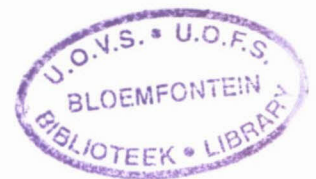


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**FIELD COMPARISON OF RESOURCE UTILIZATION AND PRODUCTIVITY OF  
THREE GRAIN LEGUME SPECIES UNDER WATER STRESS**

**KINDIE TESFAYE FANTAYE**

**FIELD COMPARISON OF RESOUCE UTILIZATION AND PRODUCTIVITY  
OF THREE GRAIN LEGUME SPECIES UNDER WATER STRESS**

**by**

**KINDIE TESFAYE FANTAYE**

A dissertation submitted  
in accordance with  
the requirement for the degree of

**Doctor of Philosophy in Agrometeorology**

In the Faculty of Natural and Agricultural Sciences  
Department of Soil, Crop and Climate Sciences  
University of the Free State

**Supervisor: Professor Sue Walker**

**Bloemfontein**

**March 2004**

Universiteit van die  
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## Declaration

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\_\_\_\_\_  
Kindie Fantaye Tesfaye

Date: March 2004

Place: Bloemfontein, Republic of South Africa

## Dedication

To my grandmother  
the late MANAHILOSH GESSESSE  
who devoted her life to children and the needy.

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**Figure 8.8.** Comparison of simulated and measured maximum leaf area index (LAI), above ground biomass at harvest (ABM), grain yield and harvest index (HI) of chickpea for three water regimes over three seasons.

## List of symbols and Abbreviations

A	rate of photosynthesis ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )
AC	height above canopy (cm)
ADM	total above ground dry matter ( $\text{g m}^{-2}$ or $\text{kg ha}^{-1}$ ; subscripts <i>b</i> for before flowering, <i>a</i> for after flowering)
AR	dry matter allocation ratio
ASW	available soil water (mm or $\text{mm m}^{-1}$ )
BN	common bean
C	well-watered (control) treatment
CEC	cation exchange capacity of soil ( $\text{mmhos cm}^{-1}$ )
CHP	chickpea
COP	cowpea
$C_p$	mean pod growth rate ( $\text{g m}^{-2} \text{ } ^\circ\text{Cd}^{-1}$ )
$C_r$	mean crop growth rate ( $\text{g m}^{-2} \text{ } ^\circ\text{Cd}^{-1}$ )
CV	coefficient of variation (%)
d	day
D	drainage (mm)
$d_a$	index of agreement
DAP	time after planting (d)
DAW	time after withholding water (d)
DLL	drained lower limit of soil ( $\text{cm}^3 \text{ cm}^{-3}$ or $\text{mm m}^{-1}$ )
DM	total dry matter ( $\text{g m}^{-2}$ or $\text{kg ha}^{-1}$ )
DOY	day of year
$D_r$	duration of reproductive growth (d or $^\circ\text{Cd}$ )
DSSAT	Decision Support System for Agrotechnology Transfer
DUL	drained upper limit of soil ( $\text{cm}^3 \text{ cm}^{-3}$ or $\text{mm m}^{-1}$ )
e	vapour pressure of air (kPa) where subscripts <i>s</i> for saturation; <i>a</i> for actual and superscript <i>o</i> for value calculated at a given temperature T
$e_w$	water use ratio or transpiration efficiency coefficient ( $\text{g kPa kg}^{-1}$ )
E	rate of transpiration ( $\text{mmol m}^{-2} \text{s}^{-1}$ ; subscript <i>s</i> for soil evaporation, mm)
ES	end of season (DOY)
ET	crop evapotranspiration (mm; superscripts <i>s</i> for seasonal, <i>b</i> for pre-flowering; <i>a</i> for post-flowering; <i>o</i> for reference evapotranspiration)
$E_w$	cumulative transpiration (mm)
F	the fraction of radiation intercepted (subscript <i>i</i> for experimental treatments)
FAO	Food and Agriculture Organization of the United Nations

GDD	growing degree day ( $^{\circ}\text{Cd}$ )
$g_s$	stomatal conductance ( $\text{mol m}^{-2} \text{s}^{-1}$ )
HI	harvest index
I	PAR measured below canopy at soil surface ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ or $\text{MJ m}^{-2} \text{d}^{-1}$ )
$I_0$	PAR measured above canopy ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ or $\text{MJ m}^{-2} \text{d}^{-1}$ )
$I_r$	irrigation (mm)
K	canopy extinction coefficient
kc	crop coefficient (subscripts <i>prev</i> and <i>next</i> for previous and next stage, respectively and <i>i</i> day number with in the growing season)
KS	Kolmogorov-Smirnov test
L	length of crops stage (subscripts <i>stage</i> and <i>prev</i> for current and previous stage respectively)
LA	leaf area ( $\text{cm}^2 \text{m}^{-2}$ or $\text{m}^2 \text{m}^{-2}$ )
LAD	leaf area duration (d)
LAI	leaf area index
LDM	leaf dry matter ( $\text{g m}^{-2}$ )
LGS	length of growing season (d)
LP	lower half of plant canopy
LS	late season/pod-filling period water stress
LSD	least significant difference
MD	mean deviation (mean bias error)
mc	measured seed moisture content (%)
ME	modelling efficiency
MS	mid-season (flowering period) water stress
N	maximum possible sunshine duration (hour)
n	measured sunshine duration (hour)
NMSA	National Meteorology Service Agency of Ethiopia
NP	number of pods ( $\text{per m}^{-2}$ )
NS	number of seeds ( $\text{per m}^{-2}$ )
O	observed data
$\bar{O}$	mean of observed data
OC	organic carbon (%)
p	dry matter partitioning coefficient
P	resource use (Chapter 1)
P	rainfall (mm, Chapter 2 and 4; subscript <i>n</i> for rainfall on a given day)
P	simulated data (Chapter 8)

