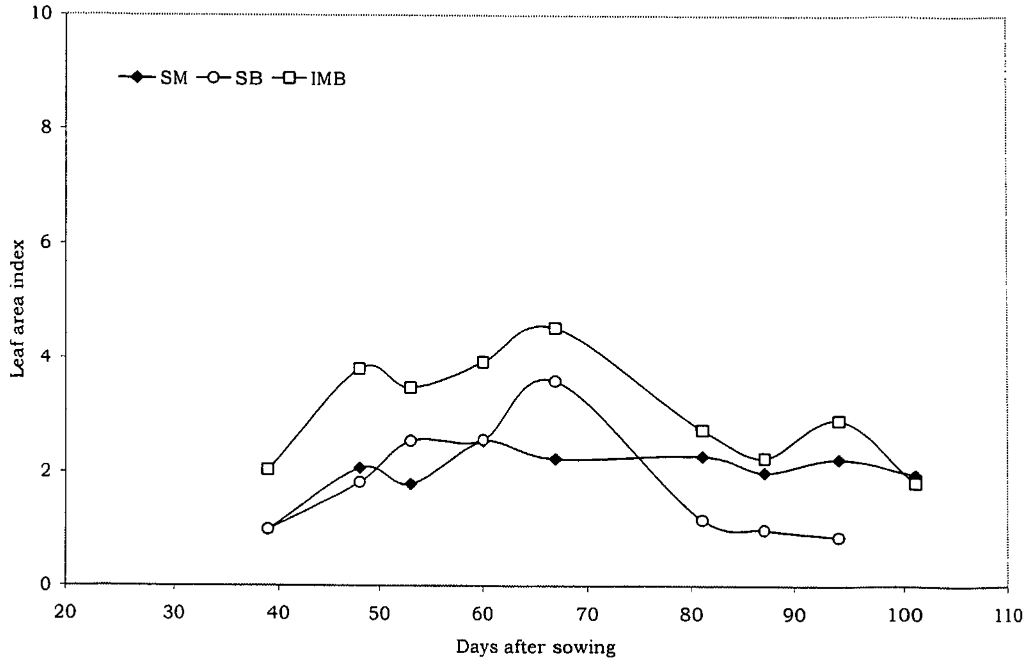


Figure 4.11d. Leaf area index for sole maize, sole bean and intercrop during the 2001/02, planting 2.

4.5. Maximum plant height

The maximum plant heights for maize and bean species were determined during the two cropping seasons.

Experiment 1 (2000-2001), planting date 1 and 2

During planting 1 the maximum heights for the various treatments were measured. The sole crop maize attained a height of 166.2 ± 14.10 cm (n=15; 3 replications), the intercrop maize 145.70 ± 6.44 cm, sole bean 47.08 ± .10 cm and intercrop bean 47.97 ± 2.51 cm (Figure 4.12). The sole maize maximum height during planting 2 , 159.76 ± 11.06 cm, intercrop maize 155.80 ± 10.76 cm, sole bean, 36.25 ± 3.20 and intercrop bean 48.75 ± 3.09 cm. The total number of plants sampled during each measurement was 12 (i.e n=12) (Figure 4.12).

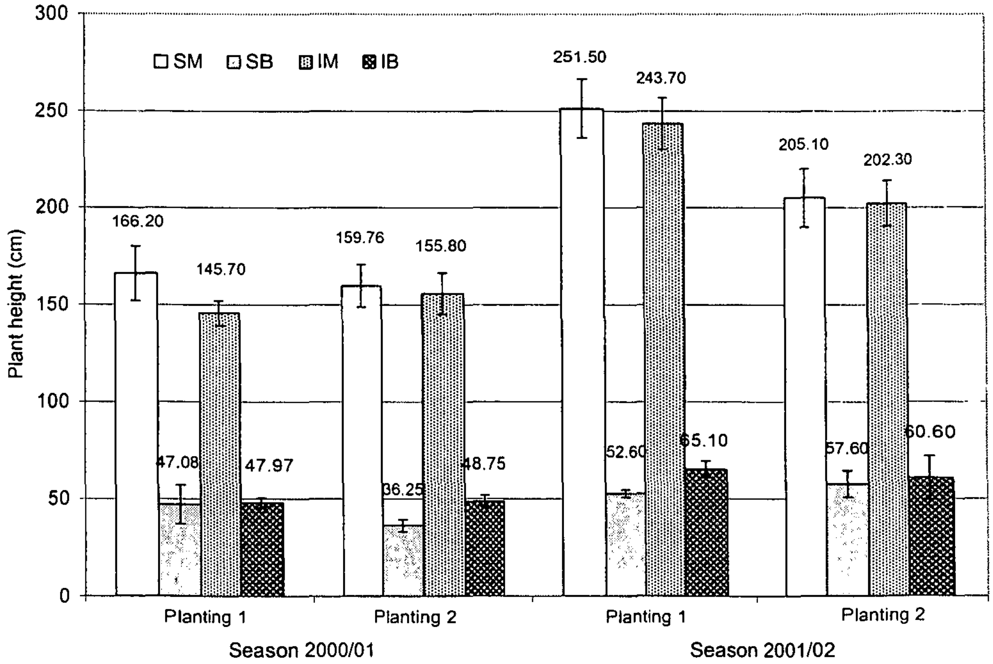


Figure 4.12. Maximum plant heights attained during all seasons and planting dates for the cropping systems.

Experiment 2 (2001-2002), planting date 1 and 2

Maximum plant heights for the crops were monitored during the season for the sole and the intercrop. During the Experiment 2, date 1 the crop maximum heights were sole maize: 251.5 ± 15.2 cm, Intercrop maize: 243.7 ± 13.2 cm, sole bean:

52.6 ± 1.81 cm and intercrop bean: 65.1 ± 4.19 cm. The plant heights for the second planting were, sole maize: 205.1 ± 15.2 cm, intercrop maize: 202.3 ± 11.7 cm, sole bean: 57.6 ± 6.8 cm, intercrop bean: 60.6 ± 11.3 cm. The heights were determined from three replications and 12 samples in total. The treatment and seasonal variation in plant heights is shown in Figure 4.5.

The results show that the sole maize crop attained a higher maximum stem growth than the intercrop maize for both dates. This is most likely due to the water availability during the different planting dates. The season 2001/02, which had better amount as well as distribution, gave taller plant. It is of interest to note particularly the differences in the maximum height of the bean species in the two treatments. The intercrop bean growing below the canopy of the maize was taller than the sole bean during the two planting dates. Experiment 2 performed better in terms of stem growth than Experiment 1.

4.6. Yield, Land and Income equivalent ratios

The grain yield for both seasons and planting dates are shown in Table 4.2. The intercrop maize showed the highest fluctuation at 67% followed by intercrop bean. The sole maize and bean had the lowest fluctuation at 49.7% and 48.3% respectively.

The ANOVA showed that the mean yields for maize was better during first planting date compared to the second planting date. However, there was no significant difference between the two planting dates at alpha = 0.05 (F-ratio = 0.02; probability level = 0.89). The analysis show that the sole maize performed significantly better than the intercrop maize at alpha = 0.05 (F-ratio = 256; probability level = 0.03). The analysis also indicates that the mean yields for SM and IM were better during the first planting date compared to the second date.
The mean yields for beans were better during second planting date compared to the first planting date (alpha = 0.05; F-ratio = 0.15; probability level = 0.72). SB performed better than IB with better mean grain yields at alpha = 0.05 (F-ratio = 2.53; probability level = 0.36). The mean yields for SB was higher during date 1 compared to date 2. On the other hand the IB performed better during date 2 compared to date 1.

Table 4.2 Seed yield in metric tonnes per hectare for the various cropping systems (sole- and intercropping) during the two seasons and plantings.

Cropping system	Planting Date	2000/01	2001/02
SM	1	2.49 ± 0.14	4.96 ± 0.26
SM	2	3.41 ± 0.47	4.49 ± 0.53
SB	1	1.69 ± 0.47	2.88 ± 0.21
SB	2	1.74 ± 0.49	1.49 ± 0.24
IM	1	1.34 ± 0.15	4.01 ± 0.39
IM	2	1.66 ± 0.54	3.86 ± 0.24
IB	1	0.88 ± 0.47	1.06 ± 0.13
IB	2	1.89 ± 0.54	0.74 ± 0.08

(mean ± standard error)

The land equivalent ratio during both seasons was greater than unity. Table. 4.3 shows the partial land equivalent ratios for beans (LER_B), maize (LER_M) and the total land equivalent ratio (LER_T) for the different planting dates as calculated based on grain yield data. This shows that the intercropping system was more effective and efficient than the sole crops in the use of environmental resources. The highest LER_T was in season 2000/01 planting 2 at 1.57. The variation in LER_T was 33% during the four planting dates. There was considerable fluctuation in yield of the bean species with the maximum yield reduction due to intercropping of 50%, while season 1, planting 2 exhibited a 15% yield increase for beans due to intercropping.

Table 4.3. The partial and total land equivalent ratios during the seasons 2000/01 and 2001/02 and various planting dates.

Year	Planting	LER_B	LER_M	LER_T
2000/01	1	0.52	0.54	1.06
2000/01	2	1.09	0.49	1.57
2001/02	1	0.37	0.81	1.18
2001/02	2	0.50	0.86	1.36

The LER_B for planting date 2 were higher than those for planting date 1 due to the cooler part of the growing season which supported growth of the C3 species (beans) compared to the C4 species (maize). Season 2000/01 intercrop bean exhibited a 9% higher yield compared to the sole cropped bean.

Adopting the long-term price ratios between the bean and maize of 5.5:1 an income equivalent ratio was calculated for the intercrop. The IER_T was not different from LER_T as the maize: bean price ratios were uniform for the intercrops and the sole crops.

4.7. Conclusion

Environmental factors including temperature and soil water played a key role in cropping system growth. Water especially was critical as rainfall which was erratic and in most cases low was the source for soil water during the seasons. Competetion for environmental resources was therefore likely to influence treatment differences in a substantial way (e.g between sole maize and intercrop maize or sole bean and intercrop bean). Such competetion could be for radiationt nutrient and water resources. The results indicate that under certain conditions the sole and intercrop species growth can be similar (e.g Experiment 1, date 1 sole bean and experiment 2, date 1 intercrop bean).

The intercrop had a higher leaf area index, most likely due to the additive sowing scheme adopted. This made it possible for the intercrop to intercept more radiant energy. It also enabled the intercrop to reduce the amount of water lost from the soil surface under the canopy due to evaporation.

Higher yields have been reported in the past in maize and bean mixtures. It was concluded that higher yields were due to the more complete utilization of environmental resources by the mixtures compare to the sole crops (Willey & Osiru, 1972). This yield has been assessed using the LER_T index in most cases.

Mukhala *et al.*, 1998 reported an LER_T of up to 1.26 ($LER_B = 0.28$, $LER_M = 0.87$) for the medium density trial at the same site. This density was almost similar to what was adopted in this trial except the cultivars and sowing patterns differed. That experiment received supplemental irrigation as opposed to rainfall in this experiment.

Tsubo (2000) conducted his experiment on the same crop combinations and found an LER_T of 1.09. ($LER_B = 0.09$, $LER_M = 1.00$), Tsubo (2000) experiment, however, benefited from full irrigation application. Oljaca *et al.*, 2000 conducting a study on plant arrangement and irrigation on maize and bean intercropping reported an LER_T of 1.54 for proportion 0.5:0.5 of maize and beans. Pilbeam *et al.*, 1994 did a study under semi-arid conditions such as experienced at this site. They observed a higher yield advantage with an LER_T of 1.21 ($LER_M = 0.74$, $LER_B = 0.28$). These examples indicate that this crop combination can confer yield advantages under various conditions.

The intercrops evidently performed better during both experiments with LER_T and IER > 1 in all planting dates. The mean intercrop LER_T was 1.29, showing a yield advantage by the cropping system. There was a substantial amount of fluctuation in the LER value between the two seasons and various planting dates.

Mohta and De (1980) and Ofori and Stern (1987) noted yield increase in soybean by 31% when components were arranged in double alternate rows relative to single alternate rows. Singh (1981) found that a wider row for the taller component produced a higher LER compared to narrow spacing. Ofori and Stern (1987) report that light penetration was markedly increased in wider row arrangement using 60 cm (52% of incoming radiation) and 90 cm (70% of incoming radiation) respectively. It can be said that the additive sowing regime with double rows of beans, wider row spacing (1 meter), simultaneous planting, a shorter maturity period maize cultivar resulted in yield advantage for the intercrop within the ecotope. The yield for the beans had a higher variability than the maize. This may have been due to the water availability and higher temperatures causing serious stress at particular times during the growing periods. The double row spacing, east west orientation and the shorter maize cultivar may have resulted in more efficient radiation utilization.

Chapter 5

Physiological and Microclimatic Basis of Precipitation Use Efficiency

5.1. Introduction

Studies of the microclimate of cropping environments involve the consideration of a number of variables including humidity, radiant energy flux, wind and temperature. Lemon (1983) noted that the aerodynamic properties of crop canopies can have a substantial effect on the efficient use of water by that crop. He reported that ambiguities concerning water vapour transport at the soil surface and in the canopy itself exist. Cionco (1983) noted that once the water vapour moves out of the domain of the soil surface or leaf surface, but is not yet out of the canopy boundary layer, the transfer of water vapour is controlled by the complex aerodynamic processes influenced by the vegetative canopy properties. Cionco *et al.* (1963) formulated a canopy flow model of roughness elements using assumptions of uniform leaf area distribution, vertical drag distribution of canopy elements and drag coefficients independent of the Reynolds number. The resulting flow within the canopy produces a relationship in which the windspeed is an exponential function of canopy height. Inoue (1963) also suggested an exponential wind profile relationship in the canopy, with windspeed as an exponential function of height; and mixing length constant with height except near the ground; and turbulence intensity constant with height. This formulation was acceptable for simple canopies where only vertical variations were important. Cionco (1978b) conducted a study of variations in turbulence intensity with canopy density and types and confirmed that a level of turbulence within canopies can be inferred from the canopy density and type. It was shown that there was an orderly increase of averaged turbulence intensity with density and structural complexity, and that turbulence was higher in warmer than in cooler weather. Cionco (1978a) provided an in-depth discussion of coupling of the canopy flow to ambient air, and noted that it essentially related to the density and type of canopy, with the more dense and complex canopies having lower coupling to the ambient air. Wallace *et al.* (1995) and Brenner (1996) provided evidence of higher humidity within an agroforestry system of *Gravillea robusta* and maize understorey component than the free atmosphere above it. Monteith (1995) discussed the accommodation between transpiration and the convective boundary layer and noted that latent heat exchange is a major component of the energy budget of vegetation. Therefore accommodation by plants in terms of water supply and demand is closely coupled to the processes of thermal accommodation by the lower atmosphere. Mixing of water vapour within and above vegetation occurs due to convection. One type of convection is through buoyancy, involving rising eddies of light warm air countered by the downward flux of cold or dry air. A second type of convection occurs with turbulence created by interaction between lateral wind and vegetation. Buoyancy and wind turbulence can involve a great depth of the atmosphere in mixing, thus involving all the air properties such as water vapour, carbon dioxide, temperature and oxygen. It has been noted that agroforestry and intercropping systems may confer microclimatic advantage in terms of water use efficiency due to the decrease of air temperature, windspeed and saturation deficit experienced by understorey crops, thereby reducing evaporative demand (Monteith *et al.*, 1991).

Higher plants intercept incident radiation using their foliage, utilize the intercepted radiant energy for photosynthesis and convert the photosynthetic products into the accumulation of plant biomass. The quantification of radiation interception and use is important as radiant energy is a key variable driving plant growth and productivity. The use of radiant energy to produce chemical energy and then its transformation into plant biomass has been studied by many researchers. de Wit (1958) and Loomis and Williams (1963) conducted some of the first analyses of increase in crop biomass in response to the amount of radiation. Shibles and Weber (1965) found a linear relationship between dry matter increase and the fraction of radiation intercepted through the entire growing season for soyabean. Monteith (1977) presented the first theoretical analysis leading to predictions of radiation use efficiency (RUE). Sinclair and Muchow (1999) provided a detailed review of radiation use efficiency. The studies show a positive correlation between plant biomass production and intercepted radiation by sole crops (Shibles and Weber, 1966; Monteith, 1977; Kiniry *et al.*, 1989) and intercropping systems (Natarajan and Willey, 1980b; Sivakumar and Virmani, 1980; 1984). Detailed reviews of radiation interception by intercrop and agroforestry systems are given by Keating and Carberry (1993) and Ong *et al.* (1996). A major challenge of radiation interception and use among intercrops is its partitioning by component crops. Estimation of radiation interception by crop components in an intercrop is rare. Marshall and Willey (1983) divided the radiation within a millet/groundnut intercrop into that captured by each species using quantum sensors above and below the sole crop and intercrop canopies. They found a higher capture of PAR by the intercrop millet compared to the sole millet and a lower capture by the intercrop groundnut compared to the sole groundnut. Azam-Ali *et al.* (1990) found a similar pattern in a sorghum/groundnut intercrop. Detailed and theoretical treatment to quantify radiation interception in a mixed crop canopy has been given by Wallace *et al.* (1990) using a cane-maize intercrop as an example. Radiation interception and use by intercrops is often investigated for the system as a whole (Willey, 1990). As in other ecological studies (Long, 1934; Golley, 1961) the use of energy value can be adopted in intercropping to convert the dry matter to a caloric energy value (Tsubo *et al.*, 2001). RUE may then be expressed as percentage of the energy value of plants per radiant energy captured by the plants, which is often referred as growth efficiency (Gallagher and Biscoe, 1978; Fasheun and Dennett, 1982; Tsubo *et al.*, 2001).

As with sole crops, most analyses of radiation interception by intercrops apply various forms of Beer's law to the penetration and interception of radiation. Azam-Ali and Squire (2002) discuss the application of Beer's law to the case of replacement and additive intercrops. Studies of precise estimates of the extinction coefficient, k for intercrop and component canopies are scarce, as is the estimate of the extent to which k changes between the sole crops and intercrops. Sivakumar and Virmani (1984) reported no significant difference between k values for sole maize (0.64 ± 0.11), sole pigeon pea (0.69 ± 0.26) and an intercrop (0.66 ± 0.07) whose LAI consisted of 2/3 maize and 1/3 pigeon pea. Wallace *et al.* (1990) found a k value for a mixture of sugarcane and maize intermediate between that of the sole crops (mixture: 0.5; sugarcane: 0.26 and maize: 0.6).

Szeicz (1974a) found k-value for field beans of 0.38 while Fasheun and Dennett (1982) found values ranging between 0.32 and 0.48 (for total solar radiation) when the leaf area index for field beans exceeded 4. Similar trends of k for field beans were reported by Szeicz (1974b) for both PAR and infrared radiation. Coulson (1985) on the other hand reported very high k values based on PAR attenuation for three different dry bean cultivars ranging between 0.83 and 2.01. Azam-Ali and Squire (2002) note that there is no widely accepted method for calculating k value of any particular species within different forms of intercrop (replacement or additive), nor of comparing it with its typical value within a sole stand. They conclude that there are still difficulties of describing radiation attenuation within heterogeneous populations even sole crops.

It has been noted that RUE is not conservative with stress (Azam-Ali *et al.*, 1989; Hughes and Keating, 1983; Shibles and Weber, 1966), especially water stress that is common when crops depend on rainfall in semi-arid environments. Adverse environmental conditions may reduce RUE due to the adverse effect on photosynthetic activity. Water stress has been documented to increase carbon partitioning to the roots (Blum, 1988; Wilson, 1988) which is normally excluded from RUE calculations. A similar situation may occur due to nutrient stress (Wilson, 1988). A major strength of RUE determined under stressful situations is that it can be used to quantify the impact of stress. Simple models in which the impact of water deficits has been related directly to RUE, crop growth and yield have been successful in simulating growth of soybean (Muchow and Sinclair, 1991), maize (Muchow and Sinclair, 1991) and wheat (Amir and Sinclair, 1991). Large within species variability in RUE has been reported for a number of species growing with no water stress (Kiniry *et al.*, 1989).

The objective of this chapter was to attempt to characterize the microclimate of the cropping systems by quantifying the vapour pressure deficit and PAR within the canopies. This was with a view of elucidating microclimatic factors which may influence the water use and efficiency by the cropping systems.

5.2. Definitions

5.2.1. Radiation

The fraction of intercepted radiation (FI) is defined as the ratio between the radiation intercepted by plants and the incident photosynthetically active radiation (PAR) above the canopy (Monteith, 1977; Sinclair and Muchow, 1999) and is presented as follows:

$$\mathrm{FI} = \frac{\sum_{i=1}^{n} \Phi_{\mathrm{PAR}^{i}}}{\Phi_{\mathrm{PAR}}} \tag{5.1}$$

where n is the number of plant species, Φ_{PAR} is the flux density of incident PAR above the canopy and Φ_{PAR^i} refer to the flux density of PAR intercepted by each of the plant species i.

Due to mutual shading among leaves, PAR interception by a foliage canopy is a diminishing returns function of leaf area index. By comparing leaf area and PAR interception in successive horizontal strata beginning at the top of a canopy, PAR flux can be related to the leaf area above it and PAR incident at the top of the canopy (Φ_{PAR}). This relationship can be represented by an analytical expression, the Bouquer-Lambert Law (Monsi and Saeki, 1953):

$$\Phi_{PAR} = \Phi_{PAR^i} \exp(-kLAI) \tag{5.2a}$$

and

$$\ln\left(\frac{\Phi_{PAR}}{\Phi_{PAR^i}}\right) = -kLAI \tag{5.2b}$$

where k is the extinction coefficient, which relates to the fraction of the PAR intercepted per unit leaf area index (LAI).

Radiation use efficiency (RUE) is the ratio between the chemical energy stored and the radiant energy intercepted by the plants (Gallagher and Biscoe, 1978) and can be represented as follows:

$$RUE = \frac{\sum_{i=1}^{n} NiE_{BY^i}}{\sum_{i=1}^{n} \Phi_{IPAR^i}} \tag{5.3}$$

where Ni is the density of plant species i, E_{BYi} is the chemical energy stored in biological yield (above ground dry matter) of plant species i, and is referred to as growth efficiency (Gallagher and Biscoe, 1978).

5.2.1. Vapour pressure deficit

See chapter 3, section 3.2.3 for the definitions and calculations involved in the vapour pressure deficit

5.3. Results and Discussions

5.3.1. Atmospheric vapour pressure deficit

The vapour pressure deficit represents an estimate of the driving force for potential evaporation and is useful in relating biomass to transpiration in plant communities. Table 5.1 shows the variation of vapour pressure deficit during each of the four planting seasons. These values were calculated only for daylight hours when transpiration was actively taking place.

Table 5.1 Seasonal average daytime (7:00-17:00 hours, SAST) weather station vapour pressure deficit (kPa) during the season 2000/01 and 2001/02.

Season	Date	Planting 1	Date	Planting 2
2000/01	23/11-30/03	2.04 ± 0.75	11/01-30/04	1.66 ± 0.86
2001/02	10/12-23/03	1.78 ± 0.66	08/01-30/04	1.26 ± 0.40

The Table 5.1 shows that season 2000/01 had a higher vapour pressure deficit compared to season 2001/02. The first planting season also consistently had a higher evaporative demand than the second planting date. This can be explained due to the declining air temperature in the second planting from January to late April. The second planting dates occurred from January to late April when the mean temperatures were rather low as the period was approaching the winter season.

5.3.2. Mean canopy vapour pressure deficits

The seasonal variation in canopy vapour pressure deficit during the active growing period for each of the various cropping systems are presented in Table. 5.2.

Table 5.2 Mean daytime (7:00-17:00 hours SAST) canopy vapour pressure deficit (kPa) for each cropping system during the various seasons and planting dates.

Treatment	Season 2000/01		Season 2001/02	
	Planting 1	Planting 2	Planting 1	Planting 2
Intercrop	0.45 ± 0.33	0.64 ± 0.87	1.39 ± 0.75	1.13 ± 0.36
Sole Maize	1.25 ± 1.45	1.17 ± 0.95	0.44 ± 0.30	0.87 ± 0.50
Sole Bean	1.53 ± 1.13	0.88 ± 0.99	1.03 ± 0.50	0.67 ± 0.55

Table 5.2 shows that the mean vapour pressure deficit within the canopy for all cropping systems was higher during planting 1 than planting 2. This is in

agreement with the trends of weather station vapour pressure deficit. The mean vapour pressure deficits were 1.02 and 0.89 kPa for the respective planting dates. The treatments exhibited the following mean vapour pressure deficit trend: SB>SM>IMB, with the overall mean values being 1.08, 0.93 and 0.90 kPa respectively. Sole bean experienced the highest variation in vapour pressure deficit during the two experimental years, followed by sole maize and lastly the intercrop. These general trends present a different picture from the individual sowing dates. It was expected that the intercrop would have significantly lower vapour pressure deficits than the sole maize and sole bean cropping systems. This could be due the higher plant density (additive sowing scheme), greater canopy roughness and lower temperature at the soil surface. The crop tends to decrease the windspeeds and therefore the turbulence and free convection within the canopy. The measurements did not present this expected pattern during the second year of the experiment where the D was highest in the intercrop.

Season 2000/01, planting 1 showed a substantially lower canopy vapour pressure deficit in the intercrop compared to the sole maize and sole bean. During planting 2 of the same season the intercrop had a lower canopy vapour pressure deficit than the sole maize and sole bean. However, the sole bean exhibited a lower canopy vapour pressure deficit than the sole maize i.e the bean and maize canopy vapour pressure deficit were reversed. The trend during this season was more in agreement with the expectation and the explanation regarding turbulent transport theory within the canopies. The first season was warmer and therefore had a higher convective exchange and more coupling with the free atmosphere above the crop, making the laminar layer thinner and the air around the canopy elements drier and therefore less humid.

In the subsequent season (2001/02, planting 1) the intercrop had a higher vapour pressure deficit than both cropping systems. During this season the sole maize had the lowest canopy vapour pressure deficit. An almost similar trend was noted during the second planting, but with the sole bean showing the lowest canopy vapour pressure deficit.

During the 2001/02 season, the intercrop was expected to have a lower vapour pressure deficit compared to the 2000/01 season given the slightly lower temperature, due to higher rainfall. Wind speed was not measured within the canopy during the experiment. The shelter effect of intercrops has been reported as major impedance on wind movement within such canopies making them more humid (assuming soil water is not limiting) due to less mixing given that the stand was vertically heterogeneous and plant density greater. With less mixing the laminar layer surrounding the leaves is relatively thicker within the intercrop, therefore, stomatal resistance is expected to be lower, effectively enhancing evapotranspiration assuming soil water is not limiting. Stomatal resistance varies depending on the stomatal aperture, which is related to radiation intensity and leaf water potential and leaf temperature as these crop are rainfed, they suffered under continual water stress, therefore it is expected that during the season either leaf water potential or leaf temperature may have been a major factor in controlling stomatal activity and therefore decreasing transpiration by the crops.

The measurements for wet and dry bulb temperature were done within the 200-400 mm height above the ground and between plant rows at a distance of about 10 m (fetch requirement was 0.01 x 10 m = 0.1m above the surface) from the edge of the plot (see size of plot in Chapter 2). This distance was considered near adequate for such measurement, although it is suspected that fetch requirements may not have been adequately met due to the roughness of the intercrop canopy.

5.3.3. Comparison of mean daytime and diurnal vapour pressure deficits

An example of the seasonal vapour pressure deficits within the three cropping systems and the weather station is shown in Figure 5.1. The trend was more or less the same for each one during the season (Figure 5.1). The weather station and SM had higher vapour pressure deficit than the SB and IMB. IMB had the lowest mean daytime vapour pressure deficit as can be seen from the Table 5.1 during the season. SM and AWS also exhibited a higher fluctuation of vapour pressure deficits compared to the SB and the IMB.

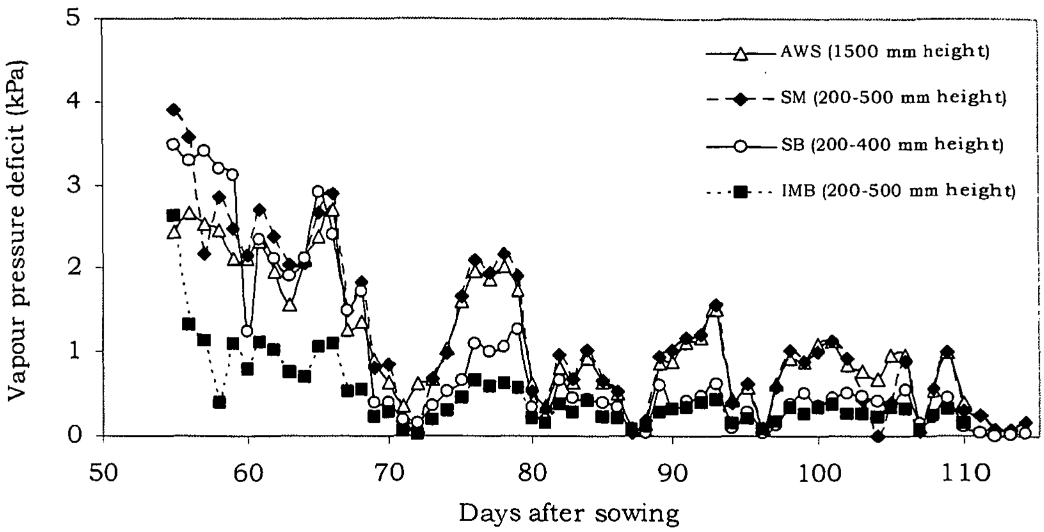


Figure 5.1. Mean daytime (7 am - 5 pm) vapour pressure deficits within crop canopies and at the weather station during season 2000/01, planting 2 season

Figure 5.2 shows a representative day of the diurnal changes in vapour pressure deficit during the late vegetative stage for SM and the reproductive stage of the beans during season 2000/01, planting 1, 56 DAS. The day was warm with fairly high windspeed (2.2 m s^{-1}), mean solar radiation (240 W m^{-2}), ETo (Penman-Monteith of 6.2 mm d^{-1}), Maximum and minimum temperature of 31.5 and 20.6 °C respectively. The SM had the highest vapour pressure deficit followed closely by the SB. The IMB had substantially low vapour pressure deficit especially during the warmer part of the day.

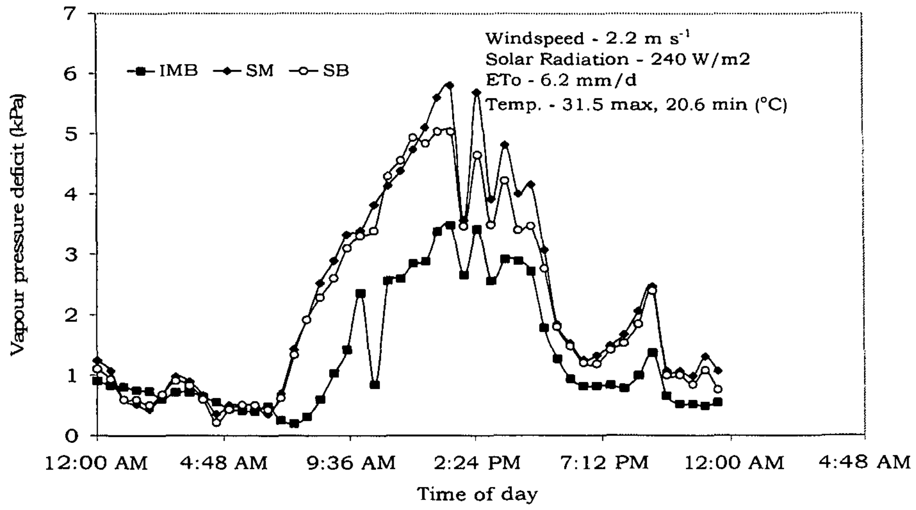


Figure 5.2. Diurnal vapour pressure curves for the cropping systems during the season 2000/01, planting 2, 56 DAS (Maize: late vegetative stage; Beans: reproductive stage)

The Figure 5.3 shows the diurnal changes in vapour pressure deficit during the season 2001/02, planting 1, 20 DAS. The day was warm with the following weather condition: solar radiation: 369 Wm-2; maximum and minimum temperature: 31.7 and 16.8 °C; windspeed; 1.8 m s^{-1} and ETo: 8.6 mm d^{-1}. The day had higher evaporative demand. The cropping systems vapour pressure deficits were not very different at this time as the crop was still in the early vegetative stages of development and the canopies were rather open and more coupled the atmospheric boundary layer above. The IMB had a slightly lower vapour pressure deficit compared to the other cropping systems given that its density was higher and at this time it was actively transpiring as it was not experiencing stress. The crop heights were more or less similar at this time and therefore most likely influenced the wind movement in a similar manner.

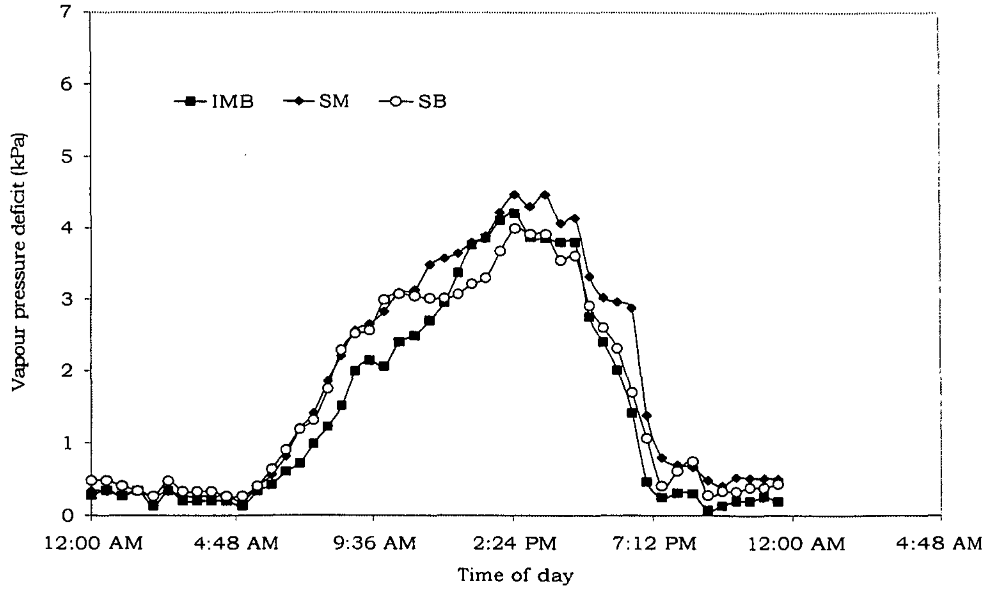


Figure 5.3. Diurnal vapour pressure curves for the cropping systems during the season 200/02, planting 1, 20 DAS (Maize and beans: early vegetative stage)

These examples exhibit variations in the vapour pressure deficits within the canopies during the development stages of the cropping systems. The early stages show little difference between the vapour pressure deficits compared to the later stages when the intercrop show more humid canopies compared to the sole maize and sole bean crops.