PAR	photosynthetically active radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ )
PDM	pod dry matter ( $\text{g m}^{-2}$ )
PFP	pod filling period (d)
PPD	potential planting date (DOY)
PTD	photothermal days
R	runoff (mm), superscript 2 for coefficient of determination
RGF	root growth factor
RH	relative humidity (%; subscripts <i>max</i> for maximum; <i>min</i> for minimum)
RI	intercepted radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ )
RMSE	root mean square error
$r_s$	stomatal resistance ( $\text{s cm}^{-1}$ )
RUE	radiation use efficiency ( $\text{g MJ}^{-1}$ )
S	soil water (mm; subscripts <i>n</i> for water stored on day <i>n</i> and <i>n-1</i> for previous day)
SAT	semi-arid tropics
SD	standard deviation
SDM	stem dry matter ( $\text{g m}^{-2}$ )
SLA	specific leaf area ( $\text{g cm}^{-2}$ )
$S_p$	species
SPAC	soil-plant-atmosphere continuum
SPD	successful planting date (d)
SR	incoming solar radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ )
$SR_0$	extraterrestrial radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ )
SW	hundred seeds mass (g)
t	time during growing season (d) where subscript <i>T</i> for thermal time ( $^{\circ}\text{Cd}$ )
T	temperature ( $^{\circ}\text{C}$ ) where subscripts <i>A</i> for air; <i>b</i> for base, <i>max</i> for maximum, <i>min</i> for minimum, <i>L</i> for leaf
	transpiration (mm; subscript <i>s</i> for seasonal; Chapter 4)
TDR	time domain reflectometry
TE	transpiration efficiency ( $\text{g mm}^{-1}$ ; subscript <i>g</i> for grain yield)
	time to emergence (days; Chapter 3)
TF	time to flowering (d)
TM	time to maturity (d)
TP	time to pod initiation (d)
$u_s$	mass flow of air per $\text{m}^2$ of leaf area ( $\text{mol m}^{-2} \text{s}^{-1}$ )
UP	upper half of plant canopy
VPD	vapour pressure deficit of air (kPa)



W	crop water use (mm)
WMO	World Meteorological Organization
$W_R$	water regime (treatments)
WS	weather station
WUE	water use efficiency ( $\text{kg ha}^{-1}\text{mm}^{-1}$ ) where subscripts <i>d</i> for total above ground dry matter; <i>g</i> for grain yield; <i>b</i> for pre-flowering; <i>a</i> for post-flowering period
Y	grain yield ( $\text{g m}^{-2}$ or $\text{kg ha}^{-1}$ )
$\alpha$	canopy PAR absorption coefficient
$\beta$	ratio of PAR to global solar radiation
$\varepsilon$	resource use efficiency
$\rho_b$	soil bulk density ( $\text{mg m}^{-3}$ or $\text{g m}^{-3}$ )
$\rho_s$	soil particle density ( $\text{mg m}^{-3}$ )
$\Delta$	carbon isotope discrimination
$\Delta c$	difference in $\text{CO}_2$ concentration through measuring chamber ( $\mu\text{mol mol}^{-1}$ )
$\Delta S$	change in soil water storage (mm)
$\Delta w$	differential water vapour concentration ( $\text{mmol mol}^{-1}$ )
$\psi_L$	leaf water potential (MPa)
$\theta_s$	soil water content at saturation ( $\text{mm m}^{-1}$ or $\text{cm}^3 \text{cm}^{-3}$ )

## Abstract

### FIELD COMPARISON OF RESOUCUE UTILIZATION AND PRODUCTIVITY OF THREE GRAIN LEGUME SPECIES UNDER WATER STRESS

by

KINDIE TESFAYE FANTAYE

PhD in Agrometeorology at the University of the Free State

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Grain legumes play a major role in low input agricultural systems by providing quality protein to the poor communities and improving the natural resource base used for the production of other rainfed cereal crops. The yield of the crops, however, is low mainly due to water shortage. This study had a major aim of comparing the resource use and productivity of beans, chickpea and cowpea under water stress and well-watered conditions in a semi-arid environment so as to facilitate crop choice and management practices in different legume producing environments.

Resource utilization and productivity studies for a given crop or cropping system involve both the crop and its growing environment. In this study, therefore, resource utilization and productivity were studied through field experimentation with three grain legume species and analysis of rainfall/water supply behaviour of ten representative grain legume growing regions in Ethiopia. The field experiments were conducted at Dire Dawa, Ethiopia. The station lies in the semi-arid belt of the eastern Rift Valley escarpment with a long-term mean annual rainfall of 612 mm and a soil dominated by Eutric Regosol. The field experiments were conducted for three seasons in 2001/2002, 2002 and 2002/2003. The treatments were three water regimes, viz., well-watered (C), mid-season (MS) and late season (LS) water stress and three species arranged in a randomised split plot design using water regimes as main plot and the species as sub-plot. The experiments involved measurements of important variables in the soil-plant-atmosphere continuum.

Analysis of the long-term rainfall of 10 stations in chapter 2 indicated the existence of major regional differences in water supply. In some of the regions (e.g. Bahir Dar, Bako and Bole) excess water is a problem while in other areas (e.g. Dire Dawa and Jijiga) water shortage is a major bottleneck for crop production. Based on water supply, the regions were grouped as ample water supply, intermediate water supply and poor water supply regions. The study indicated the need to adjust crop choice and management practices based on site and seasonal conditions.

The resource utilization and productivity of the three species was studied based on a micrometeorological approach involving phenology, growth and dry matter partitioning (Chapter 3), water use and water use efficiency (Chapter 4), radiation and radiation use efficiency (Chapter 5), water relations and carbon assimilation (Chapter 6) and yield and its components (Chapter 7). Analysis of phenology and growth indicated a reduction of leaf area and dry matter only in the MS treatment and a shortened growth period only in the LS treatment in all species. However, species differences were observed in that the reduction in leaf area due to MS stress was the least in cowpea compared to beans and chickpea. Both the timing of water supply and species influenced dry matter allocation among aboveground parts. The LS stress hastened dry matter allocation to the pod while the MS depressed it in all species. In the LS stress, beans allocated a higher percentage of the above ground dry matter to the seed than chickpea and cowpea during the mild temperature seasons while cowpea allocated the highest percentage during the high temperature season. Such high dry matter allocation to the pod is important to maintain high harvest index (HI) under water-limited environments.

Water use varied across water regimes, the highest being in the C treatment followed by the MS and LS treatments in descending order in all species. However, the MS treatments resulted in the lowest water use efficiency (WUE) in all species due to low leaf area index (LAI) and high soil evaporation. Despite differences in water use, the C and LS treatments had similar WUE in all species indicating that some periods of water stress during the late stage of crop growth may increase WUE and improve water saving in water-limited environments. WUE was also strongly negatively correlated with specific leaf area (SLA) under well-watered conditions in all species and in both seasons suggesting that it could be used as a selection criterion for high WUE in the species. The MS treatment reduced extinction coefficient ( $K$ ) and thereby reduced fractional radiation interception ( $F$ ) in all species. Radiation use efficiency (RUE) was also negatively affected by the MS stress in beans and chickpea whereas it was not affected by any of the water stress treatments in cowpea.

The relationship among soil water, leaf water potential, stomatal resistance, rate of photosynthesis ( $A$ ) and transpiration ( $E$ ), vapour pressure deficit and leaf temperature are described in Chapter 6. Cowpea, followed by beans, closes its stomata at higher level of soil water content and leaf water potential as compared to chickpea. Cowpea also has a capacity to photosynthesise and transpire at a higher rate under favourable water supply and also to maintain a slower rate of decline in  $A$  and  $E$  under low soil water status when compared with beans and chickpea. The magnitude and rate of  $A$  decline was higher and faster in the MS

than in the LS stress, and among species, it was faster in chickpea than in beans and cowpea. Stepwise regressions of data indicate that, unlike transpiration, photosynthesis could be estimated from a few weather and physiological parameters with reasonable accuracy in all the three species.

In contrast to cowpea, which is less and almost equally sensitive to both stress periods, the grain yield of beans and chickpea was found to be more sensitive to the MS than the LS stress during all seasons. The high sensitivity of beans and chickpea grain yield to the MS stress was associated with reductions in LAI, WUE, RUE and dry matter partitioning to the pod as a result of the stress. The lower grain yield reduction of cowpea under water stress is attributed to the crop's ability to adjust its stomata promptly and maintain its LAI, photosynthesis and RUE at a higher level than beans and chickpea.

Simulation of grain yield with CROPGRO in beans and chickpea gave a satisfactory result with some limitations in simulating yield components. The model has shown a promising potential to be used as a decision support tool in the semi-arid regions after further calibration and testing.

The results generally show that cowpea is more productive and resource efficient than beans and chickpea under water-limited conditions while beans is more productive and has higher resource efficiency than cowpea and chickpea under well-watered conditions. It is concluded that better productivity and optimum resource utilization can be achieved through proper crop-environment matching. Moreover, crop management and breeding practices should focus on increasing the WUE, RUE and HI of grain legumes to improve the yield of the crops in mid-season drought prone environments.

**Keywords:** Beans, Chickpea, Cowpea, Gas exchange, Radiation use efficiency, Resource utilization, Productivity, Semi-arid environment, Water deficit, Water use efficiency.

## Uittreksel

### VELD-VERGELYKING VAN HULPBRONVERBRUIK EN PRODUKTIWITEIT VAN DRIE GRAANBOONSPESES ONDER WATERSTREMMING.

deur

KINDIE TESFAYE FANTAYE

PhD in Landbouweerkunde by die Universiteit van die Vrystaat

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Graanbone speel 'n belangrike rol in lae-inset landboustelsels deurdat dit kwaliteit proteïene aan die arm gemeenskappe verskaf en die natuurlike hulpbronbasis vir die produksie van ander droëland graangewasse verbeter. Die opbrengs van die gewasse is egter laag, hoofsaaklik a.g.v. watertekorte. Hierdie studie het die hoofdoel gehad om die hulpbronverbruik en produktiwiteit van bone, keker-ertjies en swartbekboontjies tydens toestande van waterstremming en geen waterstremming te vergelyk in 'n semi-ariëde omgewing om sodoende gewaskeuse te vergemaklik en bestuurspraktyke in verskeie peulgewas-omgewings te bepaal.

Die bestudering van hulpbronverbruik en produktiwiteit binne 'n gegewe gewasstelsel behels beide die gewas en sy groei-omgewing. In hierdie studie is hulpbronverbruik en produktiwiteit dus bestudeer deur veldeksperimentering waarin drie peulgewas-spesies gebruik is en die reënval/watertoevoer van tien verteenwoordigende peulgewas groeistreke in Ethiopië ontleed is. Die veldeksperimente is uitgevoer by Dire Dawa, Ethiopië. Die stasie is in die semi-ariëde gordel van die oostelike Skeurvallei-platorand geleë. Die langtermyn gemiddelde jaarlikse reënval is 612 mm, terwyl die grond deur 'n Eutric Regosol gedomineer word. Die veldeksperimente is vir drie seisoene in 2001/2002, 2002 en 2002/2003 uitgevoer. Die behandelings was drie waterverdelings, nl. goed-gewater (C), middel-seisoen (MS) en laat-seisoen (LS) waterstremming en drie spesies in 'n ewekansige verdeelde perseelontwerp waarin waterverdelings as hoofpersele en die spesies as sub-persele gebruik is. Die eksperimente het die meting van belangrike veranderlikes in die grond-plant-atmosfeer kontinuum behels.