5.3.4. Seasonal radiation interception and leaf area

Analysis of the seasonal PAR interception was done for each of the seasons 2000/01 and 2001/02 during the first planting. The intercrop had a higher fractional interception of PAR during season 2000/01, planting 1 (Figure 5.4), compared to the sole maize and bean, with the interception being relatively higher from 40 DAS until the end of the season. The sole maize had the lowest interception throughout the growing season. Sole maize interception peaked at 60 DAS and remained constant to 90 DAS and then declined mainly due to senescence. The intercrop and sole beans had an interception that was increasing until the end of the season due to the nature of the bean growth which is indeterminate.

The leaf area development is discussed in Chapter 4 and in all cases the intercrop had the highest leaf area index. This was due to the fact that the intercrop was planted as an additive one and therefore had the full complement of both of each the sole crops.

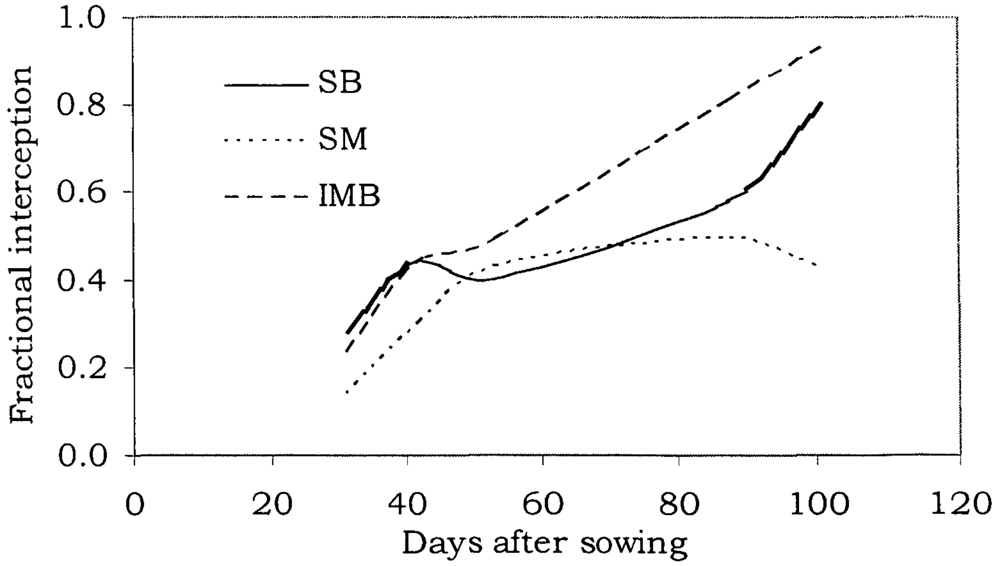


Figure 5.4. Fractional interception of PAR within the cropping system during the 2000/01, planting 1 from measurements made at the soil surface.

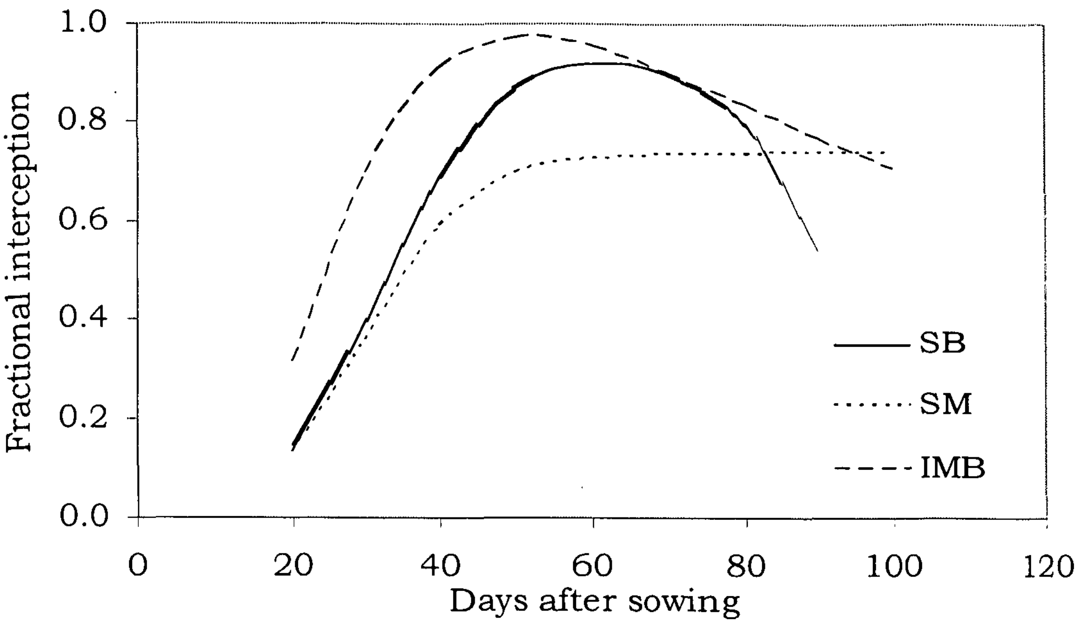


Figure 5.5. Fractional interception of PAR within the cropping system during the 2001/02, planting 1 from measurement made at the soil surface.

During the 2001/02, planting 1 the intercrop exhibited a higher PAR interception compared to the sole maize and sole bean from the beginning to end of the season (see Figure 5.5). The sole bean had a similar interception as the sole maize at the beginning of the season, but overtook the sole maize at about 30 DAS until almost 90 DAS. The sole maize interception levelled off at 50 DAS when the maize reached the peak of the vegetative phase to the end of the measurement.

Season 2001/02, planting 1 had a higher actual PAR interception compared to 2000/01, planting 1, as the season overall had more favourable growing conditions (lower temperatures, vapour pressure deficit and better rainfall distribution).

5.3.5. Attenuation of PAR within cropping systems

The relationship between radiation interception and leaf area for season 2000/01, planting 1 is shown in Figure 5.6. There was good correlation between the natural log of radiation transmission and leaf area index (LAI) in all the cropping systems (R^2 >0.75). The slope is referred to as the extinction coefficient (k), and explains the average projection of canopy elements onto a horizontal plane (Campbell and Norman, 1989).

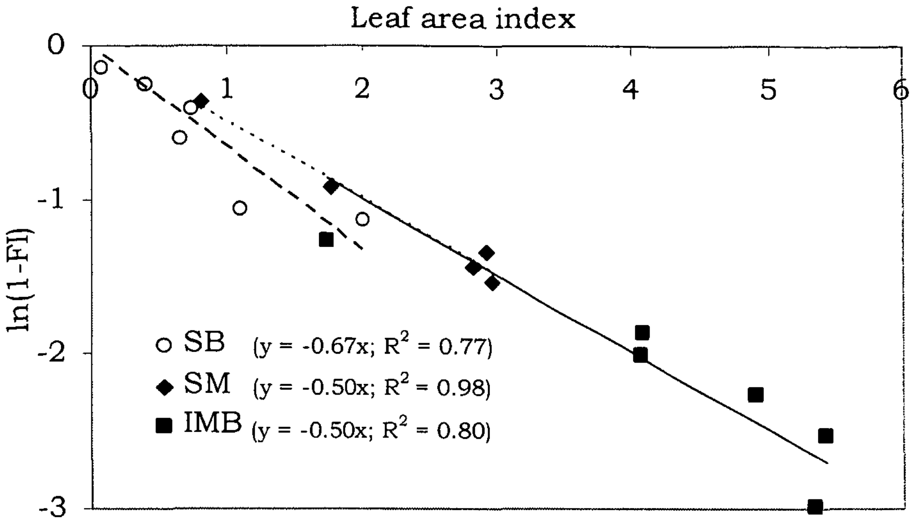


Figure 5.6. The extinction coefficient of PAR for sole maize, sole beans and intercrop canopies for season 2000/01, planting 1.

The canopies were characterized by the following extinction coefficients during season 2000/01, planting 1: sole maize: 0.52, sole bean: 0.67 and the intercrop: 0.82 (Figure 5.6). The extinction coefficient depends on the architecture of the crop. A crop with erect narrow leaves tends to have lower extinction values than those with more horizontally displayed leaf arrangements. k values vary between 0.3 to 1.5 with k values less than 1.0 normally represent non-horizontal or clumped leaf distributions, while k values greater than 1.0 being obtained for horizontal or regular leaf distributions (Jones, 1992). The range of extinction coefficients reported for maize is 0.56-0.78 (Azam-Ali *et al.*, 1994).

During the 2001/02, planting 1 the extinction coefficient for cropping systems was as follows: sole maize (0.52), sole bean (0.65) intercrop (0.82) (Figure 5.7). Tsubo (2001) found extinction coefficients for the cropping systems as follows: sole maize (0.43); sole bean (0.64) and intercrop (0.45). During the experiment conducted by Tsubo *et al.* (2001) the crops were supplied with sufficienct w ater and never experienced any stress, the cultivars used were also different from the ones used in this study (e.g. Maize: SNK 2147; Bean: PAN 127).

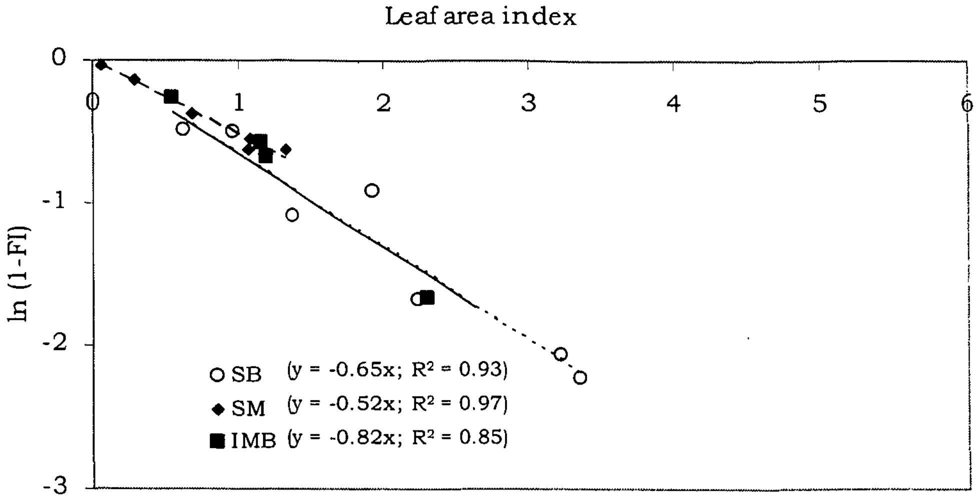


Figure 5.7. Extinction coefficient of PAR for sole maize, sole beans and intercrop canopies for season 2001/02, planting 1

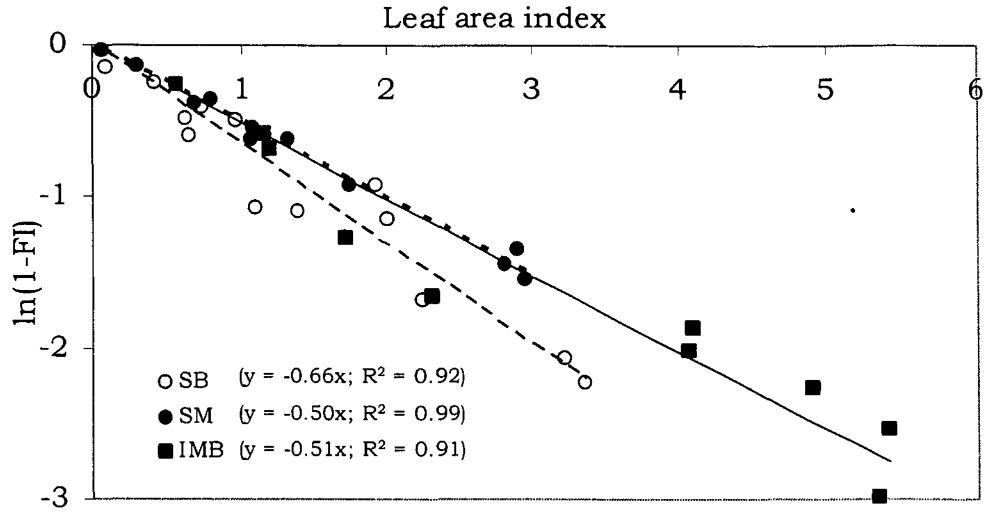


Figure 5.8. Combined extinction coefficient of PAR for sole maize, sole beans and intercrop canopies for seasons 2000/01 and 2001/02, planting 1

Figure 5.8 represents the combined k - value for both seasons and shows that the sole bean had a higher value (0.66), followed by the intercrop (0.51) and lastly sole maize (0.50). The sole bean k-value was closer to that found by Tsubo (2000) of 0.64, while those for sole maize and the intercrop were higher than his k-values of 0.43 and 0.45 respectively. Azam-Ali and Squire (2002) presented ranges in the value of k reported in literature for maize (0.56-0.78), soybean (0.45-0.96), and groundnut (0.40-0.66). The values found by this study falls close to these ranges for both the cereal (maize) and legume (bean) crops.

5.3.5. Plant energy and intercepted radiation

Conversion of the plant above ground dry matter to plant energy value was done from conversion factors determined by Tsubo *et al.* (2001). The mean energy content for maize and beans determined through calorimetry during that study gave mean values of 17.0 ± 0.9 kJ g^{-1} and 16.7 ± 0.9 kJ g^{-1} for maize and beans respectively. These values fall within the range found by other studies (Lieth, 1968, 1975; Ovington and Lawrence, 1967). Plant energy was calculated using the above conversion factors. The relationship between the cumulative PAR energy intercepted and resultant plant energy gave a very high correlation ($R^2 > 0.80$) during the 2000/01, planting 1 season (Table 5.3 and Figure 5.9). The sole maize RUE was 0.012, sole bean, 0.005 and the intercrop 0.013 (8% higher than SM). Sole bean had RUE 57% less than that of sole maize and 60% less than the intercrop. Squire (1990) note that mixed canopies of C4 and C3 species have a RUE similar to or slightly greater than the sole cereal alone, and much greater than that of the legume (Natarajan and Willey, 1980a, b; Sivakumar and Virmani, 1980; Reddy and Willey, 1981). He indicates that the RUE of the cereal is little influenced little by the legume growing in close proximity to it. The RUE of the shorter C3 is normally larger while shaded by the cereal than when growing alone. The physiological basis of the higher RUE by the C3 has not been systematically investigated, but is thought to get its basis on the photosynthesis/radiation or PAR response of C3 species, which results in the radiation being used more efficiently at low than at high intensities. The differences between sole bean and sole maize can be attributed to the C4 pathway advantage in energy conversion compared to that of C3. The RUE values found for all cropping systems were lower for maize than those found by Tsubo *et al.* (2001) and others (Sivakumar & Virmani, 1980 - 0.053 for sole maize; Coulson, 1985 - 0.017 for sole beans). This was probably due to the stress experienced by the cropping systems due to dependence on rainfall in this semi-arid environment. The aspect of variability of RUE in resource limiting situations has been discussed by researchers (Azam-Ali and Squire, 2002), who note that the normalized transpiration efficiency factor remains more conservative than RUE, especially when the supply and/or demand for water is limiting.

Table 5.3. Radiation use efficiency for the cropping systems during the seasons 2000/01, planting 1 and 2 and 2001/02, planting 1 (based on plant energy and PAR interception).

Treatment	2000/01		2001/02
	Planting 1	Planting 2	Planting 1
IMB	0.013	0.060	0.054
SM	0.012	0.039	0.043
SB	0.005	0.028	0.035

During season 2001/02, planting 1 (Table 5.3 and Figure 5.10) the RUE for sole maize was 0.043 (R^2 = 0.96), sole bean 0.035 (R^2 = 0.95) and that for the intercrop 0.054 (R^2 = 0.98). These values were closer to the season 2000/01, planting 2, which was cooler with yields higher than 2000/01, planting 1 (not shown here): sole maize: 0.039 (R^2 = 0.94); sole beans: 0.028 (R^2=0.95); intercrop: 0.060 (R^2=0.97). The season had relatively higher yields than the season 2000/01 and therefore higher RUE. The RUE was closer to those found by Tsubo *et al.* (2001) for sole maize at 0.047, sole bean at 0.024 and for intercrop at 0.043. The sole bean had higher RUE than Tsubo *et al.* (2001) sole bean during this season.

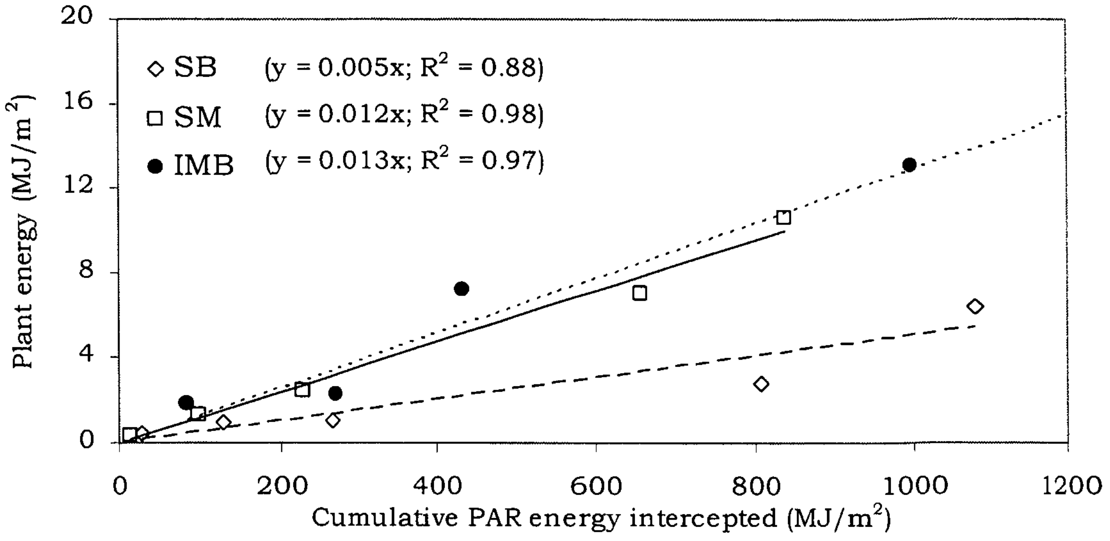


Figure 5.9. Radiation use efficiency of PAR for sole maize, sole beans and intercrop based on plant energy during the 2000/01 planting 1 season.

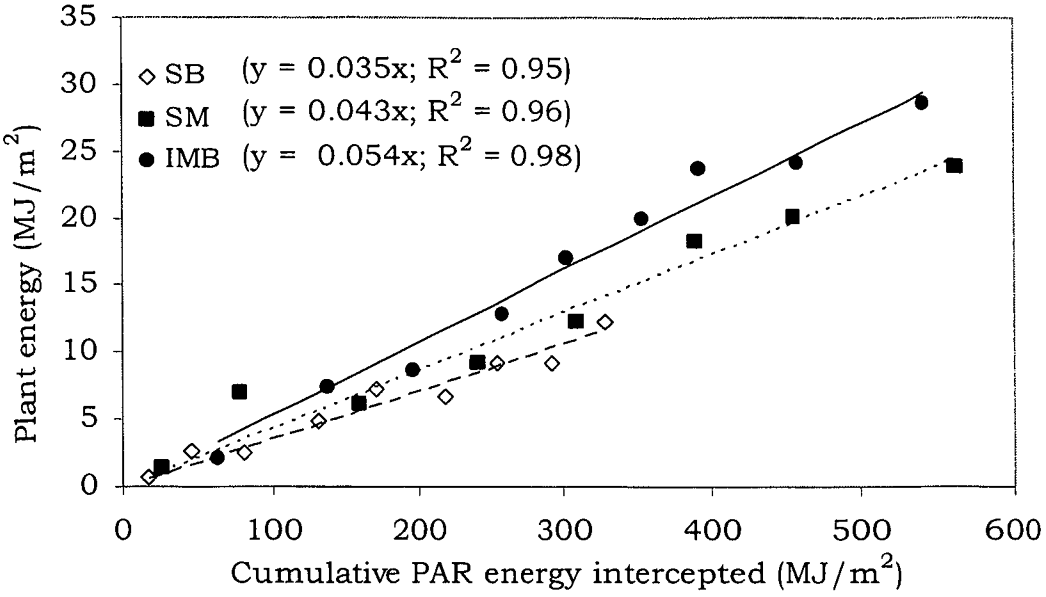


Figure 5.10. Radiation use efficiency of PAR for sole maize, sole beans and intercrop based on plant energy during the 2001/02 planting 1 season.

5.4. Conclusions

The mean values for canopy vapour pressure deficit show that the intercrop exhibited a lower vapour pressure deficit compared to the sole maize and sole bean crops. The rougher canopy exerts more friction on the wind moving within the canopy, resulting in a thicker laminar layer within the leaf-air boundary. This ensures that less water loss takes place from the stomatal pores compared to sole crop systems which have more open canopies. Wind speeds were not monitored within the canopies and therefore there was no data on the windspeeds within the respective cropping systems to confirm the above reasoning. The canopy of the intercrop also intercepts more solar energy, hence less long-wave radiation is emitted back with the result that there is less buoyant motion of air within the canopy of the intercrop and hence less coupling with the rest of the convective boundary layer. This explains the water extraction pattern for the cropping system which does not differ substantially with that of the sole crop maize (see Chapter 7, for water extraction), although the plant population is three times as high. In chapter 3, these canopy vapour pressures are not used in calculating the transpiration efficiency coefficient, although it would seem to make better sense to use them. However, due to practical difficulties of obtaining canopy vapour pressure data, weather station data is used. The canopy vapour pressure deficits for all cropping systems were lower than the weather station values indicating that it was more humid closer to the canopy.

The intercrop intercepted more PAR energy than each of the sole maize and sole bean cropping systems. This was probably due to the additive sowing scheme adopted. Season 2001/02, planting 1 exhibited a higher PAR interception compared to season 2000/01, planting 1. The season 2001/02 had better soil water availability and rainfall distribution compared to season 2000/01 which was drier and had poor rainfall distribution. The biomass accumulation was therefore higher during 2001/02, planting 1 than 2000/01, planting 1. The intercrop used radiant energy more efficiently during all seasons, followed by sole maize and finally sole beans. The season 2000/01, planting 1, had an exceptionally low RUE for the sole bean, sole maize and the intercrop, while the other seasons had relatively higher RUE with a similar trend as in 2000/01 (i.e IMB>SM>SB). This may have been due to the exceptionally high stress during this season. The RUE values for the sole maize was within the ranges found in other studies (Sinclair and Muchow, 1999). Sinclair and Muchow (1999) in their review of radiation use efficiency, reported that RUE values less than 0.8 g MJ^{-1} have been reported for legumes. Although no specific reference was given by them for the low RUE within some legumes, they emphasized the need to conduct intense studies of RUE to confirm whether it is inherently low in the legumes. The season 2001/02 had a RUE (intercepted PAR) value for sole bean equivalent to (0.035) 2.09 g MJ^{-1}, while season 2000/01, planting 2 had a RUE for the sole bean of (0.028) 1.68 g MJ^{-1}.

Sole bean had higher k-values during both seasons. This confirms the fact that beans have a more horizontal leaf exposition which is visually obvious, compared to the sole maize. In the intercrop the maize extinction coefficient played a dominant role in PAR attenuation. It has to be said however that the k-values were lower than unity, indicating that the canopy had less horizontal leaves and more clumped distribution. The crops depended on rainfall and were therefore subject to water stress during both seasons, with season 2000/01 having more stress than 2001/02 season. This may have resulted in rolling of leaves and less exposure to radiation.

Chapter 6

Cropping Systems Soil Water Extraction

6.1. Introduction

Accurate estimation and knowledge of plant water uptake is crucial in analyzing agricultural productivity. Nowhere is this more crucial than in the arid and semi-arid regions where rainfall input is variable and limiting. The extent to which water availability limits crop production depends on the balance between supply to the root system and demand by the atmosphere. Where water is relatively ample the supply to the crop becomes largely dependent on demand. However, when supply is limited the degree of root extension and ramification within the soil profile and soil physical and chemical characteristics determine the rate of extraction.

Monteith (1986) developed a mathematical framework that has extensively been adopted to describe root water extraction under water limited conditions. This framework has been used as a basis for simulating water extraction in crop models (Robertson *et al.*, 1989; Robertson *et al.*, 1993a, b; Fukai and Hammer, 1995; Singh *et al.*, 1998; Meinke *et al.*, 1993).

Water uptake by roots at various depths within the soil profile is a requirement in computing water depletion. Water uptake is a function of rooting density distribution, conductivities of the soil-root system and the availability of soil water. Rooting is a function of crop species, genotype together with soil physical and chemical parameters. Rate of water uptake is dependent on transpiration and resistance to water uptake by roots. Consideration of atmospheric evaporative demand and soil root exploration is important when examining plant water uptake on a particular soil-plant-atmosphere agro-ecosystem.

Little is known of the root water extraction behavior of intercrop systems involving more than one genotype. Studies conducted to date, have considered sole crops rather than intercrops when using this framework to analyze soil water extraction. The fitting of empirical models to rootzone water decline highlights some of the less known below ground behavior in relation to water use by intercrops and provides the basis for modelling water extraction by the crops.

The following objectives are fulfilled by this analysis:

- to estimate the rate at which growing root systems extract water by combining static root system with a function describing downward penetration of roots for SM, SB and IMB systems during the first planting seasons 2000/01 and 2001/02.
- to estimate apparent rooting depth for the three cropping systems from soil water extraction measurements;
- to quantify soil water extraction parameters of importance to root water extraction modelling;
- to compare the water extraction characteristics for a maize-bean intercrop (additive sowing plan) with those of sole crops of maize and bean.

6.2. Theory and data analysis

The procedure used for analysis was proposed by Passioura (1983) and Monteith (1986) and described in detail by many researchers (Meinke *et al.*, 1993 for sunflower; Robertson *et al.*, 1993a, b for sorghum). The analytical method for water extraction has two functions. The first describes the advancement of the extraction front depth with time. The extraction front is defined as having arrived at a particular depth when soil water begins to decline exponentially with time. The second function describes the exponential decline of water content with time once the extraction front has arrived at a particular depth.

Two assumptions are associated with the method: 1. Under continuous soil drying the extraction front resembles the root front. 2. Once the extraction front has arrived at a particular depth the root length remains more or less constant and the maximum rate of extraction occurs at the beginning of the extraction period and soil water content declines exponentially with time as described by Passioura (1983).

The downward velocity of the extraction front can be determined by plotting the soil water content for each layer against the time after sowing when the exponential decline in soil water extraction commences (t_c). The regression and extrapolation of the point when the decline commences (t_c) for each layer to the time axis gives the intercept, which designates the lag phase for the descent of the extraction front (t_o).

Continuous curves were fitted to measurements of soil water content at each depth of measurement and used to calculate extraction at the specific depth. The cumulative soil water extraction was calculated as the sum of these extractions within the total rootzone. The parameters derived from the model can be used in soil water balance modelling. The framework accounts for maximum plant available water content (PAWC) in each soil profile layer, time at which extraction front commences decline (t_c), rate at which soil water extraction front advances down the profile and the rate of water extraction in each soil layer (kl). PAWC is defined as the difference between the drained upper limit (DUL) and the crop lower limit (CLL). In this analysis the initial water content for each layer was not at DUL. The final soil water content at the end of the season did not always match the crop lower limit of water extraction, but was closer to that measured for each cropping system (see Appendix 9 and Chapter 7, Table 7.3). The time course for water extraction for each layer was fitted to the negative exponential model. The fits can be described by the following set of equations:

$$\mathrm{PAWC} = \theta_{\mathrm{DUL}} - \theta_{\mathrm{CLL}} \tag{6.1a}$$

$$\mathrm{AWC} = \begin{cases} \mathrm{PAWC} & \text{if} \quad t \le t_c \\ \mathrm{PAWC} \times \exp[(-\mathrm{kl} \times (t - t_c)] & \text{if} \quad t > t_c \end{cases} \tag{6.1b}$$

$$\mathrm{dAWC/dt} = \begin{cases} 0 & \text{if } t \le t_c \\ (-\mathrm{kl}) \times \mathrm{AWC} & \text{if } t > t_c \end{cases} \tag{6.1c}$$

where AWC is the actual available water content in each layer at time (t) in days after sowing (DAS), kl is the rate of soil water extraction (d^{-1}) (see equation 6.1c) and t_c the time of first water extraction (DAS) in each layer.

Values for t_c can be calculated from equation (6.1e) or derived from curve fits.

$$\mathrm{EF} = \mathrm{EFV} \times (t - t_0) \quad \text{if} \quad t > t_0 \tag{6.1d}$$

where EF is the depth of extraction front in cm at time t, EFV is the extraction front velocity (cm d^{-1}) and t_0 is the time (DAS) at which the extraction front starts its descent at rate EFV (DAS). Hence

$$t_c = \mathrm{EF} \times \mathrm{EFV}^{-1} + t_0 \tag{6.1e}$$

Assuming the extraction front ceases its descent at about flowering

$$\mathrm{EF}_{\mathrm{max}} = \mathrm{EFV} \times \left(\mathrm{DTF} - t_o\right) \tag{6.1f}$$

Where DTF in the above relationship represents the days to flowering. Monteith (1986) found a linear increase in EF with time up to flowering for sorghum.
Based on the equations 6.1a-6.1d cumulative water extraction at any point in time is the sum over all layers of the difference between PAWC and AWC.

The exponential equation was fitted to soil water depletion for each layer versus time only during two planting seasons, 2000/01(planting 1) and 2001/02 (planting 1) when long drying cycles existed and rainfall events were not heavy enough to affect the drying cycles. This was only possible when water supply in the form of rainfall was less than the demand imposed by the crop during most of the growing season. The top 0-300 mm layer was not included in the analysis as it is appreciably affected by soil evaporation. Extraction rates (mm d^{-1}) were calculated from means of several NWM measurements in one treatment. The treatments had three replications each with at least two access tubes except for the intercrop that had three access tubes. Readings taken on the same day and depth were examined for differences. If the readings had small standard deviations and then the mean of several tubes within a treatment were used in the analysis for exponential seasonal rootzone water decline.
Passioura (1983) suggested that kl could be assumed to be inversely proportional to root length density.

6.3. Results and discussions

6.3.2. Climate

The Table 6.1 shows the mean maximum and minimum temperatures (°C), solar radiation, (Wm^{-2}), mean daytime vapour pressure deficit (kPa) for weekly periods in the growing season. The season 2000/01, planting 1 had higher mean daytime vapour pressure deficits, higher mean solar radiation, higher mean maximum temperatures and higher mean wind speeds than season 2001/02. The season 2000/01, planting 1 therefore had a higher atmospheric evaporative demand for evapotranspiration (ET) than the season 2001/02.

Table 6.1. Weekly mean meteorological variables during the season 2000/01, planting 1 and season 2001/02, planting 1.

Week	Season 2000/01, planting 1					Season 2001/02, planting 1				
	D	Rad.	Max T	Min T	Wind	D	Rad.	Max T	Min T	Wind
	kPa	Wm^{-2}	^0C	^0C	$m\ s^{-1}$	kPa	Wm^{-2}	^0C	^0C	$m\ s^{-1}$
1	1.8	314.6	27.6	13.8	2.4	0.8	333.3	25.9	13.6	1.8
2	1.5	275.9	26.9	15.2	1.8	1.4	347.3	28.5	15.0	2.0
3	1.5	286.1	28.0	15.3	2.4	1.0	315.3	25.8	14.9	1.7
4	1.8	310.2	26.8	14.4	2.1	1.5	343.3	30.3	16.0	2.2
5	2.4	334.8	30.6	16.3	2.2	1.2	314.9	27.5	14.0	2.6
6	2.5	360.7	30.2	15.1	2.3	1.3	349.4	27.6	12.9	2.2
7	2.4	360.4	28.4	12.9	2.1	1.3	291.5	28.6	17.0	2.4
8	3.1	347.8	31.8	17.1	2.8	0.7	257.6	25.0	15.7	1.6
9	2.4	331.9	30.7	14.5	2.0	1.4	309.5	28.8	14.9	1.7
10	2.2	298.7	30.3	18.1	2.3	1.3	283.1	28.4	16.3	1.9
11	2.5	343.0	30.7	15.9	2.3	1.2	302.3	27.7	15.3	1.3
12	2.4	318.0	30.8	17.1	2.1	1.3	259.8	29.3	17.3	1.6
13	1.7	307.9	28.3	16.8	2.1	0.9	229.8	26.5	16.1	1.5
14	1.7	268.6	28.3	16.4	1.9	1.0	220.9	26.4	15.3	1.2
Mean	2.1	318.5	29.2	15.6	2.2	1.2	297.0	27.6	15.3	1.8
Stdev	0.5	29.6	1.6	1.4	0.3	0.2	42.1	1.5	1.2	0.4

6.3.3. Total water extraction

The difference between the initial and the final water contents measured during seasons are shown in Figures 6.1 and 6.2. The total water extracted during season 2000/01, planting 1 were 123, 109 and 121 mm for the IMB, SB and SM respectively. The intercrop had the highest extraction at the 0-300 mm, 600-900 mm, 900-1200 mm depths. SM had the highest extraction at 300-600 mm depth. SB had the lowest extraction at all depths within the soil profile during the 2000/01, planting 1. The differences between the total extraction for SM and IMB were not statistically significant especially in the deeper layers. Considering that the IMB had a total plant population of 120,000 plants/ha compared to the SM plant population of 40,000 plants/ha, there is an obvious conservation of water as the two cropping systems extracted more or less similar amounts of soil water during the season.