Ontleding van die lang-termyn reënval van 10 stasies in hoofstuk 2 het groot streeksverskille in die watertoevoer uitgewys. In sommige van die streke (bv. Bahir Dar, Bako en Bole) is oortollige water 'n probleem, terwyl watertekorte 'n groot demper op gewasproduksie plaas in ander gebiede (bv. Dire Dawa en Jijiga). Die gebiede is aan die hand van watertoevoer gegroepeer as streke met genoegsame watertoevoer, intermediêre watertoevoer en swak watertoevoer. Die studie het die behoefte uitgewys om gewaskeuse en bestuurspraktyke na aanleiding van die perseel en seisoenale toestande aan te pas. Die hulpbronverbruik en produktiwiteit van die drie spesies is ondersoek deur gebruik te maak van 'n mikrometeorologiese benadering wat fenologie, groei en droëmassa-skeiding (Hoofstuk 3), waterverbruik en waterverbruikseffektiwiteit (Hoofstuk 4), straling en stralingsverbruikseffektiwiteit (Hoofstuk 5), waterverhoudinge en koolstof-assimilasie (Hoofstuk 6) en opbrengs en die komponente daarvan (Hoofstuk 7) behels. Ontleding van fenologie en groei het gedui op 'n verlaging van blaaroppervlak en droëmassa in die MS behandeling alleenlik en 'n verkorte groeitydperk in slegs die LS behandeling onder alle spesies. Verskille tussen spesies is egter waargeneem aangesien die vermindering in blaaroppervlak a.g.v. MS stremming kleiner was onder swartbekboontjies in vergelyking met bone en keker-ertjies. Beide die tydsberekening van watertoevoer en die betrokke spesie het die droëmassa allokering onder bogrondse plantdele beïnvloed. Die LS stremming het droëmassa allokering na die peul versnel, terwyl MS stremming dit onder alle spesies vertraag het. Bone het meer droëmassa as keker-ertjies en swartbekboontjies na die peul geallokeer. Sodanige droëmassa allokering na die peul is belangrik om 'n hoë oesindeks (HI) in waterbepaalde omgewings te onderhou.

WATERVERBRUIK het oor waterverdelings verskil; die hoogste verbruik het in die C behandeling voorgekom gevolg deur die MS en LS behandelinge in dalende volgorde onder alle spesies. Die MS behandelings het egter gelei tot die laagste waterverbruiksdoeltreffendheid (WUE) onder alle spesies a.g.v. die blaararea-indeks (LAI) en hoë grondverdamping. Ten spyte van verskille in waterverbruik het die C en LS behandelinge soortgelyke WUE onder alle spesies gehad wat dui dat sommige tydperke van waterstremming gedurende die latere stadium van gewasgroei WUE mag laat toeneem en waterbesparing in waterbeperkte omgewings bevorder. Daar was ook 'n sterk negatiewe korrelasie tussen WUE en spesifieke braararea (SLA) onder goed-gewaterde toestande onder alle spesies in beide seisoene wat daarop dui dat dit gebruik kan word as 'n seleksiekriterium vir hoë WUE onder die spesies. Die MS behandeling het die uitdunningskoëffisiënt (K) verlaag en daardeur die gedeeltelike stralings-onderskepping (F) by alle spesies verlaag. Stralingsverbruikseffektiwiteit (RUE) was ook negatief geaffekteer deur die MS stremming in bone en keker-ertjies waarteen dit nie deur een van die waterstremmingsbehandelinge in swartbekboontjies geaffekteer is nie.

Die verband tussen grondwater, blaar waterpotensiaal, huidmondjie-weerstand, fotosintese-(A) en transpirasietempo (E), dampdrukdepressie en blaartemperatuur word in Hoofstuk 6 beskryf. Swartbekboontjies, gevolg deur bone, sluit hul huidmondjies by hoër vlakke van grondwaterinhoud en blaar-waterpotensiaal in teenstelling met keker-ertjies. Swartbekboontjies besit ook die vermoë om teen 'n hoër tempo te fotosinteer tydens gunstige watertoever en om 'n stadiger tempo van afname in A en E te onderhou ten tye van lae grondwaterstatus in vergelyking met bone en keker-ertjies. Die grootte en tempo van afname in A was hoër en vinniger in die MS- as in die LS-stremming, en tussen die spesies was dit vinniger in keker-ertjies as in bone en swartbekboontjies. Stapsgewyse regressie van die data toon dat, anders as in die geval van transpirasie, kan fotosintese met redelike akkuraatheid geskat word aan die hand van 'n paar weer- en fisiologiese parameters onder die drie spesies.

In teenstelling met swartbekboontjies wat minder en amper ewe sensitief vir stremmingsperiodes is, is daar gevind dat die graanopbrengs van bone en keker-ertjies meer sensitief is vir die MS- as die LS-stremming in al die seisoene. Die hoë sensitiwiteit van boon en keker-ertjie graanopbrengs vir die MS-stremming was geassosieer met afnames in LAI, WUE, RUE en droëmassa allokering na die peul a.g.v. die stremming. Die laer afname in graanopbrengs van swartbekboontjies onder waterstremming kan toegeskryf word aan die vermoë van die gewas om sy huidmondjies vinnig aan te pas en sy LAI, fotosintese en RUE by 'n hoër vlak as dié van bone en keker-ertjies te onderhou.

Simulering van graanopbrengs met CROPGRO vir bone en keker-ertjies het bevredigende resultate gelewer met 'n paar tekortkominge in die simulering van opbrengskomponente. Die model het 'n belowende potensiaal getoon om na verdere kalibrasie en toetsing as 'n ondersteunende besluitnemingshulpmiddel in die semi-ariëde streke gebruik te word.