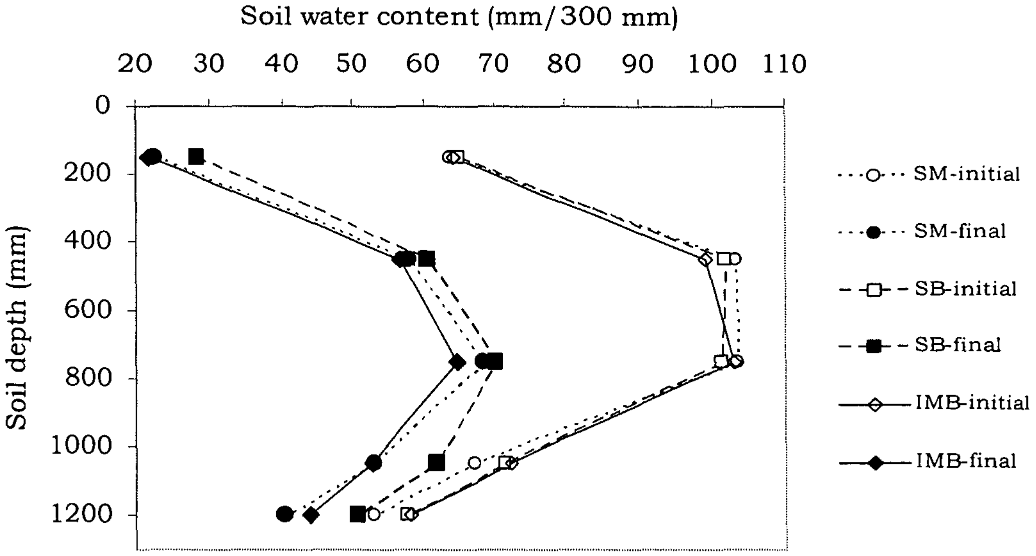


Figure. 6.1. The initial and final soil water content (mm/300 mm) for each of the cropping systems during the season 2000/01 season, planting 1.

Figure 6.2 shows the initial and final soil water content during the 2001/02, planting 1 season for all cropping systems. The difference between the initial and final water content gives an estimate of the minimum amount of water used during the season at the various depths as some redistribution and some water have been added from rainfall. The minimum amount of water used during the season was estimated as 93 mm, 73 mm and 102 mm for IMB, SB and SM respectively. This season experienced a lower atmospheric demand as shown by the meteorological variables in Table 6.1. The initial soil water status was different according to the measurements from the NWM. This may be an indication that soil was note very homogenous in terms of its texture i.e variations in clay, sand and silt contents. The SB exhibited the lowest final soil water content at all depths except at 300-600 mm. The IMB and SB had higher soil water content below the 900 mm depth at the end of season 2001/02 compared to the SM.

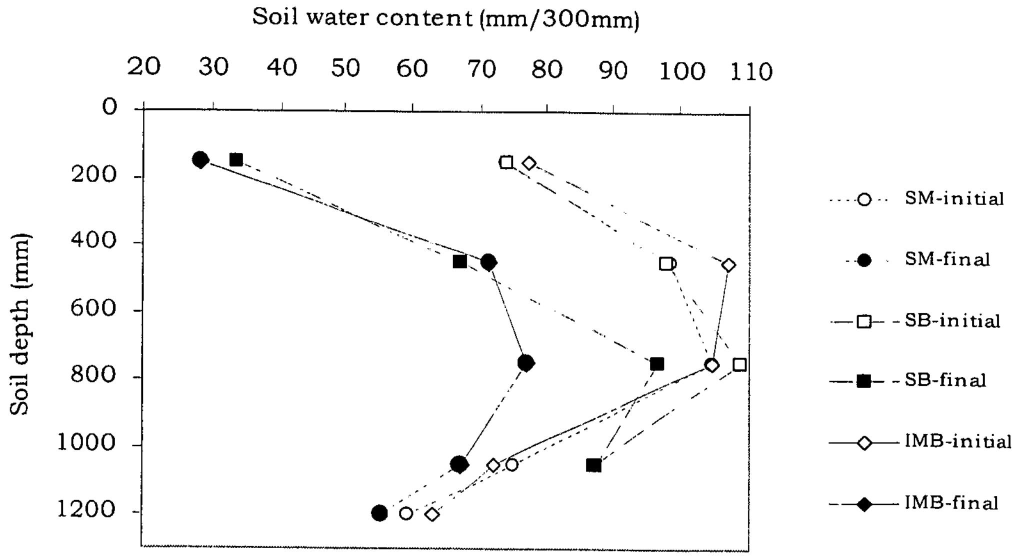


Figure. 6.2. The difference between initial and final soil water content (mm/300 mm) for each of the cropping systems during the season 2001/02 season, planting 1.

6.3.4. Soil water extraction

Extraction front velocity (EFV)

The time of arrival of the extraction front at a particular layer was estimated from the exponential curves fitted to the measured soil water contents. A sharp decline on the exponential curves signaled the start of the water extraction and the arrival of the roots within the layer, although the extraction lagged behind the arrival of the roots. The equations fitted well with an $R^2 \geq 0.86$ in all cases. The exponential fits are shown as Appendix 8.

When the drying cycle commenced, the extraction front progression with time was defined by the extraction front velocity (EFV) and t_o. The EFV is the rate at which the roots descend within the soil and depends on the species, the soil physical/chemical characteristics and the soil water status.

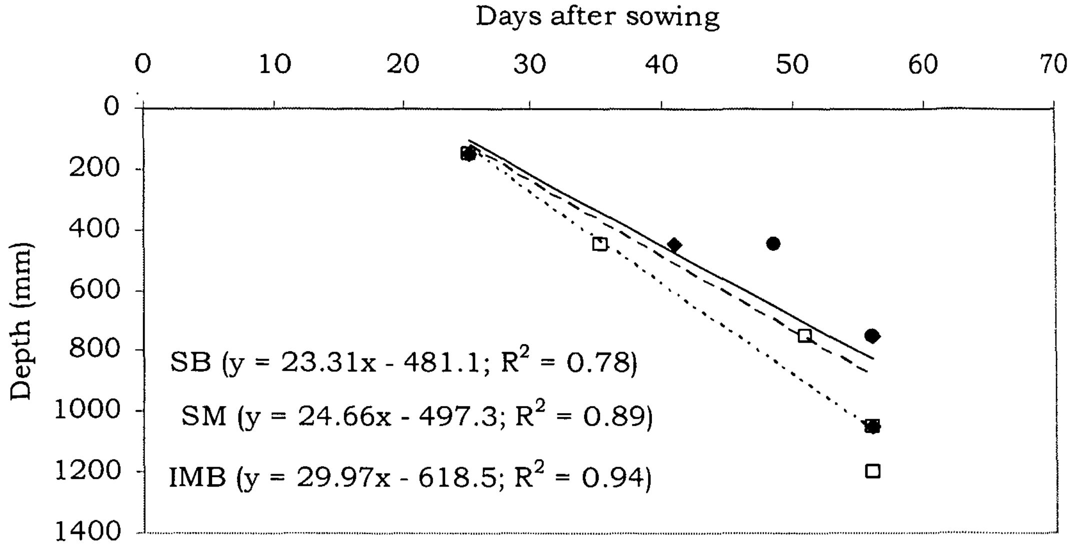


Figure 6.3: Regression of t_c against DAS for different layers within the soil profile for the cropping systems during the 2000/01, planting 1 season. The lag t_0 is the intercept with the x-axis.

The EFV values during season 2000/01, planting 1 were 2.99 cm d^{-1}, 2.47 cm d^{-1} and 2.33 cmd^{-1} for intercrop, sole maize and sole beans respectively (Figure 6.3). The start of the descent of extraction front is indicated by the value of t_o. The t_o values for season 2000/01, planting 1 were 21, 20 and 21 days for the intercrop, sole maize and sole bean respectively. During season 2001/02, planting 1 the values for both t_o and EFV were lower compared to the ones for the previous season. The t_o values were 10, 11 and 7 for intercrop, sole maize and sole bean respectively. The values of EFV for the season were 1.99 cm d^{-1}, 1.88 cm d^{-1} and 1.63 cm d^{-1} for the intercrop, sole bean and sole maize respectively (see Figure 6.4). The intercrop exhibited a higher extraction front velocity than the sole maize and sole beans during both seasons. This may have probably been due to the competition for water resources within the soil profile by both species roots. Angus *et al.* (1983) reported that root front velocity for a range of tropical species was between 2 and 4 cm d^{-1}. The values found are on edge of the range indicated by Angus *et al.* (1983) under tropical climatic conditions. Nakayama and van Bavel (1963) recorded a range in root front velocity in the field of 1.9-4.9 cm d^{-1} for sorghum, while Rees (1986) and Turk and Hall (1980) reported rates of downward rooting of 1-3 cm d^{-1} for sorghum/cowpea intercrop and cowpea.

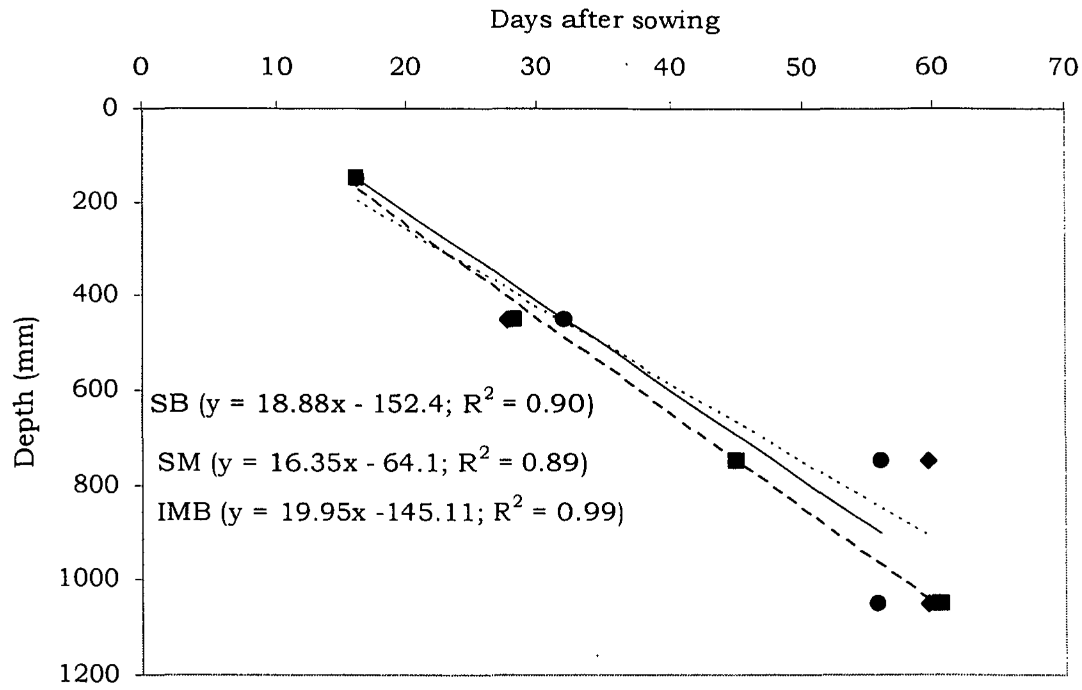


Figure 6.4: Regression of t_c against DAS for different layers within the soil profile for the cropping systems during the 2001/02, planting 1 season. The lag t_0 is the intercept with the x-axis.

Soil water extraction rates (kl)

The term kl, is the extraction decay constant (d^{-1}) and is obtained from the fitting of the volumetric water content data to time (DAS) for each depth. The decay constant has been noted to estimate the root length density and the hydraulic conductivity of the soil and can be determined by monitoring water extraction by crops. The values of the decay constant varied markedly in the experiments. The values varied from 0.023-0.1097 d^{-1}. A lower rate of the decay constant at a particular depth indicates slow rate of decline of water content. As the soil type and other conditions could be said to be similar with minor differences the variations in kl, could be mainly attributed to differences in root length density for the cropping systems. The Appendix 8 shows the parameters of the exponential function fits including the kl values at various depths

As depicted in the Figure 6.5, during season 2000/01, planting 1, the intercrop exhibited a highest extraction rate during most of the season with dual peak of 3 mm d^{-1} and 3.1 mm d^{-1} at 41 and 65 DAS respectively. The first and second peaks occurred during the vegetative and flowering period for the IMB, maize component.

The fluctuation in the extraction rate was possibly due to plant growth and soil water status. Chapter 7, Figure 7.2 indicates the soil water fluctuation during the 2000/01, planting 1. The soil water content within the 0-900 mm depth was at DUL at the beginning of the season until 30 DAS when it fell below DUL. There was low rainfall input between 18-56 DAS when most of the events were 10 mm and less, and had no significant impact on the soil water content. The lower but rising extraction rate at the beginning of the season can be explained by the increase in root length density within the soil profile as well as the progressive velocity of the root front. The second extraction peak for IMB coincided with some rainfall events around flowering period for the maize component. It is known that water demand by the crop at this stage is very high, and this can explain the peak which also coincided with some favourable soil water condition. The rainfall inputs occurred as follows: 56 DAS, 23 mm; 65 DAS, 18 mm; 80 DAS, 12.5 mm; 89 DAS, 27 mm and 95 DAS, 13.8 mm.

The extraction rate for SB was lower than that for IMB, but followed a similar pattern until the end of the season. The dual peaks occurred at DAS 48 and 65 and were 2 mm d^{-1} and 2.1 mm d^{-1} respectively. As noted in the explanations for the extraction pattern for IMB, the SB extraction also followed the rainfall input during the season.

The SM had the second highest extraction rate with two prominent peaks of 3.2 mm d^{-1} and 2.5 mm d^{-1} respectively. The second peaks of SM was lower and more extended than that of the IMB most likely due to less competition compared to the plants in the IMB. Due to the evaporation of water at the soil surface the soil water content in the top layers for the SM may have been lower than those for the IMB.

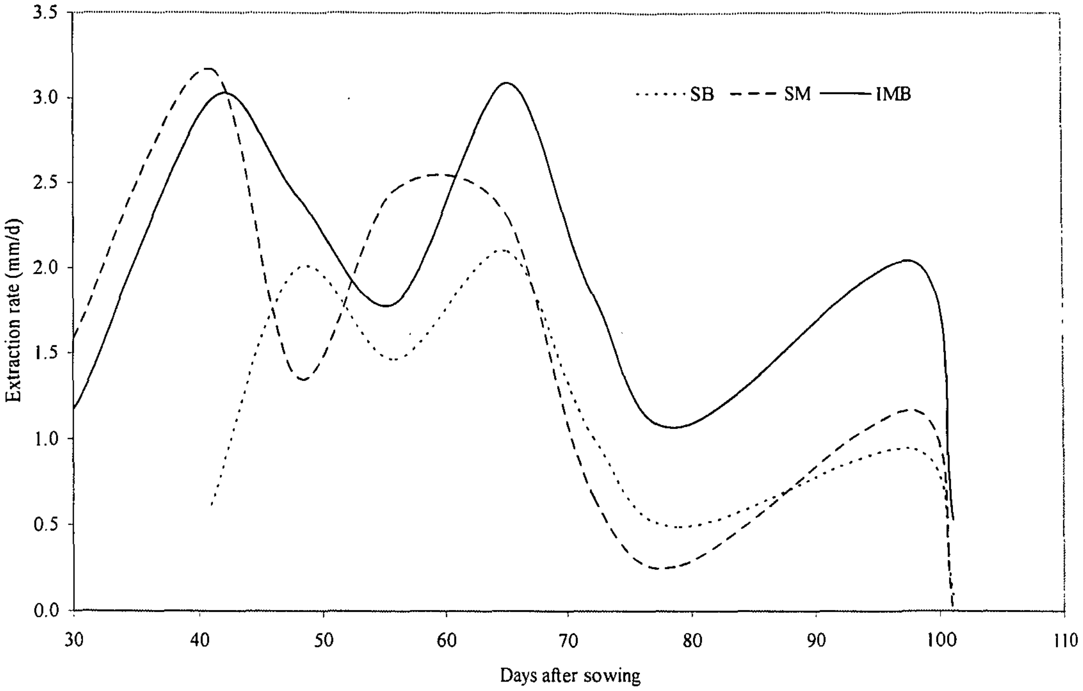


Figure 6.5. Fitted and smoothed time course of weekly soil water extraction averaged for the cropping systems during season 2000/01, planting 1.

The cumulative extraction for the season 2000/01, planting 1 is shown in Figure 6.6. This cumulative water extraction is calculated by integration of the extraction rates during the extraction period. It compares the cropping systems extractions during the season. The percentage cumulative water extraction (CWE) from the profile by 65 DAS was 52% (64 mm), 67% (59 mm) and 58% (41 mm) for the IMB, SM and SB respectively. 65 DAS represents the time when this short season maize species attained peak flowering and presumably maximum rooting depth. The higher CWE_{max} by IMB (123 mm) was most likely due to the higher plant density (additive sowing scheme). The lower extraction rates by the SB are most likely due to the legume root growth characteristics. It explores the upper layers more intensively compared to the maize a C4 species.

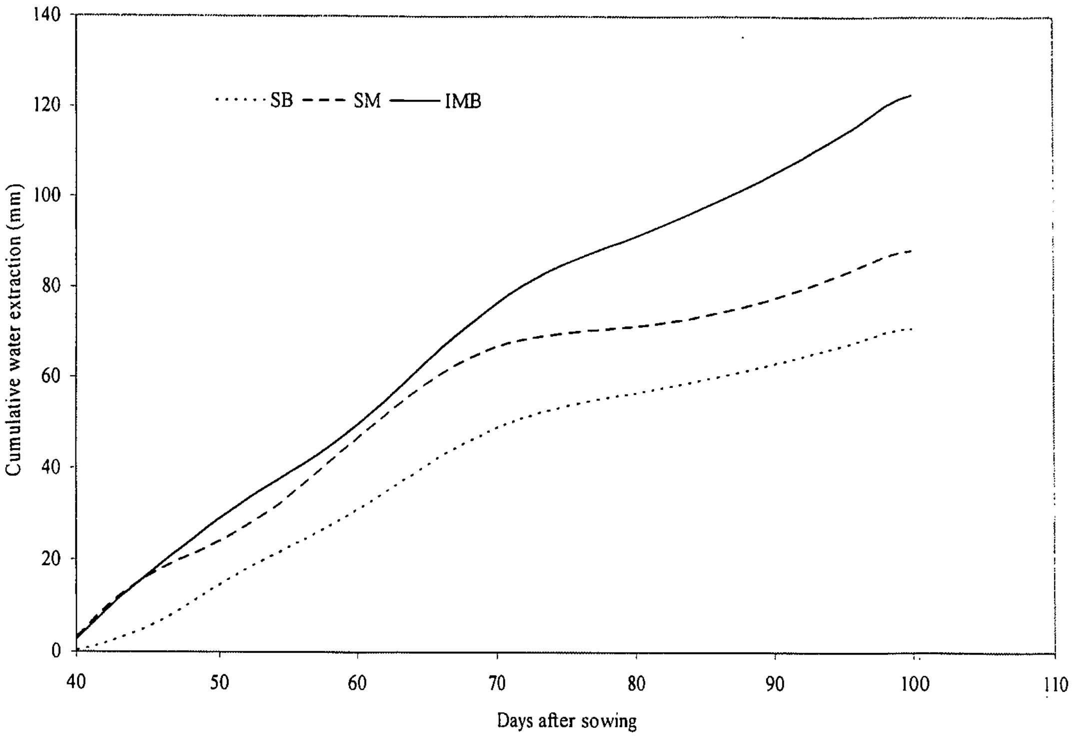


Figure 6.6 The modelled cumulative water extraction during the season 2000/01, planting 1 for each of the cropping systems.

Figure 6.7 shows the soil water extraction estimation for the cropping system during the season 2001/02, planting 1. The SB exhibited a higher extraction rate at the beginning of the season, but was surpassed by SM which attained an extraction rate of 2.7 mm d^{-1} on 38 DAS. The IMB had a lower extraction rate earlier in the season compared to SB and SM, but attained the highest extraction rate of 4.1 mm d^{-1} on 56 DAS. The SM had a second extraction peak of 3 mm d^{-1} around 60 DAS (flowering time). The SB extraction peaked at 3.2 mm d^{-1} around 56 DAS, although the peak was for a very short duration compared to that of the SM and IMB.

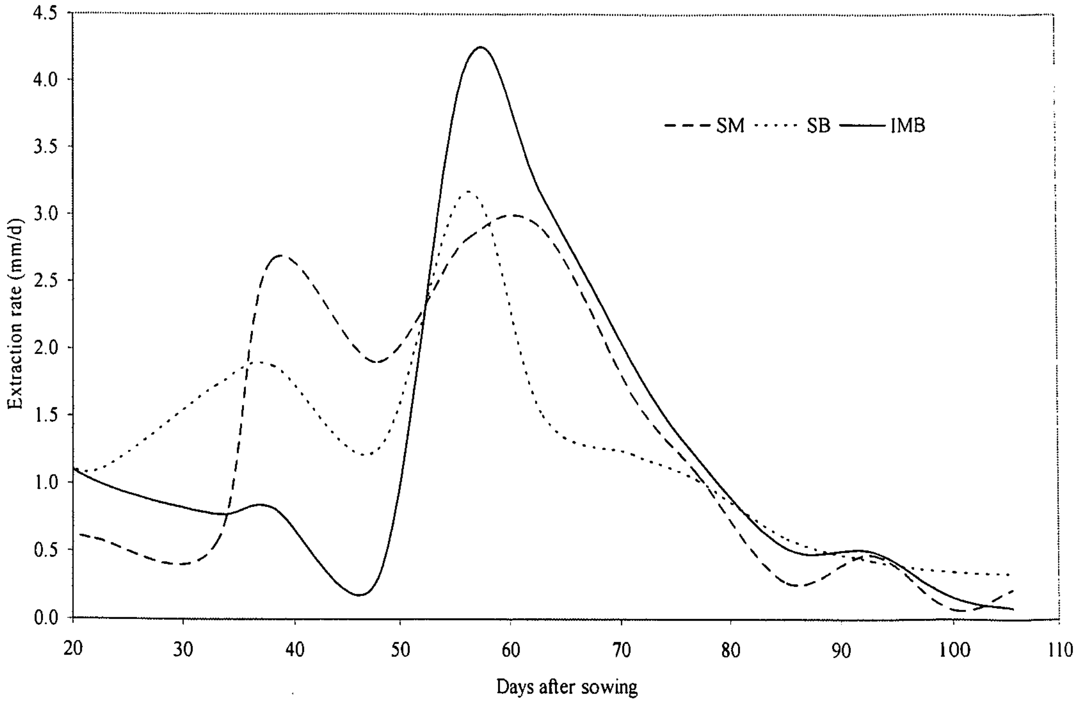


Figure 6.7. Fitted and smoothed time course of weekly soil water extraction averaged for the cropping systems during season 2001/02, planting 1.

An analysis of the cumulative water extraction for the cropping systems is shown in Figure 6.8. The SM, SB and IMB had cumulative extraction of 115 mm, 110 mm and 108 mm respectively. The SB extracted relatively more soil water earlier during the season compared to the SM and IMB (up to 60 DAS). SM and SB exhibited a higher cumulative extraction during season 2001/02, planting 1 than season 2000/01, planting 1. On the contrary the IMB had only a slightly higher cumulative water extraction during 2000/01, planting 1 compared to 2001/02, planting 1.

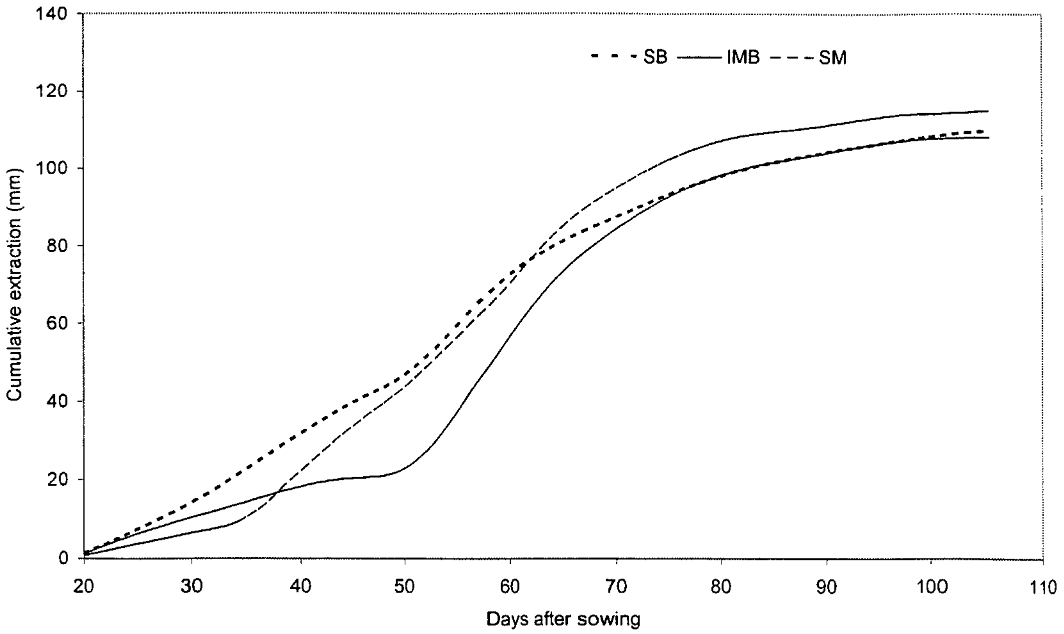


Figure 6.8 The modelled cumulative water extraction during the season 2001/01, planting 1 for the cropping systems.

Maximum depth of extraction front (EFmax)

The maximum depth of the extraction front was set by both available water within the soil profile and the crop characteristic. The soil limit was set by the rate of decline of the PAWC with depth, while the crop limit was set by the time to flowering (DTF) as the progression of the extraction front stops at about that time (Bremner *et al.,* 1986; Robertson *et al.,* 1989).

Before the time of flowering the depth of extraction front can be predicted by equation 6.1 b. This soil type can also greatly limit vertical root growth to greater depths, as was experienced at the site. An examination of the soil profile showed that very high clay content and relatively high bulk density was present at 400-700 mm depth. The exact depth may have varied from place to place at the site. Very little extraction could take place at depths greater than this. The exponential framework was used to estimate the extent of root growth extent based on the days to flowering assuming that root growth and extraction front velocity ceases at flowering (see equation 6.1f). An examination of the exponential extraction curves at greater depths also showed no decline at all showing that the roots never explored these layers i.e layers below 900 mm.

The amount of water captured by crops depends on the morphology, lateral extent as well as on the configuration of the species, especially within an intercrop (Azam-Ali and Squire, 2002). The extent and distribution of roots is normally constrained by the structure of and depth of the soil profile. Intercropping has been mentioned to promote complementarity in the use of resources including water. Maize and bean intercropping are known to extract water at different profile depths and therefore exhibit such complementarity.

Cumulative water extraction by cropping systems

Cumulative potential soil water extraction was calculated using the framework with the parameters found for each layer. Total cropping system water extraction was calculated using the average value parameters fitted to each layer and for each cropping system. The average values including EFV (cm day^{-1}), lag phase for extraction front descent t_o (days), EF_{max} (mm) (representing maximum rooting depth), CWE_{max} (mm), and total profile available water are shown in Table 6.2. Differences in CWE were evident as shown in Table 6.2 and 6.3 CWE did not correspond to the PAWC as the soil profiles were not filled to maximum content at the beginning of the experiment as evidenced by the differences in $\Theta_{initial}$ and θ_{CLL}.

Table 6.2. Extraction velocity (EFV), time of commencement of extraction front (t_o), maximum depth of extraction (EF_{max}), days from sowing to flowering (DTF), maximum cumulative water extraction (CWE_{max}) and total plant available water for the profile (PAWC) for season 2000/01.

Treatment	EFV (mm d^{-1})	t_o (days)	EF_{max} (mm)	DTF (days)	CWE (mm)	PAWC (mm)
IMB	29.9	20.6	1090	40, 57	123	121
SM	24.7	20.1	910	57	88	114
SB	23.3	20.6	450	40	71	103

Table 6.3. Extraction velocity (EFV), time of commencement of extraction front (t_o), maximum depth of extraction (EF_{max}), days from sowing to flowering (DTF), maximum cumulative water extraction (MCWE) and total plant available water for the profile (PAWC) for season 2001/02.

Treatment	EFV (mm d^{-1})	t_o (days)	EF_{max} (mm)	DTF (days)	CWE (mm)	PAWC (mm)
IMB	19.9	7.3	1100	40,57	108	121
SM	16.3	8.1	1010	57	115	114
SB	18.8	4.0	670	40	110	103

6.4 Conclusions

The framework enabled the understanding of the water extraction by the cropping systems during the season for this site. Therefore with the knowledge the parameters: EF_{max}, θ_{DUL}, θ_{CLL} and kl enables the application of the framework to predict potential water extraction by cropping systems. This approach to calculating cropping system water extraction can be employed in crop water balance modeling.

During the season 2000/01 with relatively high evaporative demand the extraction rates were higher for all the cropping systems. The intercrop exhibited the highest extraction rate at 29.9 mm day^{-1} with a difference of 10 mm day^{-1} between the two seasons. These differences can be explained by the high evaporative demand during that season. During the 2001/02 season the maize crop was much taller compared to the first season due to the stress imposed during this period. There was a serious shading effect from the tall maize on beans during the late vegetative period which resulted in less competition for soil water resources and therefore lower root activity.

Season 2000/01, planting 1 had higher mean daytime vapour pressure deficit than season 2001/02 as shown in Table 6.1. The daytime mean vapour pressure deficit during the season 2000/01 was 0.9 kPa higher compared to 2001/02 season. This supports the relatively higher EFV during the 2000/01 period as the crop extended roots at a faster rate into the deeper layers due to the higher evaporative demand imposed by the atmosphere. The greater EF_{max} during season 2001/02 compared to season 2000/01 is difficult to explain given the fact that the EFV was lower.

The time course of water extraction followed both the rainfall and phenological trend with high extraction rates taking place around rainfall inputs. The extraction pattern for the sole maize and the intercrop were more less similar in its variations showing that the dominant crop in terms of stature and biomass accumulation ability of maize probably dictated the trend. However, it has to be noted here that there is need to undertake detailed root studies for the intercrop to provide conclusive evidence of ability of maize to dictate the trend of extraction.

It is noteworthy, that the season 2000/01 had a higher vapour pressure deficit, exhibited a higher root front velocity, low maximum LAI at 4 and had higher cumulative extraction, compared to season 2001/02 that had lower vapour pressure deficit lower root front velocity, higher LAI at 8 had lower cumulative extraction during the season for the intercrop. The answer should really lie in the manipulation of water supply and demand by the cropping system which should consider the rooting system, atmospheric weather variables and the plant components (Monteith, 1986).

Chapter 7

Quantification of Precipitation Use Efficiency

7.1. Introduction.

There are three natural resource factors that influence productivity of the atmosphere-plant-soil system. They are atmospheric variables, topography and soil. A piece of land on which the three factors are, for practical purposes, homogenous, is called ecotope (MacVicar *et al.*, 1974). The detailed characterization of these three natural resource factors on a piece of land is critical, as it enables the transfer of recommendations to areas with similar natural resource attributes i.e. ecotopes (Hensley *et al.*, 2000) and extrapolation to other areas for comparison purposes.

Crop production in the semi-arid areas is limited by rainfall availability and variability. Large areas of southern Africa are covered by soils developed from aeolian deposits, often with a topsoil clay content lower than 15%. In some of the areas the more sandy topsoil is underlain by a layer with high clay content (duplex soils). This layer restricts rooting and limits plant water availability. The low mean annual rainfall of 450 to 550 mm, and high annual evaporation of 2000 to 2500 mm, result in severe crop water stress during most seasons on these ecotopes.

Mono-culture of maize with a wide row spacing usually of 1.5 to 2 meters is the predominant form of large scale cropping in drier farming areas of South Africa. Intercropping is rarely practiced within the large scale sector. As a result the soil-plant-atmosphere system interaction is simplified and is relatively easy to evaluate and quantify.

In dryland cropping systems, quantitative information on the seasonal characteristics of the soil water balance is fundamental to the understanding of water fluxes into and out of the soil. These fluxes determine the efficiency with which crops capture and convert water into useful plant biomass. The fluxes form the components of the simplified water balance appropriate for rainfed cropping in more dry areas, namely deep drainage (D_r), runoff (R) and soil surface evaporation

(E_s) which constitute losses from the system, and precipitation (P) and soil water storage (ΔS) as assets. Wallace and Batchelor (1997) indicated that for millet grown on research plots in Niger, E_s in rainfed cropping may amount to 30-35% of rainfall. Bennie *et al.* (1994) reported E_s of 75% on bare soil under similar conditions as in the experimental area. The amount of water available for transpiration (E_t) is the critical component as it contributes directly to plant yield. Rockstrom (1997) found that E_t could be as low as 5% of the rainfall in typical farmer's fields in West Africa. Wallace (2000) reports E_t values ranging from 15-30% of rainfall. Substantial increase in crop yields can be realized if the amount of water directed to transpiration could be increased. Reduction of losses should therefore be a target for increasing water use efficiency. Under rainfed cultivation adopting techniques meant to reduce E_s, R, and D_r can achieve this. A critical factor influencing both E_s and E_t is crop cover represented by leaf area index. As leaf area increases the radiant energy reaching the soil surface decreases due to increased shading. Similarly, the energy available for transpiration increases due to increased interception by the canopy. Therefore the balance of ET components shift to a higher percentage of E_t. Agro-forestry systems have demonstrated the potential for decreasing soil evaporation using canopy shade (Wallace *et al.*, 1999). Intercropping exhibits similar if not identical benefits, except for crop species combination difference.

Maize (*Zea mays*) is the staple food for smallholder farmers in Southern Africa. Maize is commonly grown by them in association with dry beans (*Phaseolus vulgaris*). The system has been adopted by the majority of smallholder farmers mainly for dietary reasons. Maize is normally grown as the principal crop, with the legume as a secondary crop. The cropping system is associated with low inputs, and essentially depends on the natural resource base. Rainfall is the single most important natural resource input in this form of cropping.

Presently, there is substantial agronomic evidence regarding yield advantage by crop mixtures, maize and bean intercrops included (Willey, 1979a, 1979b; Willey & Rao, 1981; Ahmed & Rao, 1982; Willey, 1990; Mukhala, 1998; Tsubo, 2000). A fundamental understanding of how the intercrop system captures and uses resources, especially rainfall would provide the scientific basis for recommending this practice as a viable form of rainfed cropping especially among smallholder farmers.

Response of sole crops to physical factors such as radiation, water and temperature are well documented (Monteith, 1977; Ong & Monteith, 1985). But studies of such responses are scarce and far between for intercropping systems. This is because of the practical difficulties associated with apportioning resources to intercrop components. Comparative studies of intercropping systems involving maize and beans have shown substantial improvement in water use efficiency (Reddy & Willey, 1981; Mukhala, 1998). Morris and Garrity (1993) cited many cases of intercrop advantage with particular reference to water use efficiency. Midmore (1993) noted that intercrops do relatively better compared to sole crops even under conditions where rainfall deficits diminish component crop yields (e.g. LER>2 for sorghum/groundnut and sorghum/millet, ICRISAT, 1981).

One approach that has been used to estimate transpiration, and indirectly soil evaporation is the use of the transpiration efficiency coefficient. The relation between total dry matter mass and seasonal transpiration is often linear with a slope, known as transpiration efficiency (dry matter/transpiration water ratio) (Azam-Ali and Squire, 2002). Tanner and Sinclair (1983) showed that because the ratio of CO_2 concentration in the intercellular spaces of the leaves to that of ambient air is maintained almost constant depending on plant species, the amount of dry matter produced per unit of water transpired varies only with the gradient of water vapour concentration between sub-stomatal cavity and ambient air. Monteith (1990) showed that when mean seasonal daytime saturation deficit is included as a normalizing factor, the value of transpiration efficiency coefficient appears to remain conservative and is therefore a more robust index of crop productivity, especially when water is limiting. This index is called the transpiration efficiency coefficient.

Precipitation use efficiency is an index of productivity adopted in areas where production is dependent on rainfall. PUE has been noted to take account of field water balance losses such as run-off, deep drainage and soil surface evaporation during the growing season (Hensley *et al.*, 2000). Precipitation use efficiency has been expressed with yield or biomass in the numerator. Where two different species are grown together, the yield and biomass components are bio-chemically different and therefore should be expressed in terms that enable comparison between cropping systems. Yield from two or more species can be expressed in monetary or energy terms. Monetary value expresses the opportunity cost of productive activities and possible returns to limiting resources such as water.

The process of plant growth consists of conversion of glucose to other organic compounds. Plant tissue is composed of varying proportions of five distinct biochemical groups: nitrogenous (especially proteins), carbohydrates (cellulose, hemicellulose, starch), lipids (fats, fatty acids, oils), lignin and organic acids. The weight ratio of these biochemical products to substrate varies between 0.35 and 1.0 g g^{-1} (Penning de Vries *et al.*, 1989). This is because the synthesis of plant products rich in lipids and proteins require much more energy per unit dry weight compared to carbohydrates. It is therefore more useful to adjust efficiency calculations to reflect energy equivalents for lipids and protein components. The unadjusted value for the conversion efficiency of solar radiation/water for crops which produce seeds that are high in oil or protein will be less (Muchow *et al.*, 1982; Kiniry *et al.*, 1989).

The objectives of this chapter are:

- To quantify the components of the water balance in each cropping system and compare among cropping systems.
- To determine the precipitation use efficiency (PUE) for each cropping system and compare among cropping systems.

7.2. Data analysis and calculations

The water balance relationship for dryland crop production was adopted in the computation of soil water balance components (see also Chapter 2, equation 2.3).

$$Et_g + Es_g = ET = \left(P_g + \Delta S_g\right) - (R_g + D_{rg}) \qquad (7.1)$$

where P_g is the precipitation during the growing season (mm); Et_g is the water uptake by the plant roots, essentially the transpiration from crop canopy (mm); R_g is the run-off or run-on to the field during the growing season (mm); D_g is deep drainage beyond the root zone of the crop during the cropping season (mm); Es_g is the amount of soil evaporation (mm). It will be estimated from the difference between ET and Et_g estimated using transpiration efficiency coefficient (see equation 7.4) and ΔS_g is the seasonal change in soil water content of the root zone. Es_g was obtained using the following relationship:

$$Es_g = ET - Et_g \tag{7.2}$$

Where ET is the evapotranspiration and is the sum of P_g and ΔS_g (mm). The precipitation use efficiency (PUE_g) for the growing period was calculated using the relationship by Hensley *et al.* (2000) discussed in Chapter 2, equation 2.4.

The total biomass produced per unit area is directly related to the amount of water taken up during the corresponding period. The precipitation water efficiency (PUE_T) during the growing period was calculated using equation 7.3 (de Wit, 1958 in Hanks and Ramussen, 1982).

$$PUE_T = \frac{Y}{Et_g} \quad (\text{kg ha}^{-1}\ \text{mm}^{-1}) \tag{7.3}$$

PUE_T represents the water use efficiency based on transpiration rather than evapotranspiration. The estimate of the transpiration from the components of the intercrop was done using the following relationship using the transpiration efficiency coefficients for beans and maize.

$$Et_g = Y_b\left(\frac{\overline{D}_d}{\varepsilon_w D_b}\right) + Y_m\left(\frac{\overline{D}_d}{\varepsilon_w D_m}\right) \tag{7.4}$$

where Et_g is transpiration for both intercrop maize and bean components throughout the season (mm), Y_b is the cumulative above ground biomass yield for beans in kg ha^{-1}, Y_m the cumulative above ground biomass yield for maize in kg ha^{-1}, D_d is the mean daytime vapour pressure deficit for the growing period (kPa) and $\varepsilon_w D$ is the transpiration efficiency coefficient (g kPa kg^{-1}) for both beans (b) and maize (m) (from Chapter 3). The $\varepsilon_w D$ for beans used was 3.28 g kPa kg^{-1} and that for maize 9.4 g kPa kg^{-1}.

Many studies calculate precipitation use efficiency (PUE_g) on the basis of mass yield. In this study an attempt has been made to calculate it on the basis of monetary value (MV), energy value (EV) and glucose value (GV) (see Chapter 2, Section 2.8.5).

ANOVA was used to show statistical differences between treatments for primary production for final biomass and grain yield, water use (ET), soil surface evaporation (Es_g), transpiration (Et_g) and precipitation use efficiency (PUE_g) (Monetary value, energy equivalents and yield) during the seasons.

7.3. Results and Discussion

7.3.1. Characterization of the ecotope

Climate

Long-term climate data from Bloemfontein airport including rainfall, evapotranspiration and temperature are shown in Table 7.1. This data is representative of the experimental area and is therefore used to characterize the important climate variables. The high evaporative demand and relatively low rainfall experienced in the area make it semi-arid and therefore marginal for crop production generally during the summer months of November, December, January and February. Rainfall during the growing period is very erratic with much of it in the form of high intensity thunderstorm rainfall events. The evaporative demand decreases after mid-summer towards the winter months. Radiation is not limiting in the area, however, there is a decrease in temperature towards the winter period. The aridity index (AI) is lowest during the months of November, December and January which are the important months for crop production.

Table 7.1 Long-term monthly weather data for Bloemfontein Airport meteorological station for the last 34 years ending 1992 showing the growing months.

	Jan	Feb	Mar	Apr	May	Oct	Nov	Dec	$Mean^{*4}$
T_{max} (°C)	30.8	29.0	27.0	23.3	20.3	26.0	28.1	30.1	24.4
T_{min} (°C)	15.4	14.7	12.4	7.7	2.4	9.1	11.7	13.8	8.1
T_{ave}^{*1} (°C)	23.1	21.1	19.7	15.5	11.3	17.6	19.9	22.0	15.3
Rain (mm)	81.4	99.9	74.2	56.3	18.0	46.7	61.2	61.1	556.1
ETo^{*2}(mm)	298.2	229.2	186.4	185.2	112.9	224.3	252.5	290.9	192.3
AI^{*3}	0.27	0.44	0.40	0.30	0.16	0.21	0.24	0.21	0.22

T_{ave}^{*1} – Mean Temperature; ETo^{*2} – Penman Monteith; AI^{*3} – Aridity Index = rain/ETo, $Mean^{*4}$ – Annual values

Topography

The experimental site is located in an area which is generally flat with micro-relief being the dominant topographical factor. The land at the experimental plots slopes slightly towards the eastern and northern part. The general slope was estimated to be less than 2%.

Soil

Pedological characteristics

A detailed soil description for the site has not been done. However, two pits dug on the western and eastern sections were used for bulk density description of the site which is presented as Appendix 3. The soil is classified as belonging to the Bloemdal Vrede while the ecotope is Tempe/Valsrivier. There is a very slowly permeable layer within the 600-900 mm depth and below due to clay accumulation in this layer. Root water extraction was not detected below the 900-1200 mm and beyond. Mukhala (1998) determined the textural class for the soil at the experimental site (Table 7.2).

Table 7.2 Sand, silt and clay content determined by particle size method from soil samples obtained from the West Campus experimental site (adopted from Mukhala, 1998).

Depth (mm)	Sand (%)	Silt (%)	Clay (%)
0-300	65.3	9.4	20.0
300-600	73.4	5.8	26.0
600-900	58.5	11.0	31.0

Soil water extraction and drainage characteristics

The drained upper limit (DUL) was determined at the experimental site for the top 900 mm depth as 262.5 mm (Figure 7.1). DUL was defined as the highest field measured soil water content of a soil after it had been thoroughly wetted and allowed to drain until drainage became practically negligible (Ratliff *et al.*, 1983). Figure 7.1 shows the drainage curve determined during the growing season 2001/2002. According to the textural determination done by Mukhala (1998), clay content increases with depth down the profile reaching a maximum within the 600-900 mm layer. Consequently, the water holding capacity for the soil profile increases down the profile depth with highest DUL in the 600-900 mm layer. Further, this high clay content reduces deep percolation making drainage losses negligible and enables retention of water above this layer, especially after heavy rains. An examination of the soil water content measurements during the growing season shows high soil water content at 0-300 mm and 300-600 mm layers. The 600-900 mm layer had a more variable water content confirmed by the mottling and concretions observed at test pits and auger holes. Mottles depict frequent stagnation of water within a profile layer. The presence of the mottled effect made the true bulk density and therefore porosity of the layer difficult to determine.

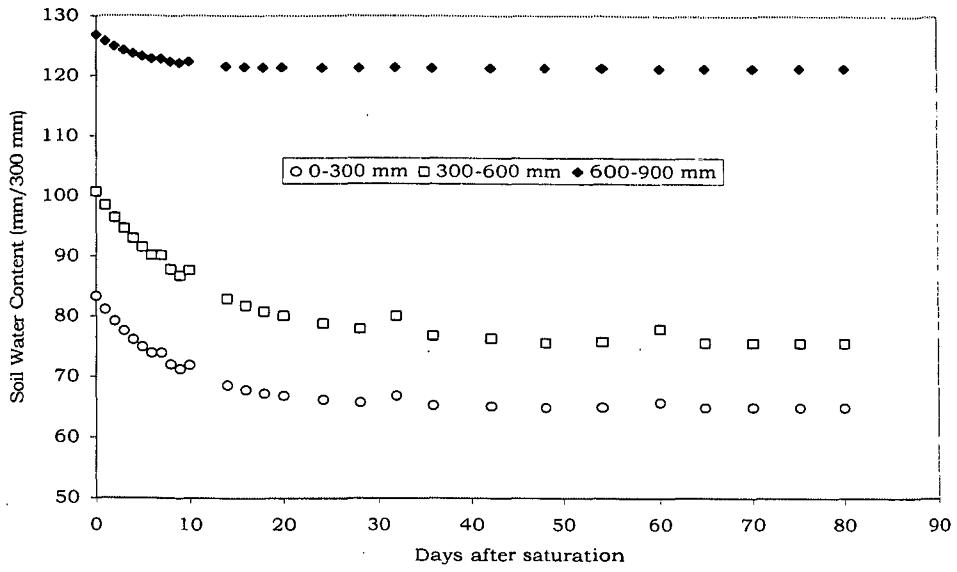


Figure 7.1. Drainage curve for the soil profile to a depth of 900 mm at a representative location within the experimental site.

From the perspective of crop production at the experimental site the 0-600 mm depth layer is therefore important as the part of the profile supplying water for the crop. The inference of greater root ramification can be made for this layer as the layer below is relatively inhospitable due to the high clay content and stronger structure.

The crop lower limit (CLL) of extractable water for the three cropping systems was determined over the profile depth of 900 mm. The lower limit was defined as the lowest field measured water content of the soil after plants had stopped extracting water and were at or near premature death or became dormant as a result of water stress (Ratliff *et al.*, 1983). Table 7.3 exhibit the values of DUL and CLL for the cropping systems over the total profile depth. The total extractable soil water (PAWC) was 114, 103 and 121 mm for sole maize, sole bean and intercrop respectively. The intercrop exhibited a slightly higher PAWC compared to the sole crop treatments. This was probably possible as a result of the potentially higher root ramification of the soil profile due to the high plant density for the intercrop being an additive sowing scheme.

The drainage curve (Figure 7.1) for the total profile was fitted to different models with the logistic model giving the best fit. The mathematical description for the total (0-900 mm) profile drainage is as follows:-

$$\theta_{DUL(0-900)} = \frac{262.5}{[(0.864\exp(-0.094t))]} \qquad \text{(mm)} \quad R^2 = 0.98 \qquad (7.5)$$

where $\theta_{DUL(0-900)}$ is the water content of the rootzone at the drained upper limit (mm) and t is the time in days after the drainage starts. The rate of drainage for the soil profile can be calculated by differentiating the equation 7.5. Similar curves can be fitted for each layer to determine the drainage rate from one layer to the next layer.

A simple relationship was used to confirm the saturated water content (θ_{sat}) for each of the profile layers. It was assumed that the saturated water content was 85% of total porosity, which is determined by the bulk density (BD), assuming bulk density of the mineral particles to be 2.65 (valid for quartz and aluminosilicate dominated soils):

$$\theta_{sat} = \left[1-\left(\frac{BD}{2.65}\right)\right] \times 85 \qquad (\%) \qquad (7.6)$$

The variation of θ_{sat} at the 0-300 mm layer was found to be very little:36.6±3.6%; while that at 400-600 mm layer was 31.7±3.1% and that at 700-900 mm was 38.9±3.4%. The mean θ_{sat} which represents the soil porosity was higher within the 0-300 mm and the 700-900 mm layer. Iron concretions were noted at 600-900 mm layer and may explain the higher saturation water content.

The high water content showed by the PAWC at the 600-900 mm layer confirms the high water content at saturation. As CLL is crop dependent, the CLL at the 600-900 mm layer may still be lower (Table 7.3), especially if the layer was not well ramified by crop roots. Mukhala (1998) found almost similar PAWC at 103 mm for the entire 0-900 soil mm depth, which is 7% lower than the mean for the cropping systems at 112.6 mm. His CLL determination was based on a soil texture calculation rather than the field measured crop lower limits and he used a single bulk density for the 0-900 profile layer.

Table 7.3. Description of the drained upper limit (DUL), cropping system lower limit (CLL) for soil water extraction and the total extractable water (PAWC) at each horizon and total water extraction for the whole profile.

Depth (mm)	DUL (mm)	Cropping system lower limit (CLL) (mm)			Total extractable soil water (PAWC) (mm)		
		SM	SB	IMB	SM	SB	IMB
0-300	64.9	22.3	28.3	21.7	42.6	36.6	43.2
300-600	75.6	57.8	60.4	54.5	17.8	15.2	21.1
600-900	121.3	68.1	69.8	64.6	53.2	51.5	56.7
Total	261.8	148.2	158.5	140.8	113.6	103.3	121.0

The DUL increased down the soil profile and was very high at 600-900 mm layer. Due to the high clay content the layer had a very high DUL value. The IMB exhibited the lowest CLL value indicating that the cropping system extracted more water then the SM and SB. It extracted 7 mm more than the SM and 18 mm more than the SB. This was probably due to the high plant density and therefore high soil volume root occupancy.

7.3.2. Seasonal water extraction

The seasonal water fluctuation for the whole profile to a depth of 900 mm and for the individual profile layers was examined. The figures 7.2 to 7.9 incorporate the limits for water extraction (DUL and CLL), the seasonal root zone water extraction and the seasonal rainfall pattern. These are used to evaluate the water extraction by the three cropping systems during the growing seasons. An analysis of the individual rootzone water extraction is done for each season and planting date to show extraction by cropping systems within these layers.

Season 2000/01 – planting 1

A total of 255 mm of rainfall was received during the cropping season. Nine of the rainfall events exceeded 10 mm and formed 184 mm (72% of the total amount of rainfall during the season). The rest of the events were below 10 mm and could have been lost immediately as evaporation, especially where the soil surface was exposed. The vegetative period between 20 and 60 DAS experienced many rainfall events lower than 10 mm, although the profile had approximately 30% and more PAWC. This was due to the high soil water content at the beginning of the season (at 270 mm and just slightly above DUL of 262 mm). This scenario underpins the importance of the pre-season water storage within the profile which compensates for the possible poor rainfall during the growing season. The soil water content dropped to near CLL for all cropping systems during the yield formation period 70 DAS and this could have had a serious effect on yield. The crop had to flower and mature with less than 30% of the PAWC (see Figure 7.2 and 7.3a-c).

The decline in the root zone water content exhibit almost similar extraction pattern for all cropping systems until DAS 40, subsequently, the sole maize extracted slightly more water than the other cropping systems, with sole beans having the lowest extraction. Overall, total profile water extraction differences between the cropping systems were not significant.

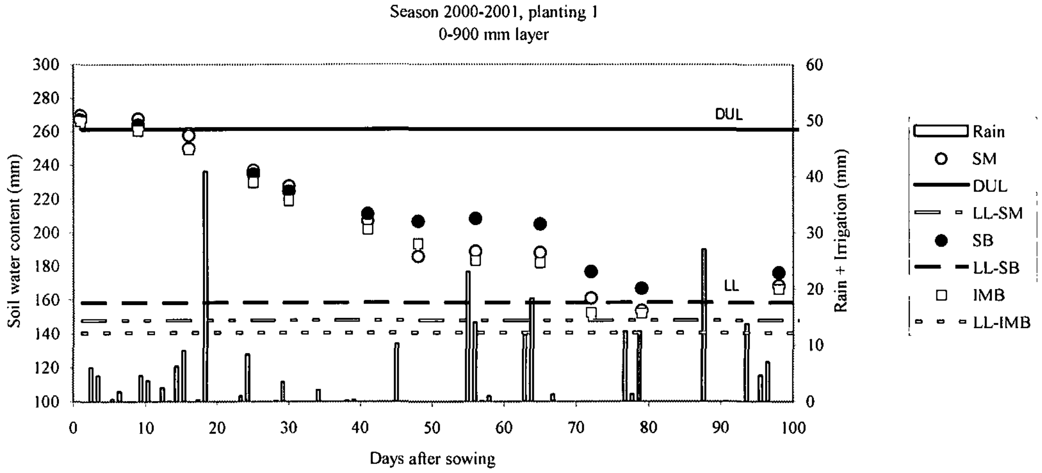


Figure 7.2. Measured changes in profile water content for 0-900 mm layer for cropping systems during 2000/01, planting 1 sole maize (SM), sole bean (SB) and intercrop (IMB).

Figures 7.3 (a), (b) and (c) show the water extraction for individual rootzone layers by sole bean, sole maize and intercrop respectively. All the systems showed a more rapid extraction within the 0-300 mm layer after DAS 25 with more than 75% of the water extracted to DAS 55. This period coincided with rapid leaf growth phase and confirms greater root ramification within this layer following the 40 mm precipitation on 19 DAS. The IMB had the highest extraction, followed by SM and finally SB. SM extraction only surpassed the IMB between DAS 45–55. This layer experienced greater fluctuation of soil water being the top layer and was also influenced by soil surface evaporation apart from the root extraction.

The 300-600 mm soil layer had soil water above DUL for almost half the season but with a narrow range for PAWC. The pattern for extraction was similar to that of 0-

300 mm layer. There was less soil water fluctuation and less rapid extraction compared to the top layer. More rapid extraction took place around flowering from 57-70 DAS for IMB and SM as maximum rooting depth is attained at reproductive time for determinate species. The 600-900 mm showed less rapid extraction during the vegetative period and a greater extraction after DAS 60 when the roots had apparently reached this layer and also during the time of greatest water demand due to high LAI.

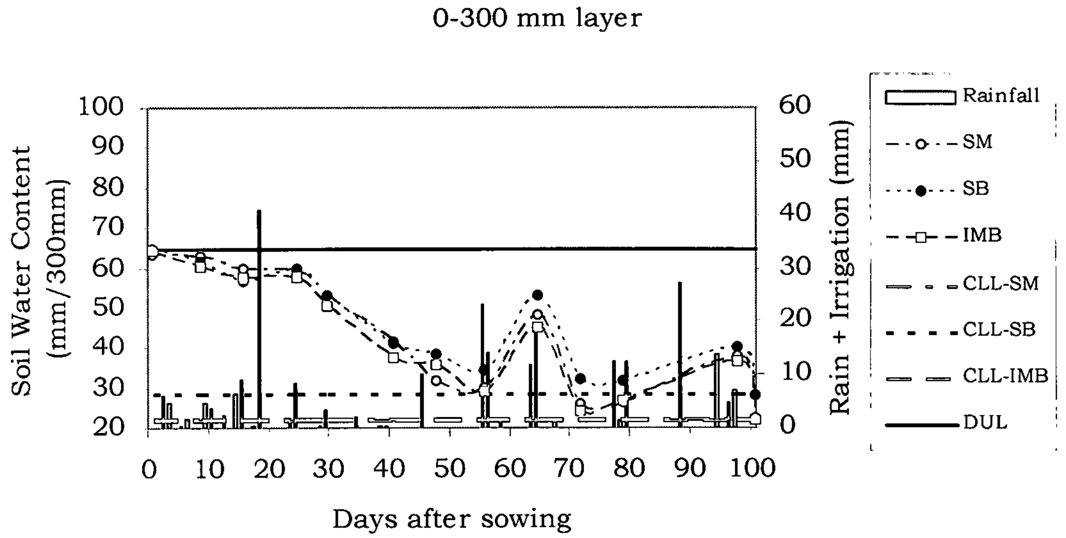


Figure 7.3 (a). Measured changes in rootzone water content for all cropping systems for 000-300 mm layer during 2000/01, planting 1 season.

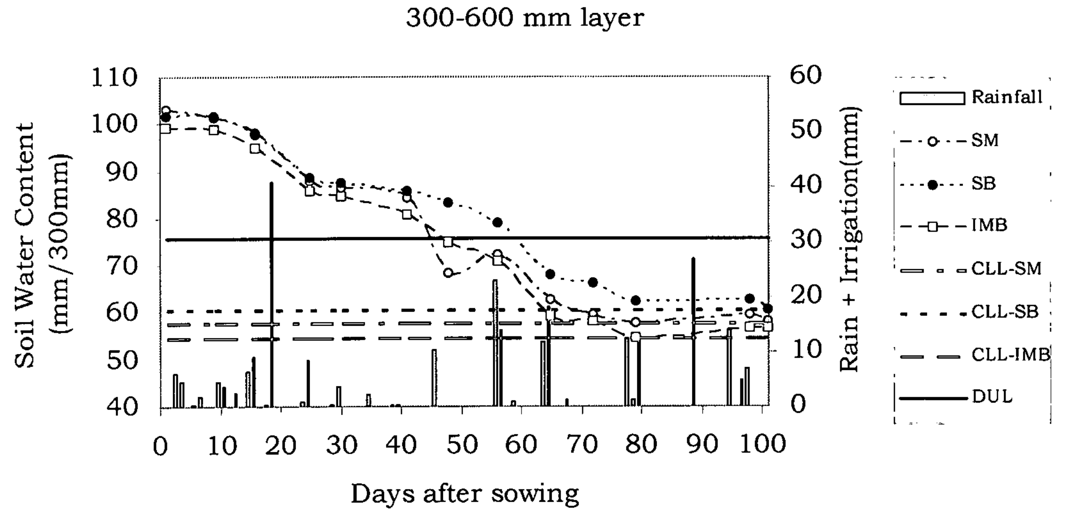


Figure 7.3 (b). Measured changes in rootzone water content for all cropping systems for 300-600 mm layer during 2000/01, planting 1 season.

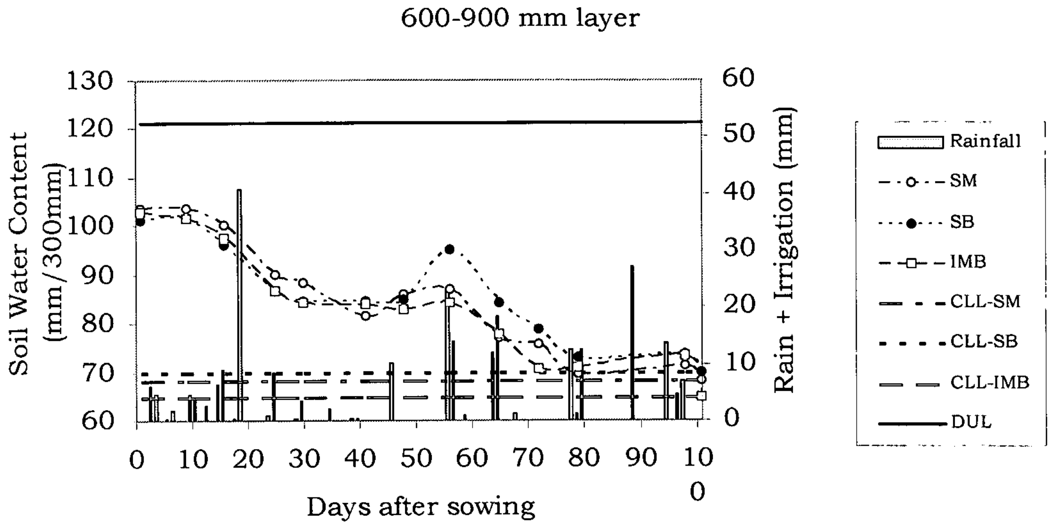


Figure 7.3 (c). Measured changes in rootzone water content for all cropping systems for 600-900 mm layer during 2000/01, planting 1 season.

Season 2000/01 – planting 2

This crop was planted on the 11/01/2001, a month after the 2000/01, planting 1, and therefore thrived during the cooler months of the late summer season. The starting soil water content was below DUL, but increased towards the end of the growing season. The lower starting water content was due to the water losses that took place before sowing.

This part of the season experienced a higher amount (325 mm) and better distribution of rainfall. The period had a lower mean evaporative demand as the season progressed towards the winter period. This ensured that the soil water content steadily increased towards the end of the season. The soil water content remained above CLL for all cropping systems until the end of the cropping period. The intercrop extracted more soil water, followed by the sole maize and sole bean during the season (see figure 7.4).

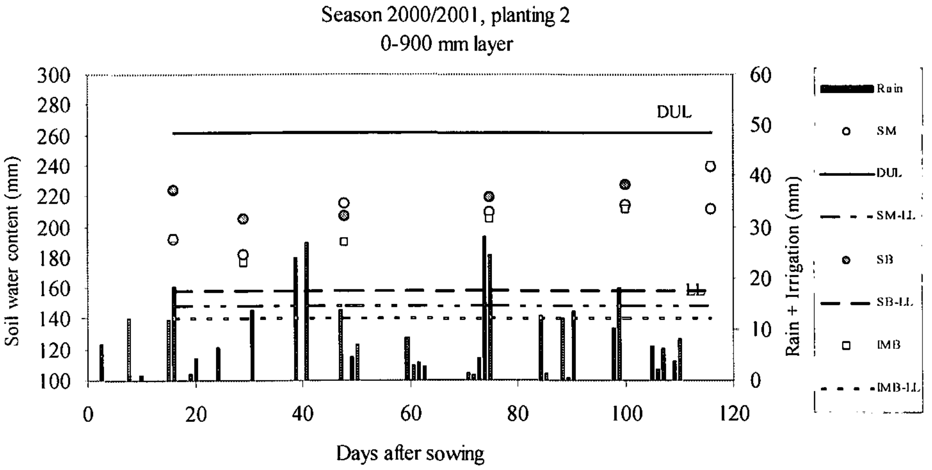


Figure 7.4. Measured changes in profile water content for 0-900 mm layer for cropping systems during 2000/01, planting 2 sole maize (SM), sole bean (SB) and intercrop (IMB).

An examination of the 0-300 mm layer, showed a higher extraction by SM, and IMB and lowest by SB (Figure 7.5 (a)). The IMB and SM extraction patterns were not significantly different, while the SB extracted much less water from this surface layer. The second planting was during the cooler period and therefore the lower evaporative demand influenced the soil water extraction. The 300-600 layer exhibited a more or less similar pattern as in the top layer. SM ended with greater depletion at the end of the season (Figure 7.5 b)

SB exhibited soil water content above DUL during the whole season at the 300-600 mm layer as in the first planting. SM had a lower θv at the beginning of the season, however this increased to DUL due to the rainfall events around DAS 40. The SM extracted more water around the yield formation period.

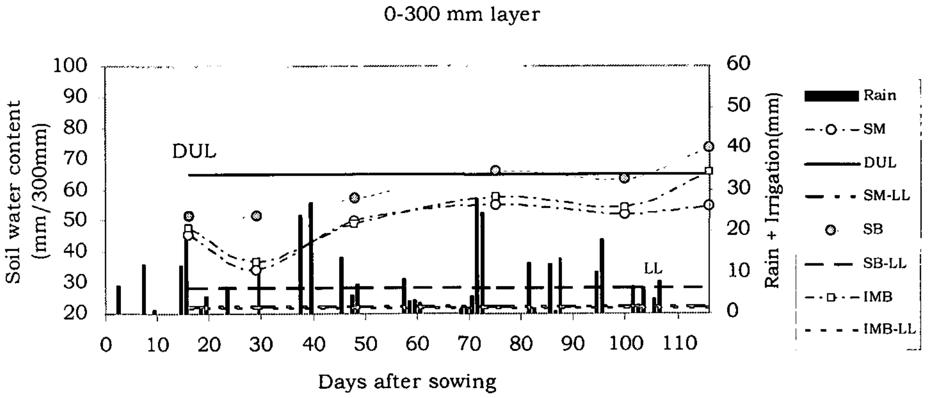


Figure 7.5 (a). Measured changes in rootzone water content for all cropping systems for 000-300 mm layer during 2000/01, planting 2 season.

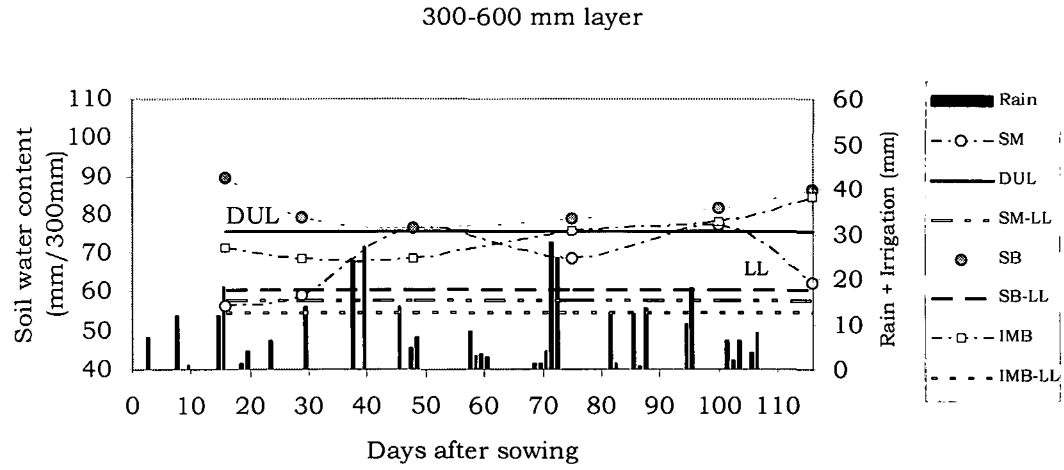


Figure 7.5 (b). Measured changes in rootzone water content for all cropping systems for 300-600 mm layer during 2000/01, planting 2 season.