Die resultate toon oor die algemeen dat swartbekboontjies meer produktief en hulpbron-effektief is as bone en keker-ertjies onder waterbeperkte toestande, terwyl bone meer produktief en 'n hoër hulpbronverbruikseffektiwiteit as swartbekboontjies en keker-ertjies openbaar ten tye van genoegsame watertoever. Die gevolgtrekking kan gemaak word dat beter produktiwiteit en optimale hulpbronverbruik bereik kan word deur middel van gepaste gewas-omgewing passing. Bowenal behoort die fokus van gewasbestuur en teelpraktyke te val op die verhoging van WUE, RUE en HI van peulgewasse om sodoende die opbrengs van die gewasse in middel-seisoen droogte-omgewings te verhoog.

**Sleutelwoorde:** Bone, Keker-ertjies, Swartbekboontjies, Gas-uitruiling, Stralingsverbruikseffektiwiteit, Hulpbronverbruik, Produktiwiteit, Semi-ariëde omgewing, Waterstremming, Waterverbruikseffektiwiteit.

## CHAPTER 1

### General Introduction

"And our water, the universal solvent, present in the air, in the soil, in plants, animals and man. Without it life could not endure."

J.A. Toogood  
Our Soil and Water

#### 1.1. Introduction

The amount of water involved in food production is significantly higher than the amount used in other sectors. Most of this water is provided directly by rainfall. Rainfed agriculture depends entirely on rainfall, and it accounts for about 60% of production in developing countries (FAO, 2003). Since the yield potential of most crops is attained under favourable water supply environments, the potential to improve non-irrigated yields is mainly restricted to areas where rainfall is subject to large seasonal and interannual variations. With a high risk of yield reductions or complete crop loss from dry spells and droughts, farmers practicing rainfed agriculture are reluctant to invest in inputs such as plant nutrients, high-yielding seeds and pest management (FAO, 2003). For resource-poor farmers in semi-arid regions, the overriding requirement is to harvest sufficient foodstuff to ensure sustained nutrition of the household through to the next harvest.

More than 20 countries in the world, the majority of them in the arid and semi-arid regions, are considered to be either water-scarce or water-stressed because of their growing population and increased demand for water which is more than the hydrological system can provide on a sustainable basis (Watson *et al.*, 1998). As a result, 800 million people are food-insecure, and 166 million pre-school children are malnourished in the developing world (Rosegrant *et al.*, 2002). Despite the increasing demand for water in these countries, the supply is diminishing due to human activities that degrade watersheds and threaten natural ecosystems (Goodrich *et al.*, 2000). Although water shortage and desertification affect all dryland areas, developing countries are particularly vulnerable to the economic and social costs associated with the decline of agricultural and natural ecosystem productivity (Goodrich *et al.*, 2000). The semi-arid tropics (SAT), which are severely affected by water shortage and environmental degradation, include parts of 49 countries in South Asia, northern Australia, sub-Saharan Africa, parts of eastern and southern Africa and some countries

of Latin America (Kumar and Abbo, 2001). One sixth of the world population inhabits these areas, and about half of the population earns less than U.S \$ 1 per day (Kumar and Abbo, 2001). Grain legumes are among the major vital crops that can produce sustainable grain yield and biomass in these harsh environments and provide quality-protein to the inhabitants. These crops also play a major role in low input agricultural systems. The prime advantage is their ability to fix atmospheric nitrogen and thereby contribute positively towards the nitrogen balance of the cropping system (Subbarao *et al.*, 1995). Their contribution of biologically fixed nitrogen is a key factor in sustaining long-term soil fertility in cereal production both in the developed and developing world (Jayasundara *et al.*, 1998). They also affect the cropping system positively by breaking disease cycles, improving soil physical conditions and mobilization of unavailable soil phosphorus (Hoshikawa, 1991). Therefore, a major rationale for including grain legumes such as chickpea in the cropping system of the SAT environments is their potential to contribute to the enhancement of the natural resource base used for the production of other crops. These other crops are mostly staple foods of the poor communities who rely on marginal rainfed lands. Enhancement of the natural resource base is achieved through an increase in soil nitrogen amount which reduces the need for fertilizer and thereby increases the saving of a household and decreases environmental degradation (Kumar and Abbo, 2001).

Grain legumes occupy about 12.58 million ha of land in Africa and accounted for an annual production of 5.56 million tons per annum during the 1980s (Saxena *et al.*, 1987). However, yield of grain legumes is generally lower and more variable than those of many other crop species (Jeuffroy and Ney, 1997), and specifically even lower in developing countries than in the developed ones (Oram and Agcaoili, 1992), being the lowest in Africa when compared with other developing countries (Al-Jibouri and Kassapu, 1987). Thus, there is a need to increase the performance of pulse crops, particularly in developing countries, where most grain legume production is for human consumption and demand is increasing due to increasing population pressure. Warm-season grain legumes like common bean and cowpea and some cool-season grain legumes such as chickpea are the most important pulses in the semi-arid and sub-humid areas of sub-tropical Africa.



Common bean (*Phaseolus vulgaris* L.) is the major dietary protein source in East Africa and Latin America (Graham and Ranalli, 1997). In Ethiopia, it occupies an area of 112 810 ha with a total production of 94 764 tons (CSA, 1997). The crop is grown as a sole crop or intercropped with other crops and usually receives less agricultural inputs under multiple cropping systems. The yield ranges from 500 kg ha<sup>-1</sup> under farm conditions in less developed countries up to 5000 kg ha<sup>-1</sup> under experimental conditions (Graham and Ranalli, 1997). About 60% of the bean production worldwide occurs under drought stress conditions (Graham and Ranalli, 1997), and this could be an even greater percentage in the semi-arid regions such as East Africa where the growing season is short and the rainfall is erratic.