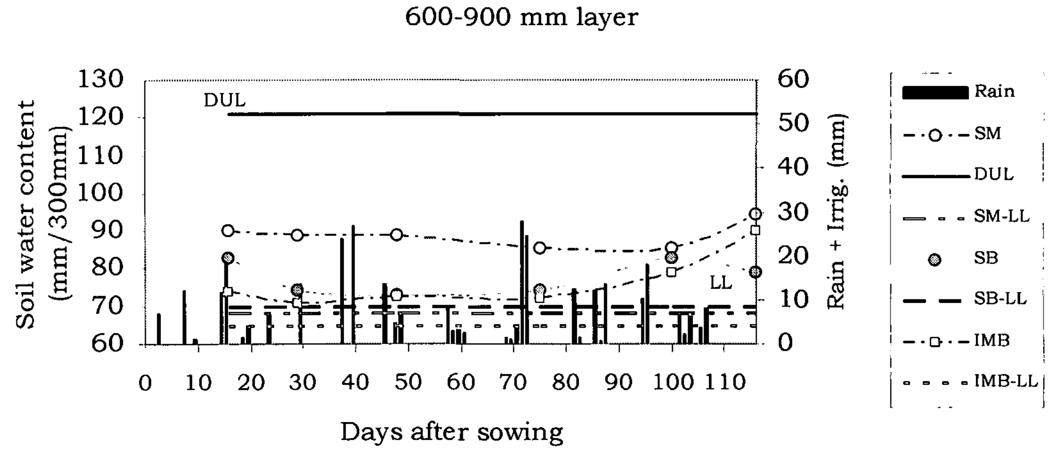


Figure 7.5 (c). Measured changes in rootzone water content for all cropping systems for 600-900 mm layer during 2000/01, planting 2 season.

Season 2001/02 – planting 1

The season had a total of 331 mm rainfall and irrigation, which was well distributed in comparison to the first season, planting 1. The soil water content at the beginning of the season until DAS 20 was above DUL. This indicates that pre-season storage and rainfall maintained water content at substantially high level that met crop water demand at the initial and vegetative growth stages. Due to the storage and good rainfall during the season the cropping systems did not experience severe stress during most of the vegetative and the reproductive period stages. This is also shown by the relatively high leaf area development during this season. Even at the close of the season the soil water content was still above CLL for all cropping systems (Figure 7.6). Substantial decline in soil water content is noted after DAS 50, which marked the reproductive phase for the maize crop. SM exhibited the highest extraction throughout the season, followed by IMB and lastly SB.

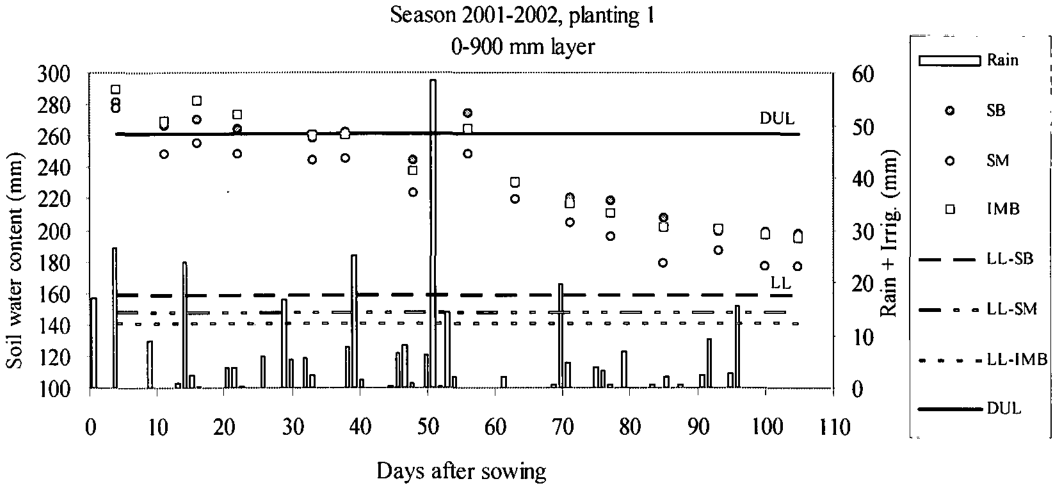


Figure 7.6. Measured changes in profile water content for 0-900 mm layer for cropping systems during 2001/02, planting 1 sole maize (SM), sole bean (SB) and intercrop (IMB).

The individual soil layer water extraction is shown in Figures 7.7 (a), (b) and (c). All the cropping systems exhibited similar pattern of extraction within the 0-300 mm layer. θ_v was above DUL initially but declined to below it after DAS 10-20. There were large fluctuations of soil water in this layer due possibly to influence of rainfall and soil surface evaporation. SM and SB had the highest extraction from the beginning of the season until DAS 35. IMB had the highest extraction from DAS 35 to 50, followed by SM and lowest SB. The differences between the cropping system extractions were not significantly different. From DAS 75 to end of the season SM exhibited the highest extraction, followed by IMB and lastly SB. In the 300-600 mm layer soil water content was above DUL for most of the season for all the cropping systems. The SM and SB exhibited the highest extraction almost throughout the season. IMB had the lowest extraction within this layer (Figure 7.7 (b)). In the 600-900 mm layer there was little extraction by all cropping systems until after 55 DAS the SM showed the highest extraction, followed by IMB and lastly SB. There was a marked extraction after DAS 60 to end of the season by all cropping systems. At this time the roots were well established and the demand for water was high after flowering.

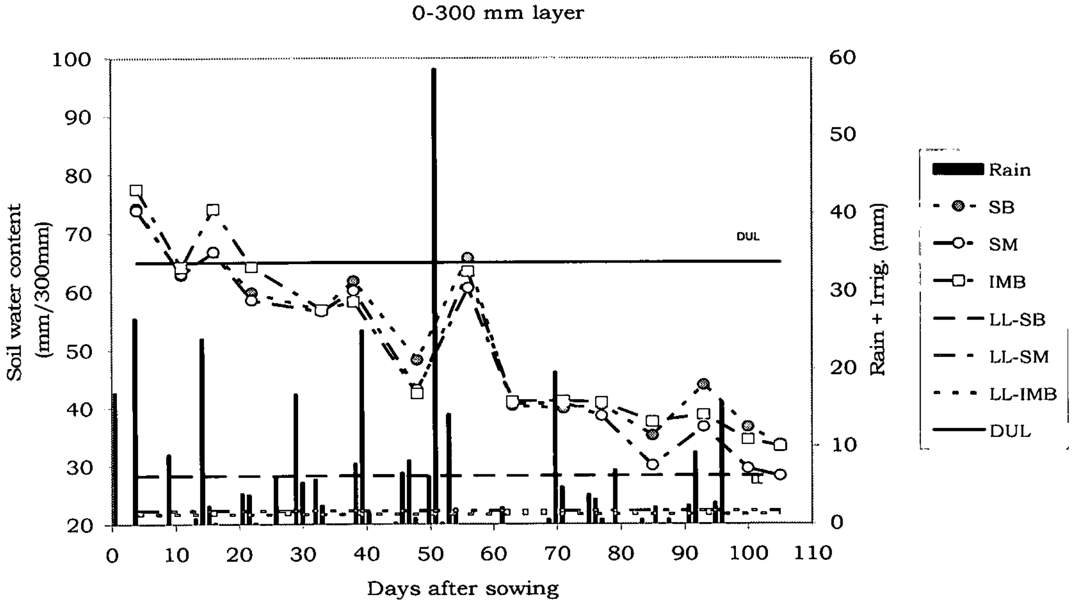


Figure 7.7 (a). Measured changes in rootzone water content for all cropping systems for 000-300 layer mm during 2001/02, planting 1 season.

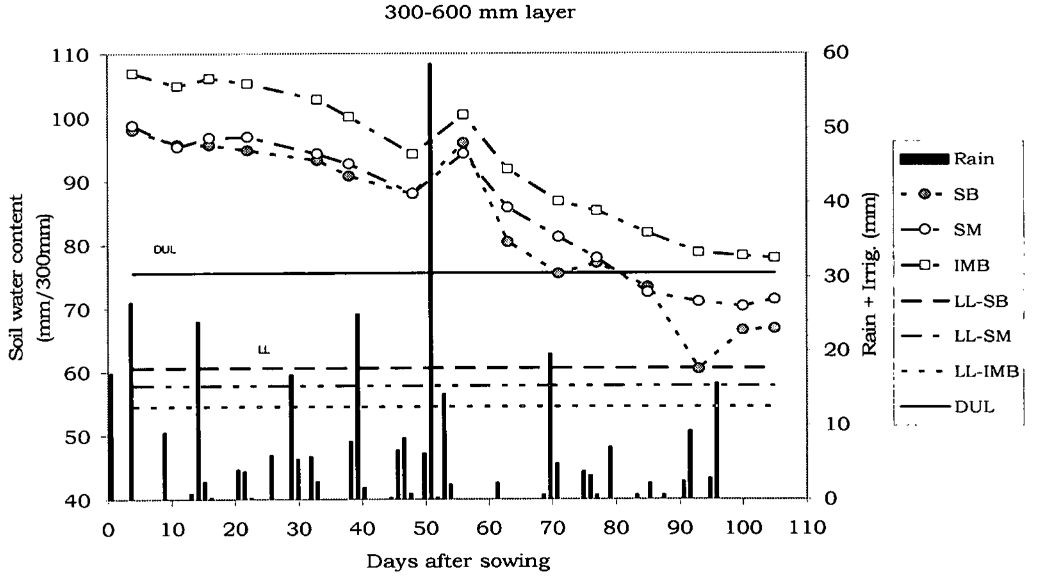


Figure 7.7 (b). Measured changes in rootzone water content for all cropping systems for 300-600 mm layer during 2001/02, planting 1 season.

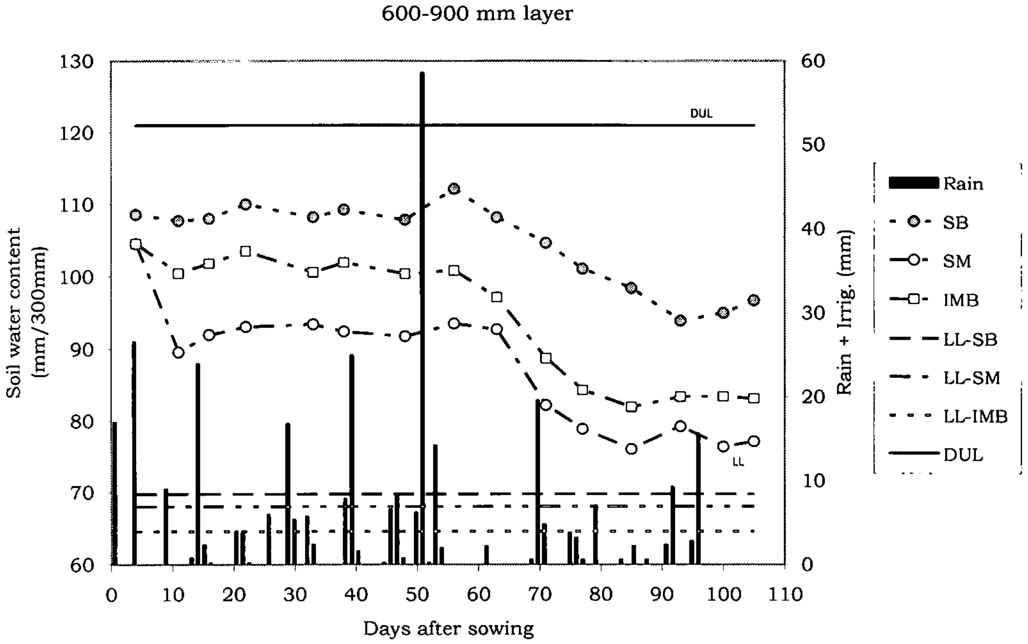


Figure 7.7. (c). Measured changes in rootzone water content for all cropping systems for 600-900 mm layer during 2001/02, planting 1 season.

Season 2001/02 - planting 2

The soil water content was below DUL initially and rose above it after the rainfall events around DAS 20 (Figure 7.8). The season was obviously less stressful for crop production as θ_v for all cropping system remained substantially above CLL until the end of the season. Much rain fell during the first 25 days of this season. The rainfall was less well distributed after this until the end of the season compared to season 2000/01, planting 1. The period between DAS 65 to the end of the season had a dry spell which was not very favorable for yield formation. The gradual decline of θ_v compared to season 2001/02, planting 1 could be attributed to the lower atmospheric demand as the period progressed towards the winter months.

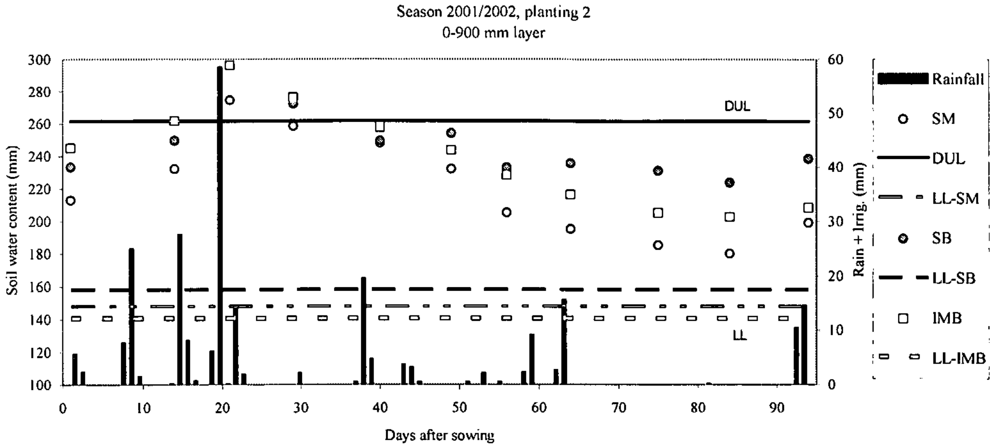


Figure 7.8. Measured changes in profile water content for 0-900 mm layer for cropping systems during 2001/02, planting 2 sole maize (SM), sole bean (SB) and intercrop (IMB).

Sole maize showed the lowest θv during the season compared to the sole bean and the intercrop. Its initial θv was about 210 mm which rose to 270 mm at DAS 21 due to the rains that fell before this time. The SM, θv then declined gradually towards the end of the season attaining 180 mm on DAS 85. The IMB exhibited almost the same pattern of θv as the SB, but diverged at DAS 57, when it extracted more water and declined towards almost a similar θv of 200 mm as the SM at the end of the season (Figure 7.8).

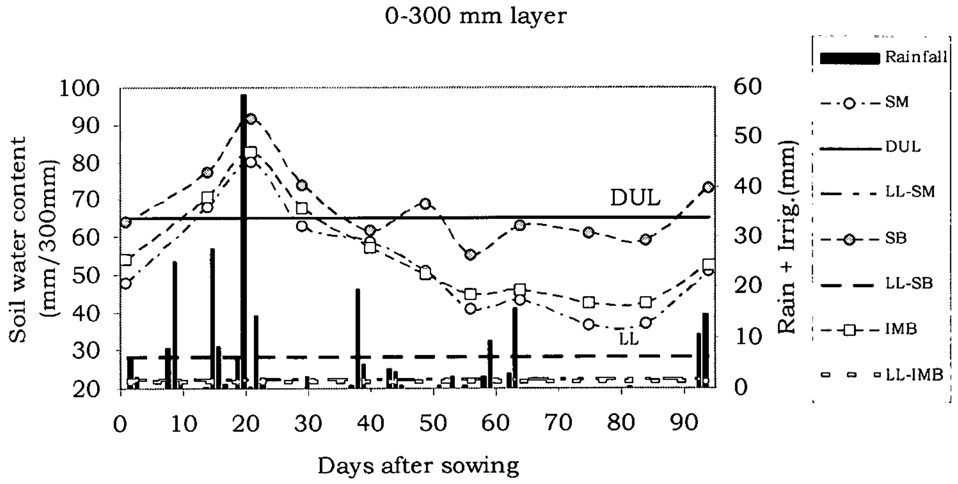


Figure 7.9. (a). Measured changes in rootzone water content for cropping systems for layer 000-300 mm during 2001/02, planting 2 season.

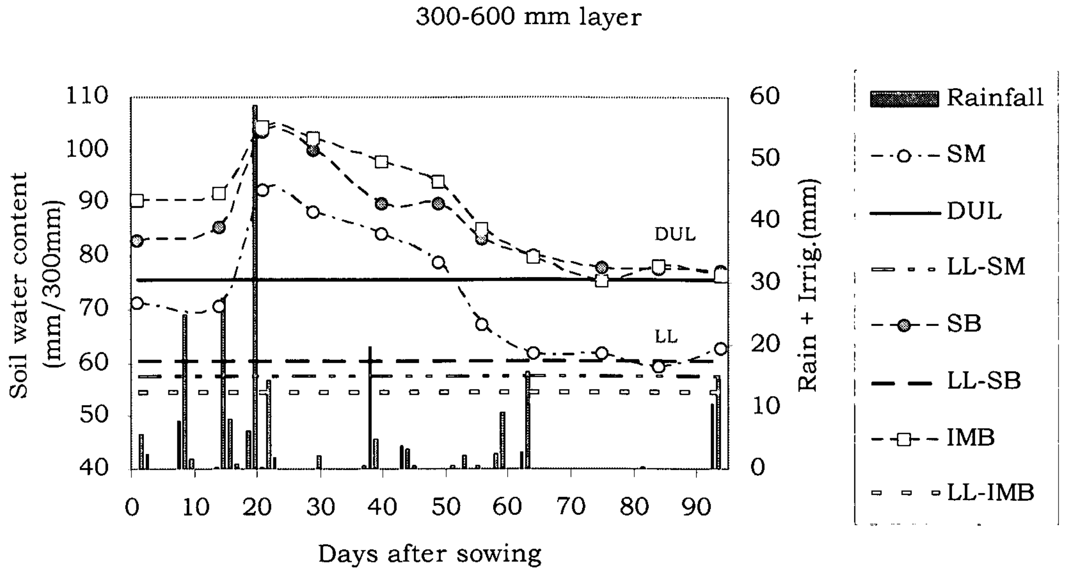


Figure 7.9 (b). Measured changes in rootzone water content for cropping systems for layer 300-600 mm during 2001/02, planting 2 season.

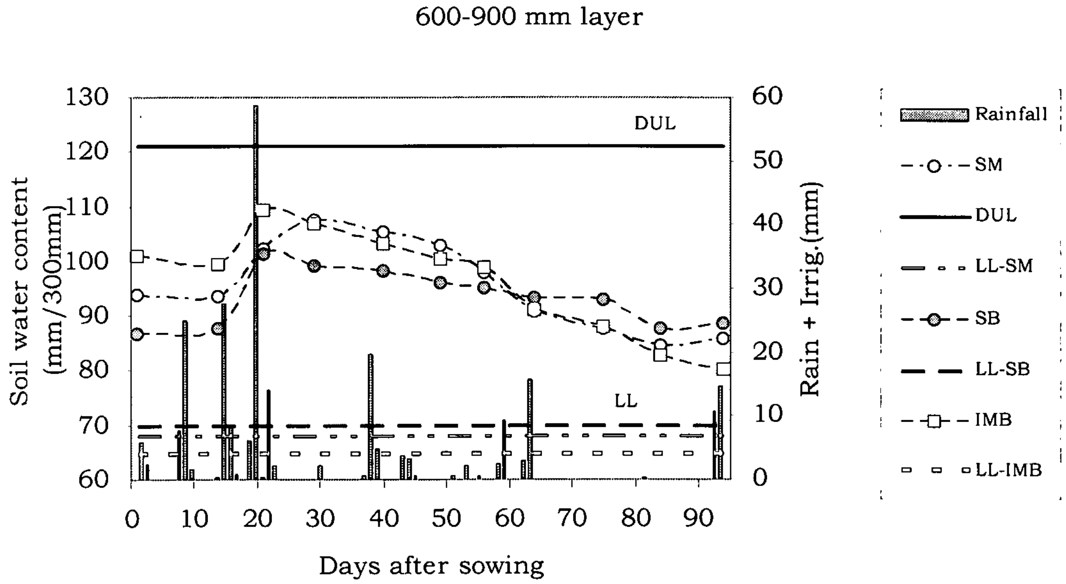


Figure 7.9 (c). Measured changes in rootzone water content for cropping systems for layer 600-900 mm during 2001/02, planting 2 season.

Figures 7.9 (a), (b) and (c) exhibit the seasonal θ_v fluctuation by profile layers during the season. Layer 0-300 mm shows that the SM extracted the highest amount of water, followed by the IMB and SB remain near to DUL. After DAS 40 there was more divergence between the IMB, SM and SB water extraction. It shows that these cropping systems had established well established roots within this layer and were extracting more water than the SB. None of the cropping systems could extract to CLL within this layer even by the end of this growing season.

In the 300-600 mm layer there was a higher extraction by SM, followed by SB and finally IMB. The water content was above DUL for a good part of the season for SB and IMB cropping systems. SM had a substantial extraction after DAS 50 to the end of the season and was the only cropping system operating below DUL for a good part of the cropping season. In the 600-900 mm layer there was little extraction by any of the cropping systems except towards the end of the season during the dry spell. The SB exhibited the lowest θ_v until DAS 60 after which, the IMB had the highest extraction. The θ_v for all the cropping systems was below DUL throughout the season. This shows that the water in this layer is available to the maize roots if the 300-600 mm layer has been depleted and there is no further addition of water.

7.3.3. Precipitation use and production efficiency

Water balance components

The final above ground biomass was used to calculate the crop transpiration for each of the cropping system. Mean daytime vapour pressure deficit (7:00-17:00 hours–SAST) for the season was used with the $\varepsilon_w D$ value and above ground biomass to calculate the cumulative Et_g (equation 7.4). The resulting transpiration was then deducted from the total water use ($P_g+\Delta S_g$) for the season (ET) by each cropping system to determine E_s. The cumulative transpiration and other components of the water balance for the season estimated on the basis of above ground dry mass are shown in Table 7.4. The ET was estimated as the sum of the growing season rainfall and measured ΔS_g. ΔS_g is the difference between the measured initial water content at planting and the measured final water content at harvest.

Table 7.4. Water balance for the cropping systems during the seasons 2000/01 and 2001/02 and sowing dates with Es_g calculated using the transpiration efficiency coefficient for dry bean and maize.

Season	Planting	Treatment	$P_g{}^{*1}$ (mm)	$\Delta S_g{}^{*2}$ (mm)	$D_g{}^{*3}$ (mm)	$R_g{}^{*4}$ (mm)	$P_g+\Delta S_g{}^{*5}$ (mm)	$Et_g{}^{*6}$ (mm)	$Es_g{}^{*7}$ (mm)
2000/01	1	SB	255	109	0	0	363	265	99
2000/01	2	SB	325	-15	0	0	310	236	74
2001/02	1	SB	331	84	0	0	415	176	238
2001/02	2	SB	254	-5	0	0	249	191	58
2000/01	1	SM	255	121	0	0	376	236	140
2000/01	2	SM	325	-20	0	0	305	139	165
2001/02	1	SM	331	100	0	0	431	178	253
2001/02	2	SM	254	14	0	0	268	152	116
2000/01	1	IMB	255	123	0	0	378	305	72
2000/01	2	IMB	325	-48	0	0	277	258	19
2001/02	1	IMB	331	95	0	0	426	230	196
2001/02	2	IMB	254	36	0	0	291	202	88

$P_g{}^{*1}$ is the precipitation during the season (mm); $\Delta S_g{}^{*2}$ is the difference between the measured sowing time soil water and final harvest soil water content (mm); $D_g{}^{*3}$ is the drainage (mm); $R_g{}^{*4}$ is the run-off or on during the season (mm); $P_g+\Delta S_g{}^{*5}$ is the evapotranspiration (mm); $Et_g{}^{*6}$ is the transpiration (mm) calculated using $\varepsilon_w D$ for beans and maize respectively (see equation 7.4), $Es_g{}^{*7}$ is the soil surface evaporation (mm) calculated as $(P_g+\Delta S_g)$- Et_g.

An analysis of the ET data showed planting 1 had a higher mean water use at 398 mm (E_g+ Et_g) compared to planting 2 at 283 mm mean for all treatments. The seasonal differences were significant at $p = 0.05$ (p-value: 0.000966). The SM had the highest mean Es_g+ Et_g during the season (344.8 mm) (n=4), followed by IMB (342.8 mm) and lastly SB (334.2 mm). The differences between the treatments were however not significant at $p = 0.05$. This analysis shows that the IMB had similar water use although it had a higher plant density at 120,000 plant compared to the SM at 40,000 plants. The likely reason for this result was perhaps due to the higher Es_g within the SM compared to the IMB during the season. Secondly, the intercrop exhibited an early and higher leaf area index compared to the sole crops as shown in Table 7.5. This most evidently reduced the energy available for soil surface evaporation and also modified the microclimate within the cropping system through higher transpiration and consequently lower vapour pressure deficit.

Table 7.5. Mean leaf area index for the cropping systems during the two seasons and planting dates. The abbreviation are: SM- Sole Maize; SB - Sole Beans; IMB – Intercrop Maize and Bean.

Season	**2000/01**			**2001/02**		
Planting 1	**SM**	**SB**	**IMB**	**SM**	**SB**	**IMB**
DAS						
0-20	0.05	0.35	0.35	0.28	0.34	0.60
20-40	0.60	0.56	0.99	1.03	1.02	2.30
40-60	1.93	0.91	2.20	2.62	3.03	6.12
60-80	2.37	1.46	3.52	2.90	3.08	5.32
80-100	2.40	2.36	4.31	3.00	1.51	3.58
Planting 2						
0-20	0.02	0.00	0.02	0.78	0.78	1.60
20-40	0.07	0.03	0.12	1.91	2.06	3.46
40-60	0.29	0.36	0.74	2.29	2.65	3.86
60-80	0.87	2.18	3.14	2.12	0.82	2.50
80-100	1.63	4.16	6.27	0.27	0.27	0.55

The second planting had a lower overall mean Et_g compared to the first planting. IMB had the highest mean Et_g during both plantings and seasons while SB and SM are close together. The trend for Et_g during planting 1 for the other treatments was SM≈SB, while SB>SM during planting 2. The overall mean Et_g was IMB>SB>SM with the means being 248.8, 217.0, 176.3 mm respectively with no statistical differences between treatments at p=0.05. The mean overall trend for Et_g as a percentage of water use (ET) was: IMB>SB>SM with values of 74.4 ± 16.7%, 67.1 ± 16.5% and 51.6 ± 9.9% respectively. These differences were not significant at p = 0.05. The analysis of the Et_g as a % of ET is shown in Table 7.6.

Table 7.6. Soil surface evaporation and transpiration as percentage of rainfall and evapotranspiration among the cropping systems during the two cropping seasons (2000/01 and 2001/02).

	% Es_g of P_g*		% Es_g of ET*		% Et_g of ET*	
Treatment	2000/01	2001/02	2000/01	2001/02	2000/01	2001/02
Planting 1						
SB	39	72	27	58	73	42
SM	55	77	37	59	63	41
IMB	29	59	19	46	81	54
Planting 2						
SB	23	23	24	23	76	77
SM	51	46	54	43	46	57
IMB	06	35	07	30	93	70

* see Table 7.4 on water budget for definitions of abbreviations used here.

Planting 1 had a higher mean Es_g compared to planting 2 for all plantings and seasons, although the differences were not statistically significant at p = 0.05. SB had the lowest mean Es_g occurring during planting 1, followed by SM and lastly IMB. During planting 2, SM had the highest mean Es_g compared to SB. Overall, the trend of Es_g was as follows: SM>SB>IMB with the mean values of 168.6, 117.2 and 93.7 mm respectively. The Es_g as a percentage of seasonal water use showed the following trend: SM>SB>IMB with values of 48.4 ± 9.9%, 32.9 ± 16.5% and 25.6 ± 16.7% respectively. These differences were however not significant at $p = 0.05$. The Es_g as a percentage of seasonal precipitation showed the following trend: SM>SB>IMB with no statistical differences between the treatment means at $p=0.05$. The Es_g as percentage of P was 56.9 ± 13.6%, 39.0 ± 23.3% and 32.1 ± 21.9% for SM, SB and IMB respectively. Table 7.6 shows the individual values for the cropping systems during all seasons and planting dates. Table 7.6 shows that Es_g as a percentage of P was lower for IMB during both seasons and planting dates. Considered together with LAI values in Table 7.5, it can be concluded that the reasons for the low Es_g was because of the higher LAI within the intercrop compared to the other cropping systems. The progression of LAI graphs shown in Chapter 4, also confirms the early higher LAI and the overall high LAI for the IMB during all the seasons.

Bennie *et al.*, (1994) reported bare soil evaporation as a percentage of rainfall of 60-70% under similar conditions. This indicates a water saving difference of 35-48% between IMB and the bare soil situation. The lower E_g on the other hand meant that most of the water saved was used by the crop for transpiration. This is confirmed by the higher transpiration estimates for IMB cropping system during both seasons.

Biomass and grain yield

The final grain yield for both maize and dry beans was used to calculate the precipitation use efficiencies for each of the cropping systems. Table 7.7 shows the biomass and grain yields for all the seasons. The yields were converted to monetary, energy and glucose equivalents to enable the calculation of precipitation use efficiency based on the different values for comparison of cropping systems. The conversions into energy equivalent was done by using 17.8 kJ g^{-1} and 16.8 kJ g^{-1} for maize cob and bean seed respectively (Tsubo, 2000).

Table 7.7. Biomass and grain yield for the cropping systems during the seasons 2000/01 and 2001/02.

Season	Planting	Treatment	Grain yield (kg ha^{-1})	Biomass yield (kg ha^{-1})	Harvest Index (HI)
2000/01	1	SB	1690	5386	0.31
2000/01	2	SB	1740	5901	0.29
2001/02	1	SB	2880	5270	0.55
2001/02	2	SB	1490	5385	0.28
2000/01	1	SM	2490	13531	0.18
2000/01	2	SM	3410	9810	0.35
2001/02	1	SM	4960	14936	0.33
2001/02	2	SM	4490	12017	0.37
2000/01	1	IB	880	3991	0.22
2000/01	2	IB	1890	4236	0.45
2001/02	1	IB	1060	2485	0.43
2001/02	2	IB	740	1817	0.41
2000/01	1	IM	1340	6263	0.21
2000/01	2	IM	1660	6217	0.27
2001/02	1	IM	4010	12383	0.32
2001/02	2	IM	3860	10906	0.35

Precipitation use efficiency

The benefit intercropping confers on water use by crops is probably due to the higher transpiration and the lower Es_g by this cropping system. Its ability to achieve early higher LAI, a much larger leaf area index and other aspects enable the cropping system to have a lower Es_g and therefore extract more of the water as Et_g. The use of transpiration efficiency coefficient made it possible to separate the Es_g and Et_g for the IMB and therefore partition the water use components further than is normally possible. It was therefore useful to do comparisons of precipitation use based on ET as well as Et_g Without losses of water in the form of R and Dr, PUE_g is equivalent to WUE_{ET}. Table 7.8 shows the PUE calculated on the basis of monetary value (MV), energy value (EV) and glucose value (GV). The PUE_g was also calculated on the basis of ET and Et_g.

Table 7.8. Seasonal PUE analysis based on energy value (EV), Monetary value (MV) and Glucose value (GV) for each of the cropping systems and planting dates during the 2000/01 and 2001/02 seasons.

		Water balance components (mm)								PUT_{ET}			PUE_{T}		
			P	ΔS	D	R	Es+T	T	Es	MV	EV	GV	MV	EV	GV
Season	Planting	Treatment	mm	mm	mm	mm	mm	mm	mm	R/ha/mm	MJ/ha/mm	GV/ha/mm	R/ha/mm	MJ/ha/mm	GV/ha/mm
2000/01	1	SB	255	109	0	0	363	265	98	30	78	9	41	107	12
2000/01	2	SB	325	-15	0	0	310	236	74	36	118	11	47	124	14
2001/02	1	SB	331	84	0	0	415	176	239	45	102	13	105	275	31
2001/02	2	SB	254	-5	0	0	249	191	58	38	94	11	50	131	15
2000/01	1	SM	255	121	0	0	376	236	140	8	199	8	12	188	13
2000/01	2	SM	325	-20	0	0	305	139	165	13	221	14	29	437	30
2001/02	1	SM	331	100	0	0	431	178	253	13	117	14	33	496	34
2001/02	2	SM	254	14	0	0	268	152	116	20	205	21	35	526	36
2000/01	1	IMB	255	123	0	0	378	305	73	19	209	9	24	127	11
2000/01	2	IMB	325	-48	0	0	277	258	19	51	101	20	55	238	22
2001/02	1	IMB	331	95	0	0	426	230	196	27	298	16	50	388	30
2001/02	2	IMB	254	36	0	0	291	202	89	32	279	21	46	402	30

The analysis of PUE_g on the basis of ET for the cropping systems in monetary term was 37.3 ± 6.1, 13.5 ± 4.8 and 32.2 ± 13.5 ZAR ha^{-1} mm^{-1} for SB, SM and IMB respectively. There was statistical difference (LSD) between the SB and SM and between SM and IMB at p=0.05. The IMB exhibited a higher standard deviation showing that there was high variability in the PUE_g based for IMB during the seasons and planting dates. The same analysis based on Et_g gave the following values: 60.9 ± 29.7, 27.0 ± 10.1 and 43.5 ± 13.7 ZAR ha^{-1} mm^{-1} for SB, SM and IMB respectively. There was a statistically significant difference between the SB and SM at p=0.05. Mean gross ZAR earning per mm transpired water were used rather than gross margins as data on variable costs were not available. Intercropping as practiced among smallholdings attracts relatively little purchased inputs, and given the advantages associated with this practices such as weed and pest suppression may perform better if gross margins are considered.

The analysis of PUE_g on the basis of EV showed the following trend: 98.2 ± 16.5, 185.5 ± 46.8 and 221.9 ± 89.5 MJ ha^{-1} mm^{-1} for SB, SM and IMB respectively. There was statistical difference (LSD) between the SB and IMB at p=0.05. The IMB exhibited the highest PUE_g base on ET (Table 7.8). The same analysis based on Et_g gave the following values: 159.2 ± 77.8, 411.8 ± 153.7 and 288.4 ± 130.9 MJ ha^{-1} mm^{-1} for SB, SM and IMB respectively. There was a statistically significant difference between the SB and SM but not between SB and IMB at p=0.05. This shows that the IMB performed better on the basis of total seasonal water use (ET) while the SM did better on the basis of Et_g. The SB was the worst in performance using the PUE_g on the basis on EV.

Lastly the treatments PUE_g were compared on the basis of assimilate glucose value. The analysis of PUE_g on the basis of GV showed the following trend: 10.9 ± 1.8, 14.2 ± 5.1 and 16.6 ± 5.7 g g^{-1}glucose ha^{-1} mm^{-1} for SB, SM and IMB respectively. There was no statistical difference (LSD) between the treatments at p=0.05. The IMB exhibited the highest PUE_g base on GV (Table 7.8). The same analysis based on Et_g gave the following values: 17.9 ± 8.7, 28.5 ± 10.7 and 23.3 ± 9.2 g g^{-1} ha^{-1} mm^{-1} for SB, SM and IMB respectively. There was a statistically significant difference between the means for the treatments at p=0.05. This shows that the SM performed better on the basis of both total seasonal water use (ET) and Et_g based on assimilate glucose value.

7.3.4. Production risk analysis

Figure 7.10 shows the cumulative distribution function (CDF) analysis for the SPI categories for the area for 30 years of rainfall data for Bloemfontein area. The CDF values were calculated for the annual, pre-season (April-November), season 1 (November-end March) and season 2 (January-end April) long term precipitation values. Positive SPI indicate greater than mean precipitation, while negative values indicate less than mean precipitation. It shows that for nearly all the periods of calculation the probability of not exceeding zero SPI value is 60%. The SPI values for both seasons and planting dates fell in the near normal drought category with SPI values of 0.2 (68% probability of non-exceedance) and -0.3 (48% probability of non-exceedance) for planting 1 and 2 respectively. The scenario is that during planting 1 the chance of attaining this category of drought or worse is almost 7 out of 10 years, while in season 2 it is almost 1 out of every 2 years.

This confirms the fact that the region is generally dry and hence soil water storage and seasonal rainfall is crucial in meeting plant water requirements during the growing season. Analysis of the probabilities for the 12 month and pre-season precipitation is therefore important. The winter and spring period which forms the pre-season period is cooler, therefore any precipitation during this period is conserved due to low atmospheric evaporative demand. This later becomes available to the summer crop during the growing season.

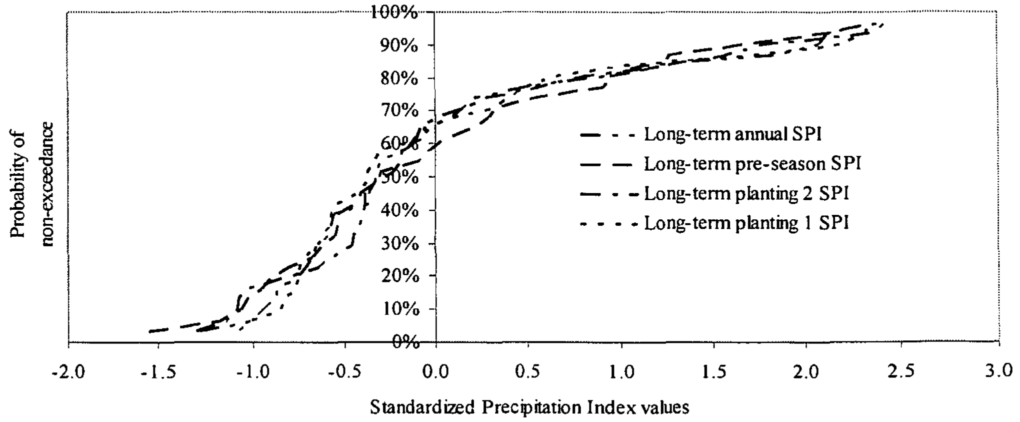


Figure 7.10. Probability of non-exceedance for SPI drought categories calculated using long term precipitation values for Bloemfontein. Long-term annual, pre-season, planting 1 and planting 2 drought categories have been used in the CDF calculation.

However, the probability values for all the SPI do not differ substantially, showing that during most of the years, summer growing rainfall forms the major portion of the water use for summer crop production.

A total consideration of the productivity of the ecotope requires taking account of all soil-cropping system-atmospheric variables that may limit crop production. In this environment precipitation forms one of the most important factors contributing to productivity and therefore the probability relating to its occurrence quantifies the possible risk faced by the production system.

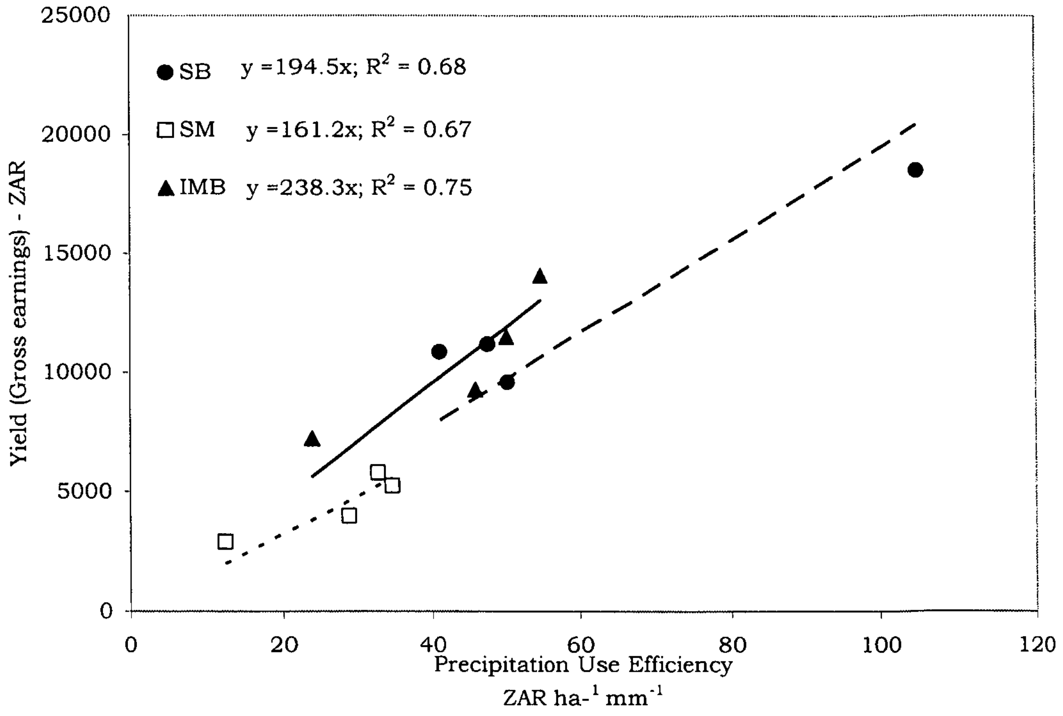


Figure 7.11. Plot of yield in monetary value (ZAR) against precipitation use efficiency based on ET and Et_g for cropping systems.

The relationship between the precipitation use efficiency and the yield based on monetary value gave a $R^2 \geq 0.65$ for the cropping systems with IMB having the highest $R^2 = 0.75$ (see Figure 7.11). The figure 7.11 shows that PUE_g accounted for more than 65% of the gross monetary returns from cropping systems and for more than 75% of the intercrop gross earnings. This is most probably true given that more of the water input as rainfall was put into biomass production in this cropping system compared to the other cropping system that lost more of the water input in the form of soil evaporation.

7.4. Conclusions

Bennie *et al.* (1994) observed that bare soil evaporation during fallow period can amount to 60-70% of rainfall. These observations were made for similar conditions under which this experiment took place (i.e semi-arid conditions of South Africa). The only difference in this study was the presence of the three different cropping systems. During the two seasons it varied between 26-49% of rainfall under the cropping systems. The results revealed lower soil evaporation for the intercrop during all the planting dates and a variety of conditions. The sole crop maize and beans had more or less similar soil surface evaporation during the seasons (Table 7.4). This confirms what has already been alluded to in many studies that intercropping system, due to an early and higher LAI is able to reduce the amount of energy available for soil surface evaporation between crops. Secondly, chapter 5 shows that the intercrop had lower vapour pressure deficit within its canopy. This lowers the capacity of the canopy to accept more water from whatever source. Water that is available at the surface is therefore lost at a slower pace than in the other cropping systems. Lower turbulence is inferred from the lower vapour pressure within the canopy i.e water vapour transport is apparently lower within the intercrop canopies compared to the sole crops. Chapter 4 confirms the higher LAI for the intercrop during the present study. The additive intercrop had a higher LAI than the sole crops so was more effective in conserving water due to soil surface cover.

The PUE_T based on transpiration varied among the cropping systems and was a function of the cropping season and environmental weather condition. The sole crop maize showed the higher PUE_T during season 2000/2001, planting 1 and 2 (42.6% and 63% higher values respectively). During season 2001/2002 intercrop maize exhibited a higher PUE_T than the sole maize (13.5% and 2% higher respectively).

PUE_T on energy basis was higher for the intercrop during all the seasons except during season 2000/01, planting 2 (Table 7.8). Hence on nutrient basis the intercrop performed better in terms of conversion efficiency of water into edible energy during both the seasons compared to the sole crops.

Chapter 8

Summary and Recommendation

8.1. Summary

Rainfall is an important source of water for crop production in the tropics, especially sub-Saharan Africa. However, rains are unpredictable in terms of onset, amount and seasonal distribution and therefore the need to research systems dependent on this uncertain and variable condition. A large percentage of the population is engaged in subsistence forms of agriculture especially in sub-Saharan Africa. This sector is poorly endowed with financial resources and is to a large extent dependent on natural resources to subsist. Traditional and time tested forms of cropping such as intercropping provide a viable solution to some of the climate variability problems that are rampant in the tropics. The major challenge that exists today is the need to improve intercrop productivity and stability in a variable environment. Intercropping of cereals and legumes is a common cropping system by farmers within the subsistence sector given its stability and ability to provide cheap plant protein source. Maize and bean is an important crop combination within this cropping system and has been adopted by many small-holder farmers.

This study compares the intercrop of maize and beans with its component sole crops on the basis of precipitation utilization. The main finding is therefore meant to confirm or negate the hypotheses proposed in Chapter 1. The hypothesis of whether intercropping of maize and beans is able to use precipitation more efficiently than the sole crops. To address this issue the project considers the concept of the ecotope, which assesses productivity of a cropping system within a set of climate, plant and topographical variables. The approach therefore has been to characterize the degree of demands placed on the ecotope by the cropping systems. The most successful cropping system would therefore be one with the highest limiting resource (precipitation) use efficiency within the ecotope. It was therefore necessary to carefully quantify resource use by each system and assess its efficiency in the use of water resources. The rest of the summary gives the processes adopted to achieve the results.

The purpose of chapter 3 was to determine the transpiration efficiency coefficient for dry beans, grown either together with maize in the intercrop or as a sole crop, in order to enable the partitioning of water use between the two components of Es_g and Et_g. This was achieved by growing the bean crop in a lysimeter during two seasons 2000/01 and 2001/02. During both seasons the ε_w calculated from the dry matter and total transpired water for the season was 1.11 and 1.63 gkg^{-1}. The normalized transpiration efficiency was 3.02 and 3.51 g kPa kg^{-1} during the season 2000/01 and 2001/02 respectively. This value included a correction for the root biomass assumed to be 20% of the top biomass.

Resource use results in biomass accumulation by the cropping systems. The quantification of biomass and the components that relate to the capture and use of the resource is crucial in determining the competitive ability of a cropping system. Both the above ground biomass, leaf area and yield were quantified. Leaf area index growth was greater for the combined intercrop components during the seasons. This would be expected to be so due to the additive sowing scheme. This had implications for both radiation and water use during the season. The intercrop intercepted more radiation (PAR) than the sole crops. It also had a better PUE though not the best PUE which was exhibited by sole bean crop.

The intercrop had a yield advantage during all the seasons although this fluctuated substantially from a LER_T of 1.06 to 1.57. The mean LER_T was 1.29. It can be said that the additive sowing regime with double rows of beans, wider row spacing (1 meter), an ultra short duration maize cultivar may have resulted in yield advantage for the intercrop. The fluctuation in yields, especially the bean yield may have been due to the rainfall regime during the various planting dates.

The mean values for canopy vapour pressure deficit show that the intercrop exhibited a lower vapour pressure deficit compared to the sole maize and sole bean crops. The rougher canopy exerts more friction on the wind moving within the canopy, resulting in a thicker laminar layer within the leaf-air boundary. This ensures that less water loss takes place from the stomatal pores compared to sole crop systems which have more open canopies. Wind speeds were not monitored within the canopies and therefore there was no data on the windspeed within the respective cropping systems to confirm the above reasoning. The canopy of the intercrop also intercepted more radiation, hence less long-wave radiation is emitted back with the result that there is less buoyant motion of air within the canopy of the intercrop and hence less coupling with the rest of the convective boundary layer. The canopy vapour pressure deficits for all cropping systems were lower than the weather station values indicating that it was more humid closer to the canopy.

The intercrop intercepted more PAR energy than sole maize and sole bean cropping systems. This may have been so due to the additive sowing scheme adopted. Season 2001/02, planting 1 exhibited a higher PAR interception compared to season 2000/01, planting 1. The season 2001/02 had better soil water availability and rainfall distribution compared to season 2000/01 which was drier and had poor rainfall distribution. The biomass accumulation was therefore higher during 2001/02, planting 1 than 2000/01, planting 1. The intercrop used radiant energy more efficiently during all seasons, followed by sole maize and finally sole beans. The season 2000/01, planting 1, had an exceptionally low RUE for the sole bean, sole maize and the intercrop, while the other seasons had relatively higher RUE with a similar trend as in 2000/01 (i.e IMB>SM>SB). The RUE values for the sole maize were within the ranges found in other studies (Sinclair and Muchow, 1999). Sinclair and Muchow (1999) in their review of radiation use efficiency, reported that RUE values less than 0.8 g MJ^{-1} have been reported for legumes. Although no specific reference was given by them for the low RUE within some legumes, they emphasized the need to conduct intense studies of RUE to confirm whether it is inherently low in the legumes. The season 2001/02 had a RUE (intercepted PAR) value for sole bean equivalent to (0.035) 2.09 g MJ^{-1}, while season 2000/01, planting 2 had a RUE for the sole bean of (0.028) 1.68 g MJ^{-1}.

Sole bean had the highest extinction coefficient value during both seasons. This confirms the fact that beans have a more horizontal leaf exposition which is visually obvious, compared to the sole maize. In the intercrop the maize extinction coefficient played a dominant role in PAR attenuation. It has to be said however that the k-values were lower than unity, indicating that the canopy had less horizontal leaves and more clumped distribution. The crops depended on rainfall and were therefore subject to water stress during both seasons, with season 2000/01 having more stress than 2001/02 season. This may have resulted in rolling of leaves and less exposure to radiation.

Chapter 6 was an attempt to quantify the water extraction for the cropping systems using a theoretical and purely mathematical approach that has been used in a number of studies to estimate water extraction by sole crops (Monteith, 1986; Passioura, 1983; Meinke *et al.*, 1993; Robertson *et al.*, 1993). It enabled the estimation of parameters of use in modeling the water extraction by the cropping system during two seasons 2000/01 and 2001/02, for planting 1. EFV (extraction front velocities), kl (extraction rates) were determined for the cropping systems during the two seasons. The highest EFV was for the IMB during both seasons followed by the SM and lastly the SB: 2.99, 2.47 and 2.33 cmd^{-1} for 2000/01, planting 1 and 1.99, 1.88 and 1.63 cm d^{-1} during 2000/01, planting 1.

Chapter 7 collated the information found for the water extraction limits, using the drainage curve and crop lower limits together with seasonal progress of rainfall and soil water measurement to track the water use by the cropping systems as the seasons advanced. The summaries for this data are provided in form of graphs for both the total soil profile (0-900mm) and the individual profile layers (0-300, 300-600 and 600-900 mm). This information is vital in assessing and comparing the cropping systems extraction abilities during the season. It also provides a good estimate of the crop systems root development by using its extraction pattern to elucidate this. The information from this analysis showed that the seasonal trends for intercrop and the sole maize were in fact not significantly different. The sole beans extracted less water in the total profile compared to the other two maize systems. It also shows that the intercrop had a lower CLL, showing a more complete extraction of water from the profile, confirming the higher root proliferation at certain depths of the profile by the intercrop compared to the sole crops due to its additive sowing.

A water balance for each season, quantified each cropping system's water use by components including precipitation (P_g), change in soil water during the season (ΔS_g), transpiration (Et_g) and soil evaporation (Es_g). It was therefore possible to quantify both the water use efficiency based on ET and Et_g and also precipitation use efficiency based on ET. The mean total seasonal water use between cropping systems were not significantly different with values for SB, SM and IMB being 334, 344 and 342 respectively. It is intriguing that the higher plant density in the IMB did not use more water during the season. The probable explanation to this is that where as the sparser canopies lost more water through Es_g early in the season the

IMB used it more in Et_g. However, due to the aridity of the ecotope there was a balance between individual plant size and water use as Et_g such that the SM and SB had larger plant sizes denoting a higher water use per plant. The IMB had more plants that were individually smaller in biomass, hence the total water use ended being the almost the same among the cropping systems. This aspect was noted by Rees (1986) while working with a sorghum-cowpea intercrop in the more similar climatic conditions of Botswana. The IMB exhibited the highest Et_g during all seasons compared to the sole crops having 48 mm more Et_g than the highest mean registered by the sole maize at 176 mm. The IMB also had the lowest Es as a percentage of ET at 33% compared to SM at 48% and SB at 46%. The mean overall water use efficiency based on Et_g for the four seasons was SB (76 ZAR ha^{-1} mm^{-1}), SM (27 ZAR ha^{-1} mm^{-1}) and IMB (48 ZAR ha^{-1} mm^{-1}). The differences between the SB and SM were statistically significant at $p < 0.050$ (LSD test). The PUE_{ET} was 37, 13 and 27 ZAR ha^{-1} mm^{-1} for SB, SM and IMB respectively. The means across the different cropping systems were significantly different at $p< 0.050$ from the ANOVA test. The LSD test showed that the means between the SB and IMB were not significant while that between SB and SM were significantly different at $p < 0.050$. What the above figures indicate is that on this ecotope the SB performed better in terms of gross returns per drop of water followed by the IMB and lastly the SM. It is possible that if the returns were based on gross margins the IMB would have performed better as the amount of variable costs involved in its production would be relatively lower than the other cropping systems. From the results for the ecotope and a purely economic and financial point of view, it would be profitable to produce sole beans and buy maize under small holder farmer conditions.

Recommendations and future studies

Complementation and competition: LER_T was used to determine advantage for the intercrop vis-à-vis the sole crops. It was shown during all the four plantings that the intercrop was more efficient in the use of land resource. Additive intercropping system was adopted for obvious reasons: farmers more often than not adopt this strategy and do not replace the primary crop with the secondary crop. Where crop species grown together as mixtures differ in their photosynthetic efficiency as well as stature, the scientific basis for replacement series based purely on absolute numbers to replace comes into question. On the basis of LER it can be said for these findings that there was more competition during planting 1 than planting 2 (more complementation took place during planting 2). It can be said that the yield advantage of IMB is not stable under this ecotope as confirmed by the wide fluctuation in LER_T, caution must therefore be exercise in making unreserved recommendations on adoption under these conditions. That essentially is where modeling should play a key role in to enable more reliable forecasting in order to match the cropping system with potential resource availability.

Precipitation use efficiency and intercropping: Decisions on the use of maize-bean intercropping should be dependent in part on climate variability and within semi-arid areas specifically on rainfall variability. Where patterns of water supply and use are reasonably stable the adoption of single species giving the highest yield and degree of safety is chosen. However, where rainfall is variable such as at the ecotope on which this experiment was conducted, intercropping would most likely increase chances of getting some harvest, where both species do not suffer equally from water stress factors. The experiment has shown that intercropping can conserve water due to the higher leaf area index and microclimatic advantage conferred to it by the shelter effect, lower turbulent transport and therefore lower vapour pressure deficit within the canopy. Water conservation for domestic food production is gaining importance under smallholder farming sector. It is therefore recommended that run-off farming techniques in combination with intercropping have the scope to improve efficiency of water use. More studies are needed in this area.

Modelling and scientific concepts that assist in optimization of resources, especially rainfall should be adopted to help farmers make informed choices on cultivars to use, plant populations to adopt, planting dates to adopt and amount of other purchased resources to use.

Future studies:

- Intercropping water resource use with conservation measures such as run-off farming, mulching (stone mulch, organic mulch etc), reduced tillage etc,
- Quantification of water use efficiency for the IMB at leaf level for both stressed and non-stressed growing conditions.
- Modelling of intercrop of beans and maize to capture the biophysical aspects into model which can be used for forecasting and estimating risk associated with this form of cropping.

- Root studies are still lacking for this cropping system. This would complement efforts that are on going in the modeling of these systems.
- Family labour: the need to quantify variable cost for cropping systems will provide a more refined PUE based on gross margins rather than gross earnings. This will provide the financial and economic driving force for choice where scarcity of variable inputs is an issue, as it normally is.

As a cropping system IMB still remains a challenging area of study with grey areas that if addressed will answer the statement of “more cash per drop”.

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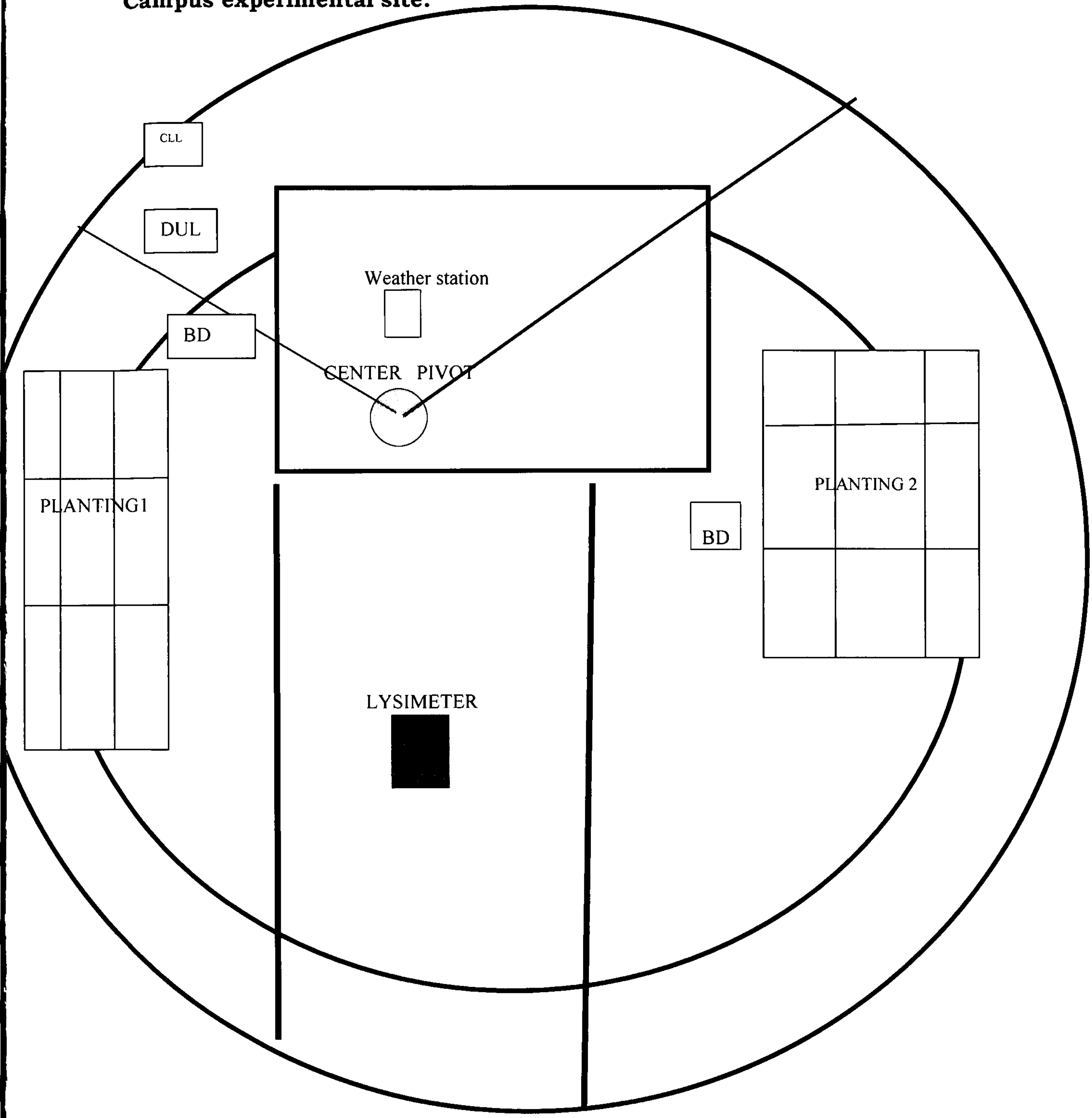
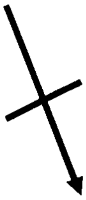
Appendix 1

Appendix 1A: Site drawing of the University of the Free State, West Campus experimental site.





BD-BULK DENSITY SITE
CLL- CROP LOWER LIMIT SITE
DUL-DRAINED UPPER LIMIT SITE
NB. Drawing not to size

Appendix 2

Appendix 2A. Calibration of the neutron water meter using values of count ratio and gravimetric soil water measurements at various depths at the West Campus Site.

Neutron Meter Reading Depth (mm)							
150 mm		450 mm		750 mm		1050 mm	
CR	Vol. %	CR	Vol. %	CR	Vol. %	CR	Vol. %
0.41	11.31	1.38	34.35	1.60	28.96	1.37	24.49
0.24	4.32	1.13	17.80	1.70	28.72	1.47	28.49
0.54	21.17	1.13	27.15	1.30	27.67	1.48	36.55
0.96	21.10	1.36	26.94	1.74	23.40	1.73	38.36
0.97	21.89	1.37	27.22	1.84	30.84	1.30	21.21
1.32	26.72	1.54	31.63	1.79	31.37	1.15	16.73
1.21	25.39	1.47	29.90	1.81	29.54	1.30	22.44
0.96	18.50	1.25	26.14	1.57	39.53	1.07	22.74
1.01	17.95	1.62	32.41	1.45	30.63	1.26	14.45
0.77	17.09	1.60	34.11	1.67	37.12	1.41	33.64
1.03	14.41	1.63	32.68	1.48	37.86	1.32	24.67
0.85	20.61	1.44	27.33	1.21	23.26	1.35	23.49
0.85	16.44	1.44	27.35	1.64	40.45	1.27	21.19
0.92	15.52	1.62	28.26	1.57	32.56	1.16	19.08
0.92	20.15	1.62	18.06	1.49	27.57	1.21	18.43
0.96	16.53	1.46	23.22	1.52	38.49	1.28	19.56
1.01	21.62	1.07	29.80	1.38	25.76	1.27	21.62
1.19	26.60	1.61	20.22	1.56	18.48	1.33	24.19
0.90	19.82	1.55	32.06	1.57	26.16	1.27	26.35
1.06	18.54	1.61	28.24	1.25	31.53	1.36	26.11
1.06	25.47	1.59	28.28	1.59	36.22	1.18	21.07
1.06	20.29	1.61	37.32	1.59	32.23	1.05	15.02
1.11	21.09	1.70	37.49	1.44	27.35	1.22	19.70
1.30	32.83	1.42	20.44	1.36	33.54	1.25	23.98
0.92	23.71	1.36	25.65	1.34	21.58	1.19	20.63
1.02	19.32			1.47	32.69		
0.95	18.49			1.31	19.75		

Neutron water probes are popular for measuring soil water contents in studies of water use. Unfortunately the calibration curves provided by either the manufacturer or determined may be incorrect for the soil within an experiment and different types of access tubing. Two methods of calibration are commonly used: (1) in situ gravimetric calibration, comparison of the neutron probe counts with measured soil water content at a number of sites; and (2) filling drums with soil at different water contents, installing a neutron probe access tube, and measuring the neutron probe counts. The first method was used during the experiment at University of the Free State, West Campus.

The calibration curve of most neutron probes can be approximated by the equation:

$$\theta_v = a + b \times CR$$

where θ_v is the volumetric water content (cm^3/cm^3) determined from gravimetric samples at the access tubes, CR is the neutron probe count ratio (actual count/standard count) taken at the access tubes (same time as gravimetric samples) and a, b are linear regression constants. The θv and CR values for the West campus site are provided in the appendix 2 Table above. The regression equations are in chapter 2.6.4 of the main document. The total amount of water (cm) to a depth Z is therefore given by the equation:

$$\int_0^z \theta_v \delta Z = aZ + b\int_0^z CR\delta R$$

The soil profile bulk density normally changes with soil depth and affects the value of a (Holmes, 1966)

The soil water percentage was calculated using the gravimetric method. This method is a classical procedure used as a check against other methods. Soil samples were put in containers, weighed moist, oven dried at 105 ^{0}C and weighed again after drying to constant weight. The mass and volumetric water contents were calculated using the following relationships:

$$\theta_m = \frac{mass \cdot water}{mass \cdot of \cdot oven \cdot dry \cdot soil}$$

$$P_m = \theta_m \times (100)$$

Plants are dependent on water from a volume of soil. Thus it is useful to calculate water content based on a volume of the soil. The volumetric water content are defined as follows:

$$\theta_v = \frac{volume \cdot of \cdot water}{volume \cdot of \cdot soil}$$

$$\theta_v = \frac{wt \cdot of \cdot water}{wt \cdot of \cdot dry \cdot soil} \times \frac{BD}{density \cdot of \cdot water}$$

$$P_v = \theta_v \times (100)$$

Water volume is used to estimate the reservoir of water in the soil volume or the water needed to wet the soil by rainfall. The soil's water volume is usually given as a depth of water in a depth of soil, as though the water measured were pulled out of the soil, placed in a container which has the same cross sectional area as the soil containing the water, and had its depth recorded. Rainfall is also measured in the same manner, assuming no percolation or evaporation..

To calculate the soil water volume as a depth of water the following relationships are used:

$$\theta_v = \theta_m \times \frac{BD}{\text{density} \cdot \text{of} \cdot \text{water}}$$

Depth of water = θ_v x (depth of soil)

$$\text{Depth.of.Water} = \theta_m \times \frac{BD}{\text{density} \cdot \text{of} \cdot \text{water}} \times \text{depth} \cdot \text{of} \cdot \text{soil}$$

Appendix 3

Appendix 3A. Bulk density determination at two profile pits at the West campus experimental site (done during the experimental season).

BULK DENSITY DATA SHEET DATE: 17/10/2002 Final bulk density sheet PIT 2- Western section Agmet site	Depth: 0-300 mm			Depth: 400-600 mm			Depth: 700-900 mm			Depth: 900-1200 mm		
SAMPLES	1	2	3	1	2	3	1	2	3	1	2	3
SAMPLE DEPTH (cm)	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66
HOLE DIAMETER (cm)	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34
CONTAINER WEIGHT (gm)	16.90	17.30	17.10	16.80	17.00	16.90	16.50	16.90	16.90	16.60	16.90	16.90
HOLE VOLUME (cm 3)	643.78	643.78	643.78	643.78	643.78	643.78	643.78	643.78	643.78	643.78	643.78	643.78
DRY WEIGHT SAMPLE (gm)	952.90	992.50	1022.40	1037.70	1053.90	1048.10	862.00	907.60	881.20	984.60	883.80	851.00
DRY SOIL WEIGHT (gm)	936.00	975.20	1005.30	1020.90	1036.90	1031.20	845.50	890.70	864.30	968.00	866.90	834.10
BULK DENSITY g cm3	1.454	1.515	1.562	1.586	1.611	1.602	1.313	1.384	1.343	1.504	1.347	1.296
Mean		1.510			1.599			1.346			1.382	
Stdev		0.054			0.013			0.035			0.108	

BULK DENSITY DATA SHEET DATE: 17/10/2002 Final bulk density sheet PIT 1- Eastern part Agmet site	Depth: 0-300 mm			Depth: 400-600 mm			Depth: 700-900 mm			Depth: 900-1200 mm		
SAMPLES	1	2	3	1	2	3	1	2	3	1	2	3
SAMPLE DEPTH (cm)	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66	7.66
HOLE DIAMETER (cm)	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34	10.34
CONTAINER WEIGHT (gm)	16.71	16.92	16.71	16.80	17.00	16.90	16.50	16.80	16.45	16.92	17.10	16.69
HOLE VOLUME (cm 3)	643.78	643.78	643.78	643.78	643.78	643.78	643.78	643.78	643.78	643.78	643.78	643.78
DRY WEIGHT SAMPLE (gm)	864.10	1074.10	1022.80	1150.90	1179.30	1050.20	975.40	992.20	1034.60	930.60	1012.10	1019.60
DRY SOIL WEIGHT (gm)	847.39	1057.18	1006.09	1134.10	1162.30	1033.30	958.90	975.40	1018.15	913.68	995.00	1002.91
BULK DENSITY g cm3	1.316	1.642	1.563	1.762	1.805	1.605	1.489	1.515	1.582	1.419	1.546	1.558
Mean		1.507			1.724			1.529			1.508	
Stdev		0.170			0.105			0.047			0.077	

Appendix 4

Appendix 4A. Time course of above ground dry matter development during the 2000/01 growing season.