Chickpea (*Cicer arietinum* L.) occupies an area of 11.1 million ha land worldwide with a total annual production of 9.1 million tons, and ranks third among the worlds food legumes (FAO, 1994). Chickpea, unlike other legumes such as grasspea, faba bean and soybean, does not contain any major anti-nutritional chemicals and hence provides high quality protein and starch to developing countries (Kumar and Abbo, 2001). Ethiopia is designated as a secondary center of chickpea diversity and is the largest producer of this crop in East Africa (Kumar and Abbo, 2001). The crop is mainly grown at an altitude of between 1400 and 2300 m in the northern and central highlands of the country. It is planted during August/September (van den Maesen, 1972) when the rainfall is diminishing and hence the growth of the crop is mainly dependent on stored soil water. About 90% of the world's chickpea is grown under rainfed conditions in a post rainy season, on marginal lands, often without monetary inputs (Kumar and Abbo, 2001). Drought is, therefore, the major constraint to increase the productivity of chickpea (Kumar *et al.*, 1996; Kumar and Abbo, 2001), the alleviation of which could lead to 50% increase in production with a value of ca. U.S. \$ 900 million (Ryan, 1997).

Cowpea (*Vigna anguiculata* L. Walp.) is one of the most widely adapted and versatile grain legume crops, grown on about 7 million ha of land in warm to hot regions of the world (Rachie, 1985; Ehlers and Hall, 1997). The largest production of cowpea comes from sub-Saharan Africa where it occupies 75% of the area of cowpea production while the rest of the production is spread over Europe, Asia, and North America (Ehlers and Hall, 1997). As indicated in the report of Singh (1987), the area allocated to cowpea in Ethiopia is estimated to be 136 000 ha with a corresponding production of 34 000 tons.

Although dry seed is the major product of cowpea for human consumption, leaves, fresh peas and fresh green pods are also consumed by people in different parts of the world (Ehlers and Hall, 1997). The nutritional quality of cowpea is similar to that of common bean but with higher levels of folic acid and lower levels of anti-nutritional and flatulence producing factors and with a fast cooking time (Bressani, 1985; Ehlers and Hall, 1997). Although, cowpea is intercropped with sorghum, pearl millet, maize, cassava or cotton in many areas (Blade *et al.*, 1997), it is also sole cropped in some areas (Ehlers and Hall, 1997). Compared to other crop species, cowpea has considerable adaptation to high temperature, drought and adverse edaphic factors (Hall and Patel, 1985; Ehlers and Hall, 1997). Therefore, because of its numerous attributes such as adaptability, versatility, productivity and nutritional quality, cowpea has been chosen by the US National Aeronautical and Space Administration (NASA) as one of few crops to be studied for cultivation on space stations (Ehlers and Hall, 1997). Although it is tolerant to numerous environmental constraints, cowpea is also responsive to favourable growing environments (Ehlers and Hall, 1997). Drought is still one of the major constraints that reduce the yield potential of cowpea in many regions (Turk *et al.*, 1980a).

Despite increasing demand and their vital role in sustaining the farming system, the expansion of cereal cropping is pushing grain legume production to smaller and more marginal areas in developing countries (e.g. Kumar and Abbo, 2001). The relegation of these crops to marginal lands together with the ever increasing water shortage results in low productivity and yield instability of the crops which further increases the demand (Kumar and Abbo, 2001). Generally, producing enough food and generating adequate income to feed the poor in the developing world is a great challenge. This challenge is likely to intensify, with a global population that is projected to increase to 7.8 billion by 2025, putting even greater pressure on world food production, especially in developing countries where more than 80% of the population increase is expected to occur (Rosegrant *et al.*, 2002). This challenge has to be tackled by increasing the productivity of rainfed agriculture in the developing countries. One of the options to meet this objective is integrated use of crop, weather and agroclimatic information so as to use the available resource efficiently and maximize productivity.

## 1.2. Motivation

Water deficit limits global food productivity more severely than any other environmental factor (Boyer, 1982; Fischer and Turner, 1978) and is the major abiotic stress in many parts of the world (Johansen *et al.*, 1992). As observed on many occasions, drought remains the single most important factor threatening the food security of many developing countries. Most developing countries that grow grain legumes have large arid regions and, in addition, several countries have experienced drought for extended periods. In severely affected areas, there appears to be a widespread malnutrition problem and unless some long-term measures are taken to enhance the cultivation of drought-resistant crops, which can provide a balanced diet, this problem will continue.

Although the demand for grain legumes is increasing from time to time, cereal-based production systems do not yet encourage the cultivation of these crops on the more productive soils (Saxena *et al.*, 1993b). As a result of many biotic and abiotic stresses, there is a large yield gap between potential and realized yields of the legume crops (Subbarao *et al.*, 1995). Constraint analysis has showed that large yield and productivity losses in grain legumes are due to water deficit (Subbarao *et al.*, 1995). There is room, however, to minimize and to a certain extent alleviate such losses through appropriate scientific research. Sustainable grain legume production in water-limited environments can be achieved through knowledge generation on agro-climate of crop growing sites, resource capture and utilization efficiency of crops, crop-weather relations and physiological adaptation mechanisms and integrating this knowledge into the decision making process.

## 1.3. Defining the drought environment

Although drought is a common and recurring phenomenon, it lacks a single universal definition mainly because the concepts and criteria of drought are relative and dependent on each water user's needs and circumstances (Whitemore, 2000). According to Wilhite and Glantz (1985) and Whitemore (2000), four commonly used definitions of drought are identified as follows:

**Meteorological drought** is defined as a period when rainfall is significantly less than the long-term average or some designed percentages thereof, or less than some fixed value.

**Agricultural drought** occurs when soil water is reduced to levels that cause reductions in yield of crops and/or pasture. Agricultural drought is further divided into early season, mid-season, terminal or intermittent drought depending on the time of its occurrence relative to the stage of crop growth.

**Hydrological drought** refers to a rainfall deficit capable of seriously reducing surface and sub-surface hydrological levels.

**Socio-economic drought** occurs when water supply is insufficient to meet water consumption for human activities such as industry, urban supply, irrigation, etc.