2000/01, Planting 1

DAS	Sole Maize Average g m^{-2}	Sole Maize Stdev g m^{-2}	Intercrop Maize Average g m^{-2}	Intercrop Maize Stdev g m^{-2}	Sole Bean Average g m^{-2}	Sole Bean Stdev g m^{-2}	Intercrop Bean Average g m^{-2}	Intercrop Bean Stdev g m^{-2}
21	8.27	4.22	5.47	2.44	26.83	18.31	24.53	5.45
31	90.75	17.46	80.55	12.69	209.16	98.12	132.40	55.59
42	305.70	55.41	259.54	53.29	474.24	121.07	340.78	62.41
53	583.95	90.58	345.90	69.57	524.19	125.00	393.93	86.55
87	972.61	142.77	566.15	52.39	278.50	49.23	223.78	51.78
101	1252.92	147.82	997.99	93.44	616.69	159.73	476.64	142.04

2000/01, Planting 2

Sole bean

DAS	Stem gm^{-2}	Seed +Pod walls gm^{-2}	Leaves gm^{-2}	Total biomass gm^{-2}
35	4.49		3.51	8.00
46	9.55		7.45	17.00
84	171.90	25.80	207.10	391.90
109	210.00	227.90	234.00	671.90
120	184.43	146.99	258.68	590.10

Intercrop Bean

DAS	Stem gm^{-2}	Seed + Pod walls gm^{-2}	Leaves gm^{-2}	Total biomass gm^{-2}
35	5.61		3.89	9.50
46	20.96		14.54	35.50
84	181.90	22.40	190.00	385.30
109	246.60	322.04	275.40	844.02
120	198.01	202.03	277.66	677.70

Sole Maize

DAS	Stem gm^{-2}	Cobs+Husks gm^{-2}	Leaves gm^{-2}	Total biomass gm^{-2}
35	9.94		2.66	12.60
46	32.35		8.65	41.00
84	273.70	197.10	127.30	598.02
109	190.90	293.10	128.04	611.90
120	179.65	594.30	207.05	981.00

Intercrop Maize

DAS	Stem gm^{-2}	Cobs+Husks gm^{-2}	Leaves gm^{-2}	Total biomass gm^{-2}
35	5.45		1.75	7.20
46	33.15		10.65	43.80
84	224.70	128.70	121.50	474.90
109	202.20	212.60	124.30	539.10
120	172.90	297.60	151.20	621.70

Appendix 4B. Time course of total dry matter development in the cropping system

2001/02, Planting 1

DAS	Sole Maize		Intercrop Maize		Sole Bean		Intercrop Bean	
	Mean $g\ m^{-2}$	Stdev $g\ m^{-2}$	Mean $g\ m^{-2}$	Stdev $g\ m^{-2}$	Mean $g\ m^{-2}$	Stdev $g\ m^{-2}$	Mean $g\ m^{-2}$	Stdev $g\ m^{-2}$
30	80.18	35.80	82.70	22.55	44.16	20.44	43.38	7.06
39	411.18	64.00	340.73	113.55	162.50	23.48	99.02	74.83
46	364.45	43.81	329.09	33.91	146.31	52.03	179.74	32.78
53	544.00	73.09	474.66	99.59	288.81	52.03	286.67	62.26
59	719.47	62.36	656.42	93.24	435.22	120.21	348.92	104.62
67	1077.30	103.39	844.45	94.89	399.14	112.67	331.29	62.32
74	1179.77	111.28	1059.58	64.49	555.03	176.01	340.88	127.78
81	1403.95	172.46	1098.08	147.14	554.47	104.47	324.65	116.58
88	1531.42	144.60	1221.89	146.33	734.66	255.69	1018.78	607.11
95	1493.64	156.98	1238.31	199.64	527.02	157.18	248.53	45.47

2001/02, Planting 2

	Sole Maize		Intercrop Maize		Sole Bean		Intercrop Bean	
DAS	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
39	79.0	23.2	80.9	18.5	48.9	27.2	48.6	15.3
48	273.0	20.8	230.1	97.8	148.6	50.5	128.6	37.4
53	245.2	180.9	301.9	51.9	165.8	60.8	118.6	45.4
60	496.3	89.6	462.3	48.7	192.3	106.6	156.5	60.0
67	564.7	137.8	621.7	76.8	342.6	110.7	200.4	58.1
81	857.3	316.7	805.8	135.4	346.6	143.4	296.8	72.2
87	906.9	191.2	764.1	160.4	258.8	72.0	137.6	75.1
94	1119.7	293.0	841.7	110.8	406.8	127.7	194.7	84.8
101	1181.5	136.1	898.2	156.5	456.4	101.9	154.8	66.9
108	1201.7	178.7	1090.6	197.7	538.5	160.9	181.7	119.3

Appendix 4C. Time course of leaf area index development in the cropping system

2000/01, Planting 1

	Sole Maize		Intercrop Maize		Sole Bean		Intercrop Bean		Intercrop
DAS	**Average**	**Stdev**	**Average**	**Stdev**	**Average**	**Stdev**	**Average**	**Stdev**	**Average**
21	0.20	0.03	0.10	0.02	0.14	0.04	0.12	0.02	0.22
31	0.58	0.10	0.53	0.09	0.65	0.24	0.46	0.13	0.99
42	1.38	0.16	1.22	0.22	1.14	0.28	0.88	0.15	2.10
53	2.16	0.27	1.34	0.24	0.99	0.21	0.78	0.20	2.12
87	2.65	0.34	2.32	0.13	1.75	0.59	1.82	0.32	4.14
101	2.13	0.20	2.01	0.10	3.22	1.05	2.62	1.25	4.63

2000/01, Planting 2

DAS	Sole Bean	Intercrop Bean	Sole Maize	Intercrop Maize	Intercrop
35	0.07	0.08	0.03	0.02	0.10
46	0.14	0.31	0.11	0.14	0.44
84	3.85	3.99	1.55	1.54	5.53
109	4.35	5.78	1.56	1.58	7.36
120	4.81	5.83	2.53	1.92	7.75

2001/02, Planting 1

	Sole Maize		Intercrop Maize		Sole Bean		Intercrop Bean	
DAS	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
30	0.75	0.35	0.85	0.22	0.91	0.37	0.89	0.13
39	1.77	0.23	1.74	0.36	1.38	0.28	2.32	1.86
46	2.65	0.11	2.50	0.11	2.23	0.64	2.83	0.43
53	2.69	0.18	2.56	0.25	3.35	0.72	4.11	0.83
59	2.92	0.12	2.67	0.16	4.61	1.23	4.90	1.49
67	2.96	0.17	2.69	0.15	2.88	0.71	2.73	0.49
74	2.82	0.15	2.63	0.21	3.22	0.95	2.29	1.08
81	2.91	0.41	2.65	0.26	1.92	0.64	1.42	0.75
88	3.28	1.28	2.64	0.12	1.92	2.61	1.26	0.73
95	2.69	0.26	2.45	0.33	0.73	0.65	0.32	0.19

2001/02, Planting 2

	SoleMaize		IntercropMaize		SoleBean		Intercrop Bean	
DAS	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
39	1.0	0.2	1.0	0.2	1.0	0.3	1.0	0.2
48	2.1	0.1	1.9	0.2	1.8	0.7	1.9	0.5
53	1.8	1.0	1.9	0.2	2.6	0.8	1.6	0.6
60	2.5	0.3	2.4	0.2	2.6	1.2	1.6	0.9
67	2.2	0.4	2.5	0.3	3.6	1.1	2.0	0.8
81	2.3	0.2	2.1	0.3	1.2	0.6	0.7	0.3
87	2.0	0.7	1.9	0.6	1.0	0.4	0.4	0.2
94	2.2	0.2	2.1	0.2	0.9	0.4	0.8	0.2
101	2.0	0.2	1.8	0.2				

Appendix 4D. Time course of stem dry matter development in the cropping system

2001/02, Planting 1

	Sole Maize		Intercrop Maize		Sole Bean		Intercrop Bean	
DAS	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
30	32.28	15.92	30.25	10.56	4.57	4.44	8.12	2.53
39	93.08	17.52	78.79	17.09	21.15	4.89	34.19	12.58
46	194.70	29.78	173.70	23.32	47.85	25.81	65.40	16.44
53	347.37	67.72	297.87	76.84	103.20	19.57	120.54	29.16
59	421.51	30.73	389.05	45.81	148.58	42.23	133.13	46.46
67	587.29	52.28	474.00	38.48	124.43	39.48	122.71	47.37
74	578.43	70.84	514.80	39.55	162.15	50.09	138.97	57.58
81	641.52	60.48	518.01	48.77	147.56	51.18	105.77	38.19
88	612.71	80.73	512.86	59.19	292.00	239.06	271.10	266.13
95	713.69	73.82	598.00	99.06	129.60	60.67	93.69	50.26

20001/02, Planting 2

	Sole Maize		Intercrop Maize		Sole Bean		Intercrop Bean	
DAS	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
39	62.8	21.7	66.9	21.6	12.5	9.9	14.3	6.4
48	269.3	27.5	249.6	60.1	64.3	25.9	54.8	15.9
53	451.5	77.1	330.7	76.5	67.8	38.9	59.3	24.7
60	588.9	112.7	554.2	59.0	80.8	38.8	72.3	29.1
67	658.8	165.4	693.0	70.1	112.6	37.3	66.9	18.8
81	976.4	279.5	746.0	178.9	94.5	55.3	104.3	57.4
87	798.3	145.4	643.2	177.7	92.1	30.1	47.3	29.4
94	888.2	191.2	730.1	83.9	93.7	29.5	56.1	21.5
101	857.1	125.3	691.1	116.5	122.1	22.7	62.1	42.4
108	831.5	139.3	716.6	156.5	159.1	49.4	95.2	98.9

Appendix 4E. Time course of leaf dry matter development in the cropping system

2001/02, Planting 1

	Sole Maize		Intercrop Maize		Sole Bean		Intercrop Bean	
DAS	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
30	47.89	22.10	52.46	13.79	39.59	16.23	35.26	5.11
39	112.51	14.89	107.63	22.19	60.10	12.05	91.76	73.72
46	169.75	15.51	155.39	11.88	98.46	30.19	114.34	23.20
53	196.63	13.31	176.79	24.77	174.23	34.30	152.84	33.03
59	217.76	13.94	189.87	16.16	206.38	56.03	152.12	44.52
67	247.79	14.29	211.49	9.56	144.29	42.10	86.05	20.57
74	238.67	13.00	223.28	17.30	138.54	40.86	80.46	52.76
81	243.11	33.90	208.66	20.46	95.17	31.78	44.00	23.08
88	273.29	106.49	207.66	9.51	95.38	129.37	299.27	309.45
95	224.49	21.33	192.98	25.79	36.27	32.44	9.87	6.03

2001/02, Planting 2

	Sole Maize		Intercrop Maize		Sole Bean		Intercrop Bean	
DAS	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
39	95.2	25.2	94.8	17.1	36.4	17.5	34.2	9.2
48	276.7	16.3	270.7	38.1	84.4	34.3	73.8	22.1
53	307.9	42.3	273.1	32.8	90.2	28.0	59.4	21.5
60	340.5	38.6	333.3	26.1	90.8	41.0	68.0	30.3
67	298.9	52.3	358.1	39.5	127.5	40.4	76.4	32.2
81	372.9	33.6	355.5	56.1	59.1	28.4	58.3	32.4
87	392.0	70.1	396.9	96.9	45.7	32.0	13.2	8.7
94	360.9	66.4	318.1	44.3	36.1	19.8	25.5	6.8
101	359.1	48.2	312.3	34.9				
108	330.3	46.4	301.4	56.8				

Appendix 4F. Time course of cobs and pod dry matter development in the cropping system

2001/02, 2-Planting 1

	Sole Maize		Intercrop Maize		Sole Bean		Intercrop Bean	
DAS	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
53					11.39	7.84	13.29	11.29
59	80.20	28.53	77.50	43.87	80.26	44.70	63.66	29.91
67	242.22	72.31	158.96	61.40	130.42	55.34	122.52	29.21
74	362.68	110.27	321.49	30.52	254.34	119.26	121.45	42.64
81	519.32	117.17	371.41	94.73	311.74	84.67	174.88	72.22
88	645.42	125.57	482.44	129.26	347.28	134.92	211.31	85.22
95	555.47	101.26	447.33	83.45	391.56	116.22	163.10	44.17

2001/02, Planting 2

	Sole Maize		Intercrop Maize		Sole Bean		Intercrop Bean	
DAS	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
60	63.2	37.7	37.0	22.7	27.7	31.5	16.2	8.4
67	171.6	73.3	192.3	81.9	102.5	46.7	57.1	30.8
81	582.4	246.6	573.9	209.3	171.5	99.9	140.7	87.9
87	623.5	215.5	488.1	186.9	121.0	48.5	77.2	66.6
94	990.4	343.5	635.3	134.3	277.0	113.0	113.1	60.6
101	1146.8	224.8	792.9	209.7	334.4	95.1	92.8	29.9

Appendix 5

Results of t-test sequential dry matter harvests during the seasons 2000/01 and 2001/02

Appendix 5A. Time course of total biomass yield during the 2001/02 growing season (planting 1). Presented are probabilities based on the F-test at probability of 0.05 for samples (n=9 for each treatment and date of harvest)

DAS	SM Mean	IM Mean	SB Mean	IB Mean	Maize p-value	Beans p-value
30	80.18	82.70	44.16	43.38	0.63	0.95
39	411.18	340.73	162.50	99.02	0.28	0.11
46	364.45	329.09	146.31	179.74	0.11	0.19
53	544.00	474.66	288.81	286.67	0.09	0.73
59	719.47	656.42	435.22	348.92	0.12	0.30
67	1077.30	844.45	399.14	331.29	0.00	0.23
74	1179.77	1059.58	555.03	340.88	0.05	0.00
81	1403.95	1098.08	554.47	324.65	0.01	0.00
88	1531.42	1221.89	734.66	1018.78	0.01	0.37
95	1493.64	1238.31	527.02	248.53	0.03	0.00

*Null Hypotheses (Ho): ($p>0.05$) Sole crop yield is not significantly different from intercrop component yield.

** Alternative Hypotheses (HA): ($p <0.05$) Sole crop biomass yield is significantly greater than intercrop component yield at.

Appendix 5B. Time course of total biomass yield during the 2001/02 growing season (planting 2). Presented are probabilities based on the F-test at probability of 0.05 for samples (n=9 for each treatment and date of harvest)

DAS	Sole Maize Mean	Intercrop Maize Mean	Sole Bean Mean	Intercrop Bean Mean	Maize p-value	Beans p-value
39	79.0	80.9	48.9	48.6	0.98	0.97
48	273.0	230.1	148.6	128.6	0.53	0.34
53	245.2	301.9	165.8	118.6	0.91	0.04
60	496.3	462.3	192.3	156.5	0.23	0.37
67	564.7	621.7	342.6	200.4	0.38	0.00
81	857.3	805.8	346.6	296.8	0.66	0.52
87	906.9	764.1	258.8	137.6	0.21	0.01
94	1119.7	841.7	406.8	194.7	0.02	0.00
101	1181.5	898.2	456.4	154.8	0.00	0.00
108	1201.7	1090.6	538.5	181.7	0.30	0.00

*Null Hypotheses (H_O): ($p>0.05$) Sole crop yield is not significantly different from intercrop component yield. i.e SM=IM; SB=IB.

** Alternative Hypotheses (H_A): Sole crop biomass yield is significantly greater than intercrop component yield i.e SM>IM; SB>IB.

Appendix 5C. Time course of leaf area index during the 2001/02 growing season (planting 1). Presented are probabilities based on the F-test at probability of 0.05 for samples (n=9 for each treatment and date of harvest)

DAS	SM Mean	IM Mean	SB Mean	IB Mean	Maize p-value	Beans p-value
30	0.8	0.8	0.9	0.9	0.03	0.95
39	1.8	1.7	1.4	2.3	0.71	0.31
46	2.7	2.5	2.2	2.8	0.01	0.07
53	2.7	2.6	3.4	4.1	0.09	0.02
59	2.9	2.7	4.6	4.9	0.15	0.34
67	3.0	2.7	2.9	2.7	0.00	0.44
74	2.8	2.6	3.2	2.3	0.00	0.21
81	2.9	2.7	1.9	1.4	0.05	0.23
88	3.3	2.6	1.9	1.3	0.31	0.47
95	2.7	2.5	0.7	0.3	0.17	0.28

*Null Hypotheses (H_O): ($p>0.05$) Sole crop yield is not significantly different from intercrop component yield. i.e SM=IM; SB=IB.

** Alternative Hypotheses (H_A): Sole crop biomass yield is significantly greater than intercrop component yield i.e SM>IM; SB>IB.

Appendix 5D. Time course of leaf area index during the 2001/02 growing season (planting 2). Presented are probabilities based on the F-test at probability of 0.05 for samples (n=9 for each treatment and date of harvest)

DAS	Sole Maize Mean	Intercrop Maize Mean	Sole Bean Mean	Intercrop Bean Mean	Maize p-value	Beans p-value
39	1.0	1.0	1.0	1.0	0.98	0.80
48	2.1	1.9	1.8	1.9	0.08	0.99
53	1.8	1.9	2.6	1.6	0.06	0.00
60	2.5	2.4	2.6	1.6	0.08	0.13
67	2.2	2.5	3.6	2.0	0.18	0.01
81	2.3	2.1	1.2	0.7	0.02	0.12
87	2.0	1.9	1.0	0.4	0.74	0.00
94	2.2	2.1	0.9	0.8	0.27	0.72
101	2.0	1.8			0.16	

*Null Hypotheses (H_O): ($p>0.05$) Sole crop yield is not significantly different from intercrop component yield. i.e SM=IM; SB=IB.

** Alternative Hypotheses (H_A): Sole crop biomass yield is significantly greater than intercrop component yield i.e SM>IM; SB>IB.

Appendix 5E. Time course of cob+ husk, pod+seed yield during the 2001/02 growing season (planting 1). Presented are probabilities based on the F-test at 95% probability for samples (n=9 for each treatment and date of harvest)

DAS	Sole Maize Mean	Intercrop Maize Mean	Sole Bean Mean	Intercrop Bean Mean	Maize p-value	Beans p-value
53			11.39	13.29		0.77
59	80.20	77.50	80.26	63.66	0.99	0.68
67	242.22	158.96	130.42	122.52	0.02	0.87
74	362.68	321.49	254.34	121.45	0.61	0.00
81	519.32	371.41	311.74	174.88	0.04	0.00
88	645.42	482.44	347.28	211.31	0.04	0.03
95	555.47	447.33	391.56	163.10	0.09	0.00

*Null Hypotheses (H_O): (p>0.05) Sole crop yield is not significantly different from intercrop component yield. i.e SM=IM; SB=IB.
** Alternative Hypotheses (H_A): Sole crop biomass yield is significantly greater than intercrop component yield i.e SM>IM; SB>IB.

Appendix 5F. Time course of cob+ husk, pod+seed yield during the 2001/02 growing season (planting 2). Presented are probabilities based on the F-test at 95% probability for samples (n=9 for each treatment and date of harvest)

DAS	Sole Maize Mean	Intercrop Maize Mean	Sole Bean Mean	Intercrop Bean Mean	Maize p-value	Beans p-value
60	63.2	37.0	27.7	16.2	0.05	0.28
67	171.6	192.3	102.5	57.1	0.69	0.01
81	582.4	573.9	171.5	140.7	0.96	0.42
87	623.5	488.1	121.0	77.2	0.30	0.25
94	990.4	635.3	277.0	113.1	0.01	0.00
101	1146.8	792.9	334.4	92.8	0.00	0.00
108	1241.5	1163.1	379.5	86.5	0.51	0.00

*Null Hypotheses (H_O): (p>0.05) Sole crop yield is not significantly different from intercrop component yield. i.e SM=IM; SB=IB.
** Alternative Hypotheses (H_A): Sole crop biomass yield is significantly greater than intercrop component yield i.e SM>IM; SB>IB.

Appendix 6.

Appendix 6A. Estimates of the Richards growth function parameters from curve fits for total dry matter during season 2000/01 – planting 1 and 2.

2000/2001 - planting 1	Parameter					
Cropping System	φ	λ	γ	δ	s.e	r^2
Sole Maize	1020.570	1.354	0.073	0.137	5.541	1.0000
Intercrop Maize	592.460	-0.491	0.064	0.043	41.637	0.9956
Sole Bean	600.620	1.250	0.120	0.079	42.544	0.9962
Intercrop Bean	468.479	0.652	0.106	0.058	33.219	0.9961
2000/2001 - planting 2						
Sole Maize	1036.556	-1.033	0.036	0.024	226.669	0.9620
Intercrop Maize	610.429	0.998	0.061	0.059	47.721	0.9966
Sole Bean	631.000	293.735	3.270	39.953	57.850	0.9957
Intercrop Bean	760.850	150.304	1.593	24.258	117.800	0.9875

Appendix 6B. Estimates of the Richards growth function parameters from curve fits for total dry matter during season 2001/2002 – planting 1 and 2.

2001/2002 - planting 1	Parameter					
Cropping System	φ	λ	γ	δ	s.e	r^2
Sole Maize	1556.000	9.204	0.128	2.444	80.681	0.9920
Intercrop Maize	1276.000	7.337	0.108	1.923	55.378	0.9941
Sole Bean	545.610	22.441	0.373	4.174	14.939	0.9987
Intercrop Bean	343.910	28.954	0.533	6.546	64.484	0.9107
2001/2002 - planting 2						
Sole Maize	1486.960	0.157	0.039	0.085	54.450	0.9943
Intercrop Maize	1076.680	0.389	0.048	0.090	69.086	0.9851
Sole Bean	1083.760	-0.498	0.018	0.113	66.640	0.9354
Intercrop Bean	207.070	29.901	0.456	11.037	50.752	0.8073

Appendix 7

Appendix 7A. Analysis of variance for relative growth rates between the treatments within the planting dates.

Year	Date	Comparison	Prob. level	F-ratio	Decision (5% level)
2000/01	1	SM v IM	0.863275	0.03	Accept
2000/01	1	SB v IB	0.824096	0.05	Accept
2000/01	2	SM v IM	0.897729	0.02	Accept
2000/01	2	SB v IB	0.834037	0.05	Accept
2001/02	1	SM v IM	0.924953	0.01	Accept
2001/02	1	SB v IB	0.713073	0.14	Accept
2001/02	2	SM v IM	0.917376	0.01	Accept
2001/02	2	SB v IB	0.132900	0.65	Accept

Null Hypotheses (H_O): ($p>0.05$) Sole crop yield is not significantly different from intercrop component yield. i.e SM=IM; SB=IB. The decision is therefore to accept null hypotheses.

Appendix 8

Appendix 8A. Curve fitting parameters for the exponential water extraction curve of θ versus DAS by the cropping systems

450 mm depth

Cropping system	SM	IMB	SB	SM	IMB	SB
Year	2000/01	2000/01	2000/01	2001/02	2001/02	2001/02
t_c	39.48	40.30	47.25	27.41	25.66	29.21
kl	0.05	0.07	0.04	0.09	0.09	0.02
θ_u	33.90	32.98	33.95	32.33	35.40	32.03
θ_l	23.44	21.61	24.06	23.44	17.39	21.00
R^2	0.96	0.91	0.94	0.94	0.91	0.95

750 mm depth

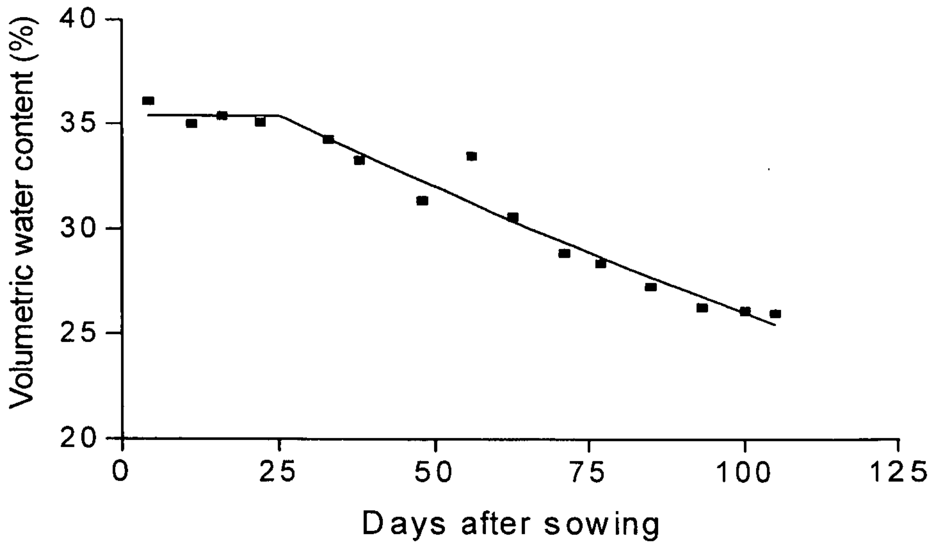
Cropping system	SM	IMB	SB	SM	IMB	SB
Year	2000/01	2000/01	2000/01	2001/02	2001/02	2001/02
t_c	57.91	60.36	61.87	66.13	61.02	62.82
kl	0.06	0.05	0.06	0.06	0.06	0.05
θ_u	35.25	34.48	34.83	30.81	33.94	36.34
θ_l	29.24	28.83	26.69	25.73	27.56	30.96
R^2	0.86	0.97	0.96	0.91	0.90	0.87

1050 mm depth

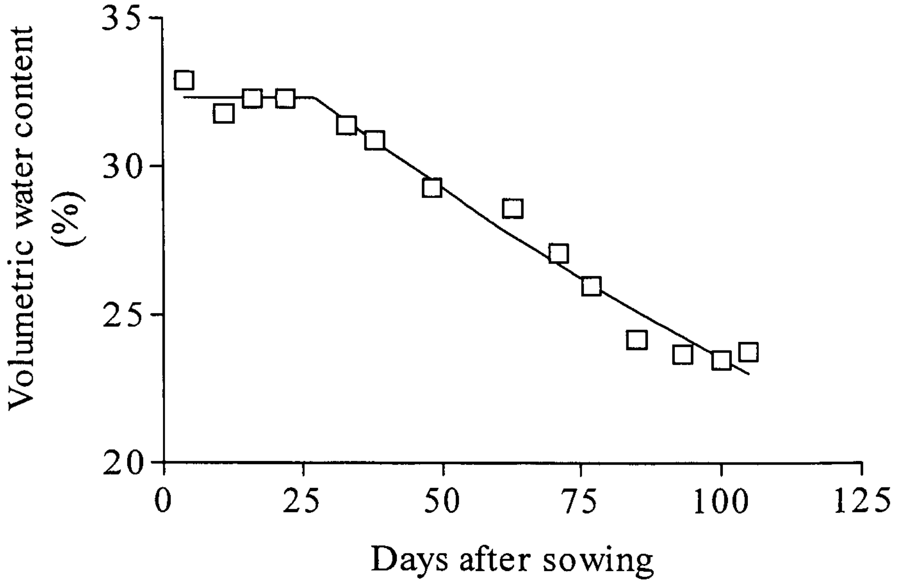
Cropping system	SM	IMB	SB	SM	IMB	SB
Year	2000/01	2000/01	2000/01	2001/02	2001/02	2001/02
t_c	72.11	72.11		68.83	69.03	74.49
kl	0.04	0.03		0.03	0.11	0.05
θ_u	24.79	24.79		23.71	25.40	29.42
θ_l	23.90	23.90		22.08	23.51	28.84
R^2	0.89	0.89		0.95	0.93	0.92

Appendix 8B: Fitted curve example for water extraction

450 mm depth, Intercrop
2001-2002



450 mm depth, Sole Maize
2001-2002



Appendix 9

Appendix 9A: Weather data for season 2000/01, planting 1 and 2

Planting 2 DAS	Planting 1 DAS	Date	Rain mm d^{-1}	Radiation W m^{-2}	ETo mm d^{-1}	Temp Ave (°C)	Temp Max (°C)	Temp Min (°C)	Windspeed m s^{-1}
	1	23-Nov	0.0	341	6.6	20	26.4	13.4	1.8
	2	24-Nov	0.0	361	8.9	22	29.1	15.3	2.7
	3	25-Nov	0.0	368	7.7	21	28.7	13.0	2.2
	4	26-Nov	4.6	189	3.9	20	26.2	13.4	2.8
	5	27-Nov	0.0	197	3.7	19	23.0	15.1	1.8
	6	28-Nov	0.4	179	2.6	18	20.4	15.6	1.5
	7	29-Nov	1.8	362	6.9	21	27.5	13.8	1.6
	8	30-Nov	0.0	303	5.7	21	28.5	13.4	1.4
	9	1-Dec	0.0	345	7.1	22	29.3	15.5	1.9
	10	2-Dec	4.6	271	6.7	25	30.9	18.3	2.5
	11	3-Dec	3.7	273	6.2	22	28.8	14.9	1.9
	12	4-Dec	0.0	366	8.3	22	30.1	13.4	2.4
	13	5-Dec	2.5	320	7.4	22	30.2	14.5	2.4
	14	6-Dec	0.1	292	7.2	24	31.8	15.9	2.9
	15	7-Dec	6.3	259	6.3	21	27.1	15.6	3.6
	16	8-Dec	9.0	221	3.6	20	25.3	15.1	1.8
	17	9-Dec	0.0	294	5.5	21	26.2	15.4	2.1
	18	10-Dec	0.3	250	4.3	21	25.4	17.3	1.7
1	19	11-Dec	40.9	123	2.3	18	20.4	15.5	1.8
2	20	12-Dec	0.0	390	7.6	18	23.8	12.0	1.8
3	21	13-Dec	0.0	389	7.7	18	26.3	9.7	1.2
4	22	14-Dec	0.0	377	9.0	23	29.9	16.6	2.2
5	23	15-Dec	0.0	384	8.9	23	31.1	14.6	1.8
6	24	16-Dec	1.0	193	4.7	22	26.4	17.3	2.9
7	25	17-Dec	0.2	315	7.6	22	29.7	15.1	2.8
8	26	18-Dec	0.0	359	8.7	21	31.0	11.9	1.6
9	27	19-Dec	0.0	358	8.4	24	31.2	16.0	2.3
10	28	20-Dec	0.0	232	5.9	23	29.3	17.0	2.9
11	29	21-Dec	0.2	343	6.8	22	28.5	15.8	1.9
12	30	22-Dec	3.5	321	6.2	23	29.4	17.3	1.7
13	31	23-Dec	0.0	361	8.1	24	31.1	17.8	1.9
14	32	24-Dec	0.0	370	10.7	26	33.4	18.4	3.1
15	33	25-Dec	0.0	371	8.7	22	28.1	15.0	2.3
16	34	26-Dec	0.0	388	7.9	21	29.1	12.8	1.4
17	35	27-Dec	2.1	319	7.2	23	28.9	17.3	3.1
18	36	28-Dec	0.0	344	7.6	23	29.5	17.0	2.5
19	37	29-Dec	0.0	377	10.1	24	31.7	17.1	2.5
20	38	30-Dec	0.0	393	10.4	22	31.8	13.1	1.8
21	39	31-Dec	0.2	333	9.8	23	32.5	13.4	2.5
22	40	1-Jan	0.3	277	4.7	14	16.8	10.8	3.9
23	41	2-Jan	0.0	378	7.5	15	22.8	8.0	3.1
24	42	3-Jan	0.0	379	7.0	17	26.6	8.0	1.2
25	43	4-Jan	0.0	379	8.2	21	30.3	12.6	1.3
26	44	5-Jan	0.0	372	9.0	24	32.7	16.0	1.6
27	45	6-Jan	0.0	371	9.5	26	35.0	17.3	1.6
28	46	7-Jan	0.0	367	9.2	26	34.3	17.9	2.1
29	47	8-Jan	0.0	347	8.8	25	32.5	17.6	3.2
30	48	9-Jan	0.0	370	11.3	27	35.0	19.8	3.4
31	49	10-Jan	0.0	388	11.6	26	33.8	18.3	2.7
32	50	11-Jan	0.0	392	10.8	25	34.8	14.4	1.9
33	51	12-Jan	0.0	355	10.2	26	35.5	16.4	2.8
34	52	13-Jan	0.0	271	7.4	26	30.2	21.0	2.2
35	53	14-Jan	0.0	310	6.7	17	21.1	12.2	3.1
36	54	15-Jan	0.0	379	7.9	18	25.9	9.2	1.8
37	55	16-Jan	0.0	380	8.7	21	29.9	11.2	1.4
38	56	17-Jan	0.0	364	8.0	23	31.8	15.1	1.7
39	57	18-Jan	0.1	304	6.8	25	31.2	18.0	2.9
40	58	19-Jan	1.0	276	6.7	24	31.4	17.1	2.0
41	59	20-Jan	0.0	259	6.1	24	30.6	17.5	2.2
42	60	21-Jan	0.0	362	9.0	24	33.9	13.6	1.5
43	61	22-Jan	0.0	357	8.6	26	33.6	18.3	2.3
44	62	23-Jan	0.0	307	9.7	27	33.0	20.8	2.7
45	63	24-Jan	11.8	256	5.6	26	32.1	19.0	1.9
46	64	25-Jan	18.3	340	7.0	23	29.0	16.3	2.8
47	65	26-Jan	0.0	286	5.2	22	27.1	16.7	2.1
48	66	27-Jan	0.0	296	5.9	23	29.2	17.4	2.1
49	67	28-Jan	1.3	250	5.2	23	28.1	18.4	1.9
50	68	29-Jan	0.0	326	6.8	24	30.4	17.7	1.9

51	69	30-Jan	0.0	339	8.6	25	31.8	18.1	2.4
52	70	31-Jan	0.0	378	9.0	24	31.8	15.5	1.8
53	71	1-Feb	0.0	325	8.5	25	32.3	17.4	2.8
54	72	2-Feb	0.0	316	9.2	23	31.8	14.5	2.8
55	73	3-Feb	0.0	354	9.1	21	27.5	15.2	2.6
56	74	4-Feb	0.0	365	7.6	21	29.0	12.6	1.5
57	75	5-Feb	0.0	345	6.9	23	30.1	14.9	1.7
58	76	6-Feb	0.0	341	7.7	25	33.0	17.8	1.1
59	77	7-Feb	0.0	331	8.0	26	33.3	18.9	2.3
60	78	8-Feb	1.3	280	7.3	26	32.3	19.4	2.7
61	79	9-Feb	0.0	289	6.3	22	28.8	15.2	2.4
62	80	10-Feb	0.0	319	6.9	23	28.2	16.8	2.3
63	81	11-Feb	0.0	323	6.7	23	29.7	16.6	1.9
64	82	12-Feb	0.0	217	5.1	24	28.7	18.6	2.3
65	83	13-Feb	0.0	249	5.2	24	29.7	17.4	2.3
66	84	14-Feb	0.0	572	6.7	22	27.0	17.6	2.1
67	85	15-Feb	0.0	442	6.7	22	29.1	15.0	1.6
68	86	16-Feb	0.0	385	7.4	24	31.5	16.6	1.8
69	87	17-Feb	0.0	237	6.1	25	31.8	18.5	2.4
70	88	18-Feb	27.0	53	0.7	17	20.3	14.1	2.3
71	89	19-Feb	0.0	302	5.9	20	25.9	13.9	1.8
72	90	20-Feb	0.0	270	5.5	22	28.6	15.3	1.2
73	91	21-Feb	0.1	305	6.1	23	29.0	16.6	1.8
74	92	22-Feb	0.0	234	5.1	23	28.9	17.8	2.0
75	93	23-Feb	0.1	257	6.2	25	31.2	18.4	2.0
76	94	24-Feb	13.8	253	5.7	22	27.4	16.4	2.6
77	95	25-Feb	0.0	260	4.6	22	27.2	16.1	1.6
78	96	26-Feb	4.7	242	4.3	21	27.3	15.0	1.6
79	97	27-Feb	7.1	243	4.1	19	23.8	14.4	1.7
80	98	28-Feb	0.0	260	4.5	19	24.9	13.9	1.2
81	99	1-Mar	0.0	309	5.9	20	26.7	13.9	1.0
82	100	2-Mar	0.0	314	6.5	22	30.2	14.6	0.9
83	101	3-Mar	0.0	294	6.7	23	32.0	14.8	1.3
84	102	4-Mar	0.0	309	6.6	24	30.5	17.3	1.2
85	103	5-Mar	0.0	252	5.9	26	30.4	20.8	2.1
86	104	6-Mar	0.0	260	6.2	25	31.3	18.1	1.5
87	105	7-Mar	0.0	240	6.2	26	31.5	20.6	2.2
88	106	8-Mar	0.2	265	6.1	25	31.3	19.2	1.6
89	107	9-Mar	2.9	252	6.5	25	32.2	18.4	2.1
90	108	10-Mar	3.4	288	6.3	24	31.0	17.4	1.7
91	109	11-Mar	2.7	255	5.9	24	30.7	17.8	2.6
92	110	12-Mar	0.0	291	7.5	23	29.5	16.8	2.3
93	111	13-Mar	0.0	276	5.8	21	29.1	12.2	2.1
94	112	14-Mar	0.0	263	5.1	21	27.6	14.2	1.7
95	113	15-Mar	0.0	275	5.5	22	28.8	15.1	0.9
96	114	16-Mar	0.0	230	4.7	22	30.0	14.7	0.9
97	115	17-Mar	0.0	257	6.3	25	31.3	17.7	1.9
98	116	18-Mar	0.0	202	4.2	20	24.6	14.9	2.1
99	117	19-Mar	1.4	235	5.4	20	25.0	14.1	3.2
100	118	20-Mar	1.2	131	2.1	19	22.6	14.4	2.0
101	119	21-Mar	4.2	177	2.8	18	23.1	13.1	1.3
102	120	22-Mar	28.0	81	0.9	17	20.1	13.9	1.4
103	121	23-Mar	24.6	37	0.8	16	17.1	14.6	1.6
104	122	24-Mar	0.0	201	3.5	19	23.2	15.0	1.6
105	123	25-Mar	0.0	227	4.2	19	23.8	15.1	1.1
106	124	26-Mar	0.0	258	5.3	20	26.2	13.0	1.0
107	125	27-Mar	0.0	264	5.6	20	27.4	12.7	0.9
108	126	28-Mar	0.0	256	5.0	20	28.0	12.1	0.7
109	127	29-Mar	0.0	221	4.4	21	28.6	14.2	0.6
110	128	30-Mar	0.0	225	4.8	22	27.9	16.4	1.4
111		31-Mar	0.0	113	2.0	19	22.1	15.9	1.8
112		1-Apr	0.7	89	1.1	16	18.5	13.8	1.2
113		2-Apr	9.6	225	3.7	18	24.3	11.8	1.2
114		3-Apr	0.4	177	2.9	18	22.4	13.7	1.3
115		4-Apr	1.2	212	3.9	18	23.6	11.9	1.6
116		5-Apr	0.0	137	2.2	17	21.6	13.3	1.9
117		6-Apr	0.0	127	1.9	16	19.4	13.5	2.0
118		7-Apr	14.0	31	0.0	15	16.8	13.6	1.9
119		8-Apr	13.5	79	0.7	16	19.2	12.9	1.6
120		9-Apr	0.1	215	3.6	15	20.5	9.6	0.9
121		10-Apr	0.0	206	3.6	15	20.7	8.5	0.9
122		11-Apr	0.0	227	3.7	16	22.7	9.9	0.8
123		12-Apr	0.0	218	3.9	17	23.7	9.4	0.9
124		13-Apr	0.0	228	4.4	18	25.1	11.1	0.8
125		14-Apr	0.8	111	1.4	16	19.6	12.8	1.3
126		15-Apr	10.2	134	2.0	17	22.1	11.9	1.7
127		16-Apr	17.9	47	0.3	14	15.9	12.4	1.7

128		17-Apr	0.1	177	2.6	15	19.0	10.3	0.5
129		18-Apr	0.0	206	3.4	15	21.3	8.1	0.7
130		19-Apr	0.0	170	2.8	15	21.8	8.8	0.7
131		20-Apr	0.0	192	3.0	17	23.9	10.5	0.5
132		21-Apr	0.0	193	3.3	17	23.9	10.8	1.0
133		22-Apr	6.6	182	3.3	17	23.0	11.5	1.3
134		23-Apr	2.1	172	3.2	17	21.8	12.9	5.6
135		24-Apr	6.3	149	2.9	17	21.1	12.8	2.9
136		25-Apr	0.0	188	3.1	15	20.4	9.3	0.7
137		26-Apr	3.7	182	3.5	16	23.4	9.4	1.7
138		27-Apr	8.0	46	0.2	13	15.3	11.0	1.6
139		28-Apr	2.6	176	2.5	14	19.2	9.1	0.9
140		29-Apr	0.6	197	3.6	15	21.8	7.6	1.0
141		30-Apr	0.2	86	1.3	14	18.8	9.3	1.0
		1-May	0.3	73	0.8	14	16.5	10.5	1.5
		2-May	0.2	39	0.1	13	14.5	11.6	1.8
		3-May	0.1	40	0.2	13	15.2	11.6	1.4
		4-May	0.1	128	1.7	14	18.2	9.7	1.8
		5-May	0.0	68	0.9	7	13.0	1.2	2.6
		6-May	0.5	187	2.0	5	9.8	-0.1	1.3
		7-May	0.3	183	2.4	8	14.4	0.8	0.6
		8-May	0.1	182	2.8	11	18.5	2.6	0.6
		9-May	0.0	176	3.1	13	21.3	5.5	0.7
		10-May	0.1	180	3.4	15	22.5	6.8	0.9
		11-May	0.0	177	3.1	14	22.6	4.9	0.5
		12-May	0.0	173	3.1	14	22.8	5.7	0.5
		13-May	0.1	172	2.9	15	23.1	6.1	0.5
		14-May	0.0	171	2.9	15	23.0	7.0	0.4
		15-May	0.0	170	3.0	14	22.2	6.5	0.6
		16-May	0.0	168	2.9	13	21.2	5.7	0.6
		17-May	0.1	161	2.7	13	20.9	5.3	0.6
		18-May	0.0	168	2.8	13	21.5	4.5	0.5
		19-May	0.0	163	3.3	13	21.1	5.0	0.9
		20-May	0.0	165	3.2	13	20.3	6.3	1.0
		21-May	0.0	159	3.6	14	21.1	5.9	1.4
		22-May	0.0	166	2.7	10	16.6	3.4	0.8
		23-May	0.0	162	2.8	10	18.3	1.6	0.7
		24-May	0.0	160	3.2	12	21.2	3.0	0.8
		25-May	0.0	153	3.6	14	22.5	4.7	2.4
		26-May	0.0	157	2.6	10	16.7	4.2	1.6
		27-May	0.0	164	2.5	10	18.8	1.4	0.5
		28-May	0.0	149	2.4	11	19.2	3.6	1.2
		29-May	0.0	140	2.7	15	18.8	10.4	2.2
		30-May	0.0	119	1.8	-10	19.7	-40.0	91.0

Appendix 9B. Weather data for season 2001/02, planting 1 and 2.

Planting 2	Planting 1	Date	Rain	Radiation	ETo	Temp	Temp	Temp	Windspeed
DAS	DAS		mm d^{-1}	W m^{-2}	mm d^{-1}	Ave (°C)	Max (°C)	Min (°C)	m s^{-1}
	1	11-Dec	0.1	377.6	7.6	19.4	24.4	13.3	1.8
	2	12-Dec	0.0	364.3	6.9	19.1	25.8	10.7	1.6
	3	13-Dec	22.7	210.9	4.2	19.2	24.3	14.5	3.1
	4	14-Dec	0.0	361.1	7.0	20.7	27.2	13.9	1.4
	5	15-Dec	0.0	352.8	6.6	21.9	27.6	15.7	1.0
	6	16-Dec	0.0	353.5	8.4	24.2	29.7	19.1	2.3
	7	17-Dec	0.0	383.6	8.9	22.3	28.9	15.3	1.6
	8	18-Dec	8.5	259.4	5.6	20.8	30.3	15.6	2.1
	9	19-Dec	0.0	359.6	7.9	20.3	27.1	14.9	3.0
	10	20-Dec	0.0	355.2	6.6	18.2	24.6	11.3	1.5
	11	21-Dec	0.0	373.2	8.0	21.0	28.4	12.4	1.2
	12	22-Dec	0.9	346.9	8.0	24.1	30.8	16.2	2.3
	13	23-Dec	22.6	172.6	2.7	17.1	21.7	14.4	1.7
	14	24-Dec	1.7	275.8	4.8	20.1	25.4	13.7	1.5
	15	25-Dec	0.1	374.2	7.9	20.2	24.5	15.2	2.1
	16	26-Dec	0.0	377.3	7.0	19.4	25.5	12.8	1.4
	17	27-Dec	0.0	305.7	5.5	20.4	25.8	15.1	1.3
	18	28-Dec	0.0	355.8	7.4	22.6	27.9	16.4	1.7
	19	29-Dec	3.6	345.9	7.3	23.3	29.9	16.8	2.1
	20	30-Dec	2.5	337.4	6.6	22.3	29.8	17.0	2.1
	21	31-Dec	0.2	298.6	7.1	22.0	29.4	16.8	2.8
	22	1-Jan	0.0	369.0	8.6	23.6	31.7	16.3	1.8
	23	2-Jan	0.0	383.1	8.1	22.6	30.6	12.1	1.3
	24	3-Jan	9.5	315.8	6.8	22.0	29.5	16.1	3.1
	25	4-Jan	0.1	368.6	8.1	24.3	30.5	17.5	2.1
	26	5-Jan	0.0	330.9	7.5	23.5	30.9	16.4	2.1
	27	6-Jan	12.2	308.0	7.9	23.4	30.2	17.1	2.9
	28	7-Jan	4.4	271.7	5.5	19.1	24.2	10.9	2.9
1	29	8-Jan	0.0	380.8	8.0	18.6	27.1	7.9	1.5
2	30	9-Jan	5.7	239.4	4.8	19.5	28.4	15.4	3.0
3	31	10-Jan	2.0	356.9	7.7	22.3	28.3	15.3	3.0
4	32	11-Jan	0.2	271.0	6.8	23.1	29.6	18.7	3.4
5	33	12-Jan	0.0	376.2	7.9	19.3	25.0	12.9	1.7
6	34	13-Jan	0.0	383.0	8.3	19.3	27.8	8.9	1.1
7	35	14-Jan	0.0	369.3	8.1	21.2	29.4	11.3	1.5
8	36	15-Jan	5.9	274.8	6.4	21.2	29.6	17.3	3.2
9	37	16-Jan	21.6	315.7	7.5	22.0	30.1	16.1	3.4
10	38	17-Jan	1.0	358.0	7.4	19.8	23.9	14.6	3.1
11	39	18-Jan	0.0	375.7	6.9	16.9	22.9	11.1	1.1
12	40	19-Jan	0.0	369.8	8.0	20.9	29.5	10.8	1.7
13	41	20-Jan	0.0	354.3	7.5	23.3	29.9	16.6	2.1
14	42	21-Jan	0.4	318.2	7.1	25.0	31.4	17.9	1.6
15	43	22-Jan	11.8	332.4	7.0	24.7	31.5	18.0	1.9
16	44	23-Jan	6.2	312.6	6.8	23.8	29.3	17.0	2.2
17	45	24-Jan	1.0	282.4	6.1	22.9	29.8	17.6	2.6
18	46	25-Jan	0.1	300.7	7.0	20.5	27.8	16.0	3.4
19	47	26-Jan	5.3	140.3	2.5	18.1	20.5	15.8	2.6
20	48	27-Jan	48.9	86.3	1.0	17.1	19.4	15.1	2.6
21	49	28-Jan	0.0	258.1	4.1	19.9	25.0	16.9	1.8
22	50	29-Jan	14.2	123.6	1.4	19.4	22.3	17.7	1.3
23	51	30-Jan	7.6	319.8	6.0	21.0	27.5	17.0	1.2
24	52	31-Jan	0.0	310.0	6.0	21.3	26.9	15.5	1.5
25	53	1-Feb	0.0	351.3	6.7	20.2	26.4	12.8	1.4
26	54	2-Feb	0.0	354.1	6.9	21.3	27.8	15.2	1.2
27	55	3-Feb	0.0	334.8	6.9	22.5	30.0	13.8	1.1
28	56	4-Feb	0.0	341.5	8.4	25.2	32.0	17.5	1.8
29	57	5-Feb	0.0	335.3	7.4	24.3	31.2	17.5	1.6
30	58	6-Feb	2.9	289.1	7.1	23.4	31.2	16.0	1.9
31	59	7-Feb	0.0	301.5	6.1	20.1	26.9	13.7	2.5
32	60	8-Feb	0.0	219.2	3.7	18.0	23.5	14.2	2.0
33	61	9-Feb	0.0	345.4	6.4	19.2	27.1	11.8	1.1
34	62	10-Feb	0.0	308.2	6.3	22.2	29.7	14.7	1.4
35	63	11-Feb	0.0	339.9	8.7	24.7	32.0	17.0	2.3
36	64	12-Feb	1.0	244.8	6.4	24.1	30.3	19.1	2.1
37	65	13-Feb	0.2	294.4	7.4	23.5	30.1	18.2	2.6
38	66	14-Feb	8.2	270.5	5.2	19.2	25.9	15.2	2.2
39	67	15-Feb	17.8	191.9	3.2	19.3	23.8	15.1	2.1
40	68	16-Feb	0.0	332.2	6.3	20.9	27.3	15.0	0.9
41	69	17-Feb	0.0	303.6	5.8	20.8	27.0	15.4	1.6
42	70	18-Feb	0.0	308.6	6.0	20.7	27.3	14.0	1.3
43	71	19-Feb	2.6	299.3	5.7	20.4	26.7	15.7	1.5
44	72	20-Feb	2.5	289.8	5.5	21.3	27.3	17.1	1.5

45	73	21-Feb	0.7	311.2	6.2	21.1	27.1	15.4	1.4
46	74	22-Feb	0.0	295.9	5.9	21.2	27.9	15.2	1.2
47	75	23-Feb	0.0	307.8	6.5	22.7	30.7	14.4	0.8
48	76	24-Feb	0.0	314.8	6.7	24.2	31.5	16.0	1.3
49	77	25-Feb	0.0	284.3	6.4	24.6	31.4	18.0	1.6
50	78	26-Feb	0.0	285.7	6.0	23.7	29.6	17.8	1.6
51	79	27-Feb	0.6	235.1	4.9	22.1	28.7	17.9	1.8
52	80	28-Feb	0.1	234.0	5.0	22.3	28.9	18.6	1.9
53	81	1-Mar	3.3	212.4	3.7	20.9	26.1	16.9	1.2
54	82	2-Mar	0.0	252.3	5.4	21.9	29.1	16.1	1.6
55	83	3-Mar	0.8	239.1	4.6	23.0	28.5	17.0	1.0
56	84	4-Mar	0.0	278.7	5.6	22.3	28.4	16.4	1.6
57	85	5-Mar	0.0	233.1	4.6	21.4	27.0	16.6	1.9
58	86	6-Mar	2.3	161.5	2.7	20.3	24.9	17.6	1.3
59	87	7-Mar	8.8	248.3	4.6	20.4	26.9	14.4	1.5
60	88	8-Mar	0.0	268.2	5.2	20.3	25.2	15.3	1.9
61	89	9-Mar	0.0	179.7	3.0	20.0	24.7	15.1	1.4
62	90	10-Mar	2.3	68.7	0.8	18.2	23.2	16.8	1.2
63	91	11-Mar	8.4	173.4	2.9	18.6	23.2	16.1	1.2
64	92	12-Mar	0.1	230.0	3.8	18.9	24.6	15.0	1.0
65	93	13-Mar	0.0	274.5	5.6	20.3	26.8	14.9	1.5
66	94	14-Mar	0.0	262.5	5.6	20.8	28.4	12.6	1.0
67	95	15-Mar	0.0	282.0	6.0	21.8	29.3	14.7	1.1
68	96	16-Mar	0.0	255.4	5.3	22.4	29.1	16.9	1.3
69	97	17-Mar	0.0	274.5	6.0	22.4	30.1	15.0	0.9
70	98	18-Mar	0.0	250.8	5.8	22.6	29.5	15.8	1.6
71	99	19-Mar	0.1	225.0	5.3	22.8	27.9	18.5	1.4
72	100	20-Mar	0.0	256.9	5.9	21.9	29.9	13.9	1.3
73	101	21-Mar	0.0	274.6	7.6	22.1	31.4	13.7	1.5
74	102	22-Mar	0.0	275.8	7.2	22.5	31.2	12.0	1.3
75	103	23-Mar	0.0	266.2	5.7	22.4	30.8	14.9	1.2
76		24-Mar	0.0	244.5	5.0	22.3	28.6	16.8	1.6
77		25-Mar	0.0	251.5	5.4	22.8	29.9	16.4	1.3
78		26-Mar	0.7	229.8	5.5	23.3	29.5	17.8	1.5
79		27-Mar	0.0	223.6	5.4	20.9	27.0	14.6	1.7
80		28-Mar	0.0	271.0	5.1	14.6	21.3	7.2	1.7
81		29-Mar	0.0	269.7	5.3	15.1	25.3	5.8	0.9
82		30-Mar	0.0	263.9	5.7	17.2	27.9	7.5	1.0
83		31-Mar	0.0	267.0	5.8	17.9	29.2	6.6	0.7
84		1-Apr	0.0	245.1	6.0	21.2	29.5	12.4	1.7
85		2-Apr	0.0	183.1	4.3	21.5	28.2	13.7	1.1
86		3-Apr	0.0	214.0	5.2	20.7	30.0	12.1	1.0
87		4-Apr	0.0	244.5	6.4	21.9	29.1	12.8	1.7
88		5-Apr	0.0	134.0	3.6	21.6	26.6	17.6	1.9
89		6-Apr	0.0	258.0	5.1	15.9	21.7	10.0	1.7
90		7-Apr	0.0	255.1	5.2	14.5	24.4	5.9	1.1
91		8-Apr	0.0	202.6	5.7	18.5	27.2	9.2	2.0
92		9-Apr	9.9	87.6	1.0	15.7	19.0	14.0	2.2
93		10-Apr	15.5	145.2	2.2	15.3	20.1	11.7	1.9
94		11-Apr	0.1	237.3	4.2	14.1	21.7	8.2	0.8
95		12-Apr	0.0	173.8	3.1	15.9	23.3	7.1	1.1
96		13-Apr	0.0	220.7	4.1	18.1	24.4	12.4	0.9
97		14-Apr	0.0	219.7	4.0	17.9	24.8	10.7	1.0
98		15-Apr	0.0	202.5	3.9	17.6	25.5	10.9	0.9
99		16-Apr	0.0	169.1	4.0	18.4	25.4	13.4	1.6
100		17-Apr	0.0	211.1	4.9	18.6	27.1	10.9	1.3
101		18-Apr	0.0	218.2	6.2	18.3	25.6	11.3	1.8
102		19-Apr	0.0	220.5	4.3	15.2	24.3	8.2	0.9
103		20-Apr	0.0	219.6	4.5	14.8	26.8	3.9	0.7
104		21-Apr	0.0	206.5	4.5	16.4	26.9	5.1	0.9
105		22-Apr	0.0	186.1	4.0	18.9	26.3	11.9	1.2
106		23-Apr	0.0	172.2	4.1	17.7	24.9	10.9	1.4
107		24-Apr	0.4	137.2	2.6	16.7	22.4	12.4	1.8
108		25-Apr	0.0	181.4	4.2	18.6	25.4	13.1	1.5
109		26-Apr	0.0	182.6	4.1	17.7	26.6	9.8	1.0
110		27-Apr	0.0	190.0	4.3	18.8	27.7	9.6	1.0
111		28-Apr	0.0	185.4	4.3	19.5	27.7	10.8	0.9
112		29-Apr	0.0	184.7	5.5	20.6	28.5	10.7	1.6

Appendix 10

Appendix 10A: Rainfall and irrigation during 2000/01, planting 1 and 2.

Date Season 1	Rain Season 1	Irrigation Season 1	Date Season 1	Rain Season 2	Irrigation Season 2
23-Nov	0	0	11-Jan	0	0.0
24-Nov	0	0	12-Jan	0	0.0
25-Nov	0	6	13-Jan	0	7.0
26-Nov	4.6	0	14-Jan	0	0.0
27-Nov	0	0	15-Jan	0	0.0
28-Nov	0.4	0	16-Jan	0	0.0
29-Nov	1.8	0	17-Jan	0	0.0
30-Nov	0	0	18-Jan	0.1	11.9
1-Dec	0	0	19-Jan	1	0.0
2-Dec	4.6	0	20-Jan	1	1.0
3-Dec	3.7	0	21-Jan	0	0.0
4-Dec	0	0	22-Jan	0	0.0
5-Dec	2.5	0	23-Jan	0	0.0
6-Dec	0.1	0	24-Jan	11.8	0.0
7-Dec	6.3	0	25-Jan	18.3	0.0
8-Dec	9	0	26-Jan	0	18.3
9-Dec	0	0	27-Jan	0	0.0
10-Dec	0.3	0	28-Jan	1.3	0.0
11-Dec	40.9	0	29-Jan	0	0.0
12-Dec	0	0	30-Jan	0	4.2
13-Dec	0	0	31-Jan	0	0.0
14-Dec	0	0	1-Feb	0	0.0
15-Dec	0	0	2-Feb	0	0.0
16-Dec	1	0	3-Feb	0	6.5
17-Dec	0.2	8.2	4-Feb	0	0.0
18-Dec	0	0	5-Feb	0	0.0
19-Dec	0	0	6-Feb	0	0.0
20-Dec	0	0	7-Feb	0	0.0
21-Dec	0.2	0	8-Feb	1.3	0.0
22-Dec	3.5	0	9-Feb	0	13.8
23-Dec	0	0	10-Feb	0	0.0
24-Dec	0	0	11-Feb	0	0.0
25-Dec	0	0	12-Feb	0	0.0
26-Dec	0	0	13-Feb	0	0.0
27-Dec	2.1	0	14-Feb	0	0.0
28-Dec	0	0	15-Feb	0	0.0
29-Dec	0	0	16-Feb	0	0.0
30-Dec	0	0	17-Feb	0	24.0
31-Dec	0.2	0	18-Feb	0	0.0
1-Jan	0.3	0	19-Feb	0	27.0
2-Jan	0	0	20-Feb	0	0.0
3-Jan	0	0	21-Feb	0.1	0.0
4-Jan	0	0	22-Feb	0	0.0
5-Jan	0	0	23-Feb	0.1	0.0
6-Jan	0	0	24-Feb	13.8	0.0
7-Jan	0	10.2	25-Feb	0	0.0
8-Jan	0	0	26-Feb	4.7	0.0
9-Jan	0	0	27-Feb	0	0.0
10-Jan	0	0	28-Feb	0	7.1
11-Jan	0	0	1-Mar	0	0.0
12-Jan	0	0	2-Mar	0	0.0
13-Jan	0	0	3-Mar	0	0.0
14-Jan	0	0	4-Mar	0	0.0
15-Jan	0	0	5-Mar	0	0.0
16-Jan	0	0	6-Mar	0	0.0
17-Jan	0	23	7-Mar	0	0.0
18-Jan	0.1	13.9	8-Mar	0.2	0.0
19-Jan	1	0	9-Mar	2.9	5.4
20-Jan	1	1	10-Mar	3.4	0.0
21-Jan	0	0	11-Mar	2.7	0.0
22-Jan	0	0	12-Mar	0	0.0
23-Jan	0	0	13-Mar	0	0.0
24-Jan	11.8	0	14-Mar	0	0.0
25-Jan	18.3	0	15-Mar	0	0.0
26-Jan	0	0	16-Mar	0	0.0
27-Jan	0	0	17-Mar	0	0.0
28-Jan	1.3	0	18-Mar	0	0.0
29-Jan	0	0	19-Mar	1.4	0.0
30-Jan	0	0	20-Mar	1.2	0.0
31-Jan	0	0	21-Mar	4.2	0.0
1-Feb	0	0	22-Mar	28	0.0

2-Feb	0	0	23-Mar	24.6	0.0
3-Feb	0	0	24-Mar	0	0
4-Feb	0	0	25-Mar	0	0.0
5-Feb	0	0	26-Mar	0	0.0
6-Feb	0	0	27-Mar	0	0.0
7-Feb	0	0	28-Mar	0	0.0
8-Feb	1.3	11.2	29-Mar	0	0.0
9-Feb	0	0	30-Mar	0	0.0
10-Feb	0	12.5	31-Mar	0	0.0
11-Feb	0	0	1-Apr	0.7	0.0
12-Feb	0	0	2-Apr	9.6	5.0
13-Feb	0	0	3-Apr	0.4	0.0
14-Feb	0	0	4-Apr	1.2	0.0
15-Feb	0	0	5-Apr	0	0.0
16-Feb	0	0	6-Apr	0	12.2
17-Feb	0	0	7-Apr	14	0.0
18-Feb	0	0	8-Apr	13.5	0.0
19-Feb	0	27	9-Apr	0.1	0.0
20-Feb	0	0	10-Apr	0	0.0
21-Feb	0.1	0	11-Apr	0	0.0
22-Feb	0	0	12-Apr	0	0.0
23-Feb	0.1	0	13-Apr	0	0.0
24-Feb	13.8	0	14-Apr	0	0.0
25-Feb	0	0	15-Apr	10.2	0.0
26-Feb	4.7	0	16-Apr	17.9	0.0
27-Feb	0	0	17-Apr	0.1	0.0
28-Feb	0	7.1	18-Apr	0	0.0
29-Feb	0	0	19-Apr	0	0.0
1-Mar	0	0	20-Apr	0	0.0
2-Mar	0	0	21-Apr	0	0.0
	135.2	120.1	22-Apr	6.6	0.0
		255.3	23-Apr	2.1	0.0
			24-Apr	6.3	0.0
			25-Apr	0	0.0
			26-Apr	3.7	0.0
			27-Apr	8	0.0
			28-Apr	0	0.0
			29-Apr	0	0.0
			30-Apr	0	0.0
			1-May	0	0.0
			2-May	0	0.0
			3-May	0	0.0
			4-May	0	0.0
			5-May	0	0.0
			6-May	0	0.0
				216.5	143.4
					359.9

Appendix 10B: Rainfall and irrigation during the 2001/02, planting 1 and 2.

Date	Rain	Irrigation	Date	Rain	Irrigation
Season 1	Season 1	Season 1	Season 2	Season 2	Season 2
10-Dec	17.0	0.0	8-Jan	0	0.0
11-Dec	0.0	0.0	9-Jan	5.8	0.0
12-Dec	0.0	0.0	10-Jan	2.4	0.0
13-Dec	26.6	0.0	11-Jan	0	0.0
14-Dec	0.0	0.0	12-Jan	0	0.0
15-Dec	0.0	0.0	13-Jan	0	0.0
16-Dec	0.0	0.0	14-Jan	0	0.0
17-Dec	0.0	0.0	15-Jan	7.8	0.0
18-Dec	9.0	0.0	16-Jan	25	0.0
19-Dec	0.0	0.0	17-Jan	1.6	0.0
20-Dec	0.0	0.0	18-Jan	0	0.0
21-Dec	0.0	0.0	19-Jan	0	0.0
22-Dec	0.8	0.0	20-Jan	0	0.0
23-Dec	24.0	0.0	21-Jan	0.2	0.0
24-Dec	2.4	0.0	22-Jan	6.6	21.0
25-Dec	0.2	0.0	23-Jan	8.2	0.0
26-Dec	0.0	0.0	24-Jan	0.8	0.0
27-Dec	0.0	0.0	25-Jan	0	0.0
28-Dec	0.0	0.0	26-Jan	6.2	0.0
29-Dec	4.0	0.0	27-Jan	58.6	0.0
30-Dec	3.8	0.0	28-Jan	0.2	0.0
31-Dec	0.2	0.0	29-Jan	14.2	0.0
1-Jan	0.0	0.0	30-Jan	2	0.0
2-Jan	0.0	0.0	31-Jan	0	0.0
3-Jan	6.0	0.0	1-Feb	0	0.0
4-Jan	0.0	0.0	2-Feb	0	0.0
5-Jan	0.0	0.0	3-Feb	0	0.0
6-Jan	16.8	0.0	4-Feb	0	0.0
7-Jan	5.4	0.0	5-Feb	0	0.0
8-Jan	0.0	0.0	6-Feb	2.2	0.0
9-Jan	5.8	0.0	7-Feb	0	0.0
10-Jan	2.4	0.0	8-Feb	0	0.0
11-Jan	0.0	0.0	9-Feb	0	0.0
12-Jan	0.0	0.0	10-Feb	0	0.0
13-Jan	0.0	0.0	11-Feb	0	0.0
14-Jan	0.0	0.0	12-Feb	0	0.0
15-Jan	7.8	0.0	13-Feb	0.6	0.0
16-Jan	25.0	0.0	14-Feb	19.6	0.0
17-Jan	1.6	0.0	15-Feb	4.8	0.0
18-Jan	0.0	0.0	16-Feb	0	0.0
19-Jan	0.0	0.0	17-Feb	0	0.0
20-Jan	0.0	0.0	18-Feb	0	0.0
21-Jan	0.2	0.0	19-Feb	3.8	0.0
22-Jan	6.6	0.0	20-Feb	3.2	0.0
23-Jan	8.2	0.0	21-Feb	0.6	0.0
24-Jan	0.8	0.0	22-Feb	0	0.0
25-Jan	0.0	7.0	23-Feb	0	0.0
26-Jan	6.2	0.0	24-Feb	0	0.0
27-Jan	58.6	0.0	25-Feb	0	0.0
28-Jan	0.2	0.0	26-Feb	0	0.0
29-Jan	14.2	0.0	27-Feb	0.6	0.0
30-Jan	2.0	0.0	28-Feb	0	0.0
31-Jan	0.0	0.0	1-Mar	2.2	0.0
1-Feb	0.0	0.0	2-Mar	0	0.0
2-Feb	0.0	0.0	3-Mar	0.6	0.0
3-Feb	0.0	0.0	4-Mar	0	0.0
4-Feb	0.0	0.0	5-Mar	0	0.0
5-Feb	0.0	0.0	6-Mar	2.4	0.0
6-Feb	2.2	0.0	7-Mar	9.2	0.0
7-Feb	0.0	0.0	8-Mar	0	0.0
8-Feb	0.0	0.0	9-Mar	0	0.0
9-Feb	0.0	0.0	10-Mar	2.8	0.0
10-Feb	0.0	0.0	11-Mar	15.6	0.0
11-Feb	0.0	0.0	12-Mar	0	0.0
12-Feb	0.0	0.0	13-Mar	0	0.0
13-Feb	0.6	0.0	14-Mar	0	0.0
14-Feb	19.6	0.0	15-Mar	0	0.0
15-Feb	4.8	0.0	16-Mar	0	0.0
16-Feb	0.0	0.0	17-Mar	0	0.0
17-Feb	0.0	0.0	18-Mar	0	0.0
18-Feb	0.0	0.0	19-Mar	0	0.0
19-Feb	3.8	0.0	20-Mar	0	0.0
20-Feb	3.2	0.0	21-Mar	0	0.0
21-Feb	0.6	0.0	22-Mar	0	0.0
22-Feb	0.0	0.0	23-Mar	0	0.0
23-Feb	0.0	0.0	24-Mar	0	0.0
24-Feb	0.0	0	25-Mar	0	0
25-Feb	0.0	0	26-Mar	0	0
26-Feb	0.0	0	27-Mar	0	0
27-Feb	0.6	0	28-Mar	0	0

28-Feb	0.0	0	29-Mar	0.2	0
1-Mar	2.2	0	30-Mar	0	0
2-Mar	0.0	0	31-Mar	0	0
3-Mar	0.6	0	1-Apr	0	0
4-Mar	0.0	0	2-Apr	0	0
5-Mar	0.0	0	3-Apr	0	0
6-Mar	2.4	0	4-Apr	0	0
7-Mar	9.2	0	5-Apr	0	0
8-Mar	0.0	0	6-Apr	0	0
9-Mar	0.0	0	7-Apr	0	0
10-Mar	2.8	0	8-Apr	0	0
11-Mar	15.6	0	9-Apr	10.6	0
12-Mar	0.0	0	10-Apr	14.6	0
13-Mar	0.0	0	11-Apr	0	0
14-Mar	0.0	0	12-Apr	**233.2**	**21.0**
15-Mar	0.0	0			
16-Mar	0.0	0			
17-Mar	0.0	0			
18-Mar	0.0	0			
19-Mar	0.0	0			
20-Mar	0.0	0			
21-Mar	0.0	0			
22-Mar	0.0	0			
23-Mar	0.0	0			
24-Mar	0.0	0			
25-Mar	**324.0**	**7.0**			