In the agronomic sense, drought refers a severe reduction in grain yield attributable to plant water deficit (Subbarao *et al.*, 1995). Although the magnitude or predominance of a particular type of drought is region specific, grain legumes grown under rainfed production system are prone to drought at any stage during their growth cycle (Subbarao *et al.*, 1995). Therefore, grain legumes grown under rainfed agricultural conditions can be exposed to multiple drought stresses during the vegetative or reproductive phase of growth. When drought occurs during the vegetative stage, the crop's recovery from the drought depends on subsequent rainfall. On the other hand, terminal drought is the most critical stress factor for grain legume crops grown on stored soil water during post-rainy season (Subbarao *et al.*, 1995), and under conditions when the seasonal rainfall is not sufficient to recharge the soil water for reproductive growth.

Therefore, characterization of the drought pattern of the target environment is the first step in designing strategies to alleviate drought stress (Subbarao *et al.*, 1995). As pointed out by the same authors, this step has been inadequately addressed in drought research programs, mainly because of the complexity of the task. However, there is now opportunity to deal with the problem because of the development of water balance models and GIS (to assist in spatial visualization of the drought pattern) (Subbarao *et al.*, 1995) as well as progress made in developing models for analysis of daily rainfall. This knowledge has the potential to allow estimation of long-term crop losses due to drought stress, and the potential gains from alleviating drought stress through genetic and management options (Subbarao *et al.*, 1995). Since a characteristics of drought

resistance that is useful in one environment may not be useful in another, identifying the drought behaviour of a given environment also has a potential advantage in fitting specific drought resistance traits to specific environments and production systems (e.g. Ludlow and Muchow, 1990). In general, "Identifying the climatic risks in the target environment, identifying the functional components of yield affected by the environment in the selected crops, and understanding the physiological processes affected are important prerequisites to a successful crop improvement for drought prone environments" (Turner *et al.*, 2001).

#### 1.4. Resource Utilization

Water and radiation, together with temperature, are the major natural resources that govern the growth, development and productivity of crop plants. The capture and utilization of these resources by plants has been the subject of many studies in the tropics and other environments (e.g. Monteith, 1977a, b; Squire, 1990; Morris and Garrity, 1993; Monteith, 1994; Monteith *et al.*, 1994; Ong *et al.*, 1996; Williams, 2000; Black and Ong, 2000).

In the resource capture approach, the productivity of a process is the product of the amount of resources captured and the efficiency with which the resources are used in producing the required product (Williams, 2000). This can be explained as

$$Y = P\varepsilon \quad (1.1)$$

where Y is the product, P is the resource used and  $\varepsilon$  is the resource use efficiency. The importance of this model in crop production is that it expresses productivity based on resource acquisition, its conversion to biomass and the distribution of this biomass to grain yield (Williams, 2000). Williams (2000) also indicated that the amount of resource captured by crops depends on the availability of the resource and crop management practices.

Radiation capture and utilization depend on the fraction of intercepted photosynthetically active radiation (PAR) and its efficiency in producing dry matter (Black and Ong, 2000). Though the method is criticized for its technical and theoretical difficulties, intercepted radiation is commonly measured as the difference between the

total quantity of incident radiation and the quantity transmitted through the canopy to the soil surface (Sinclair and Muchow, 1999; Black and Ong, 2000). The amount of radiation intercepted greatly depends on the quantity received at top of canopy, canopy size and duration and fractional interception (Squire, 1990; Black and Ong, 2000). Seasonal changes in fractional interception depend mainly on canopy architecture and phenology of a given crop species. For example, the increase of fractional interception is more rapid in cereals than in legumes because of differences in leaf initiation and expansion (Squire, 1990). However, variation in fractional interception between crops is smaller than the variation in green leaf area index. This is mainly because the extinction coefficient is larger in those crops with slow canopy expansion, and as a result maximum fractional interceptions differ little between crops grown under non-limiting conditions (Black and Ong, 2000). Because of the difference in the duration of ground cover, mean seasonal fractional interception values are generally lower in short-duration cereals and legumes than perennial species (Squire, 1990; Black and Ong, 2000). In any crop stand growing under optimal conditions (with adequate soil water, sufficient nutrient supply, free from weed or insect infestation, and free of harmful pathogenic activities), the dry matter (DM) production will increase linearly with the cumulative amount of photosynthetically active radiation (PAR; 0.4-0.7  $\mu\text{m}$ ) that is intercepted (or absorbed) by the canopy (Green, 1987). The efficiency of converting the intercepted PAR into stand dry matter is defined by Monteith's (1977a) integral function:

$$RUE_i = \frac{DM}{\int_{t_1}^{t_2} \alpha F_i (\beta SR) dt} \quad (1.2)$$

where RUE is the radiation-use efficiency (the subscript  $i$  denotes the experimental treatments),  $t$  is the time of the growing season,  $F_i$  is the fraction of radiation intercepted by the stand canopy and is a function of canopy development and stand duration,  $\alpha$  is the canopy absorptivity of PAR, and  $\beta$  ( $= 0.50$ ) is the ratio of PAR to global solar radiation (SR). This model is well known as Monteith's "resource capture concept". RUE can be affected by adverse environmental factors such as water stress which affect photosynthetic activity. Therefore, RUE can be used to quantify the impact of stress factors by comparing the observed values with those obtained under non-stress conditions (Arkebauer *et al.*, 1994).

Similar to radiation, DM production also depends on the capture and utilization of water. The ratio of dry matter produced to water transpired or lost as evapotranspiration is known as water use ratio or water use efficiency (Sinclair *et al.*, 1984; Cooper *et al.*, 1988; Turner, 1997; Black and Ong, 2000). Therefore, dry matter production can be expressed as

$$DM = e_w \sum E_w \quad (1.3)$$

where  $e_w$  is water use ratio,  $\sum E_w$  is cumulative transpiration and DM is dry matter (Black and Ong, 2000). As observed in several studies, DM is linearly related to the quantity of water transpired suggesting that  $e_w$  is conservative (Azam-Ali, 1983; Connor *et al.*, 1985; Copper *et al.*, 1987). This close relationship between DM and  $E_w$  results from the close linkage between  $CO_2$  and  $H_2O$  vapor fluxes through the stomata in opposite directions. Atmospheric vapor pressure deficit (VPD) affects the flux of  $CO_2$  and  $H_2O$  and it is considered as one of the most important factors that limit the productivity of dryland areas (Squire, 1990). Although an active growing plant under well-watered condition transpires at a rate determined by the prevailing atmospheric demand, transpiration under water-stress condition is dictated by both plant (stomata adjustment, rooting characteristics and leaf movement) and environmental factors (air humidity, temperature and radiation load). In annual crop plants the canopy conductance (or its reciprocal resistance) influences transpiration, particularly in stressed or senescent canopies (Black and Ong, 2000). According to Ong *et al.* (1996), water use efficiency during sustained drought is mainly controlled by the regulation of canopy size rather than leaf conductance. The balance between transpiration and water absorption depends on soil and atmospheric conditions, and a reduction in transpiration usually result in decreased assimilation and growth (Black and Ong, 2000).  $C_3$  species have a far lower WUE and RUE than  $C_4$  species (Squire, 1990; Sinclair and Muchow, 1999; Black and Ong 2000), and hence there is a need to improve the water and radiation use efficiencies of  $C_3$  species, particularly under dry environments.

### 1.5. Drought resistance framework

Drought resistance in crop plants can be studied using the “drought resistance framework” and the “resource capture or yield component framework” (Turner, 2000; Turner *et al.*, 2001). The drought resistance framework involves the identification of specific morphological, physiological and biochemical characteristics that lead to

improved yield in dry environments. The resource capture or yield component framework involves yield variation in terms of characteristics affecting water use and water use efficiency, radiation use and radiation use efficiency, partitioning of assimilates and the harvest index (Passioura, 1977; Turner, 2000; Turner *et al.*, 2001).

The major components of the drought resistance framework are: (1) drought escape, which involves earliness, (2) dehydration postponement, which involves maintenance of turgor by stomatal regulation, accumulation of abscisic acid and/or osmotic adjustment, and (3) dehydration tolerance, which involves membrane stability, tolerance to low leaf water potential and accumulation of proline (Subbarao *et al.*, 1995; Turner *et al.*, 2001).

The resource capture or yield component framework involves the use of crop growth models to study yield using physiological components that can effectively integrate a number of complex processes into fewer biologically meaningful parameters (Turner *et al.*, 2001). As summarized in Turner *et al.*, (2001), yield variation in grain legumes can be analyzed using several resource capture models. Firstly, grain yield (Y) can be explained using two components as follows:

$$Y = ADM * HI \quad (1.4)$$

where ADM is total above-ground dry matter and HI is harvest index. Eq. (1.4) can be further partitioned into functional components that can describe detailed physiological processes for ADM and HI (Duncan *et al.*, 1978) as follows:

$$Y = C_r * D_r * p \quad (1.5)$$

where  $C_r$  is crop growth rate,  $D_r$  is duration of reproductive growth and  $p$  is the partitioning coefficient (proportion of  $C_r$  portioned to yield). Y can also be analyzed as a function of radiation interception and use as described by Monteith (1977a) as

$$Y = RI * RUE * HI \quad (1.6)$$

where RI is cumulative intercepted radiation and RUE is radiation use efficiency. In contrast, Passioura (1977) described yield in water deficit environments as a function of water use and water use efficiency as

$$Y = W * WUE * HI \quad (1.7)$$

where W is amount of water utilized by the crop and WUE is water use efficiency.



Each subcomponent of the various yield models represents an integrated function of a number of physiological, morphological and biochemical characters (Hardwick 1988a; Turner *et al.*, 2001) and hence provide an integrated measure of crop performance in a given environment. Any potential characters for drought adaptability can thus be evaluated based on its functional relationship and strength of its correlation to one of the yield components (Turner *et al.*, 2001). Both the drought resistance and yield component frameworks have been widely exploited in the improvement of yield in cereal crops under drought prone environments (Ludlow and Muchow, 1990; Richards, 1996; Turner 1997; Turner *et al.*, 2001). However, such information is still lacking for most grain legumes.

### 1.6. Rationale

Water stress reduces crop growth on nearly all arable land (Solh, 1993) and severely limits agricultural productivity (Boyer, 1982). Drought is probably the most important stress factor limiting crop yields worldwide (Jones and Corlett, 1992). Furthermore, it is often difficult to distinguish between direct effects of drought and its interactions with other factors such as harmful pathogenic soil fungi, low soil fertility, and high air temperatures. Drought affects every aspect of plant growth and the worldwide losses in yield from drought probably exceed the loss from all other causes combined (Kramer, 1980). Therefore, drought at any one stage of crop growth is the primary reason that crop yields fall below their genetic potential and vary from year to year.

The drought-prone areas of Ethiopia cover about 60% of the total area of the country (MoA, 1998) and account for 46% of the total cultivated land but contribute less than 10% of the total crop production in the country as a result of water stress (Reddy and Kidane, 1994). These drought prone areas are characterized by erratic rainfall and a hot dry climate with low annual precipitation amount and a short crop growing season (Simane, *et al.*, 1998; Reddy and Kidane, 1994). Although beans and cowpea are usually grown by farmers in arid and semi-arid zones and chickpea is grown solely on residual soil water in the relatively highland areas of the country, there is no scientific data that support the choice of the crops for the stated environments. Although information is available about the drought response of the individual crops in the

literature, it is difficult to compare the 'true' performance of the species because of environmental, experimental and technical variations during the experiments. Moreover, little research has been conducted on grain legumes that can be used to compare the actual performance of the different crops and their resource utilization efficiency under water stress conditions and to identify the most appropriate environmental conditions for each crop.

### **1.7. Objectives**

The major thrust of this study was to compare resource utilization and productivity of common bean, cowpea and chickpea under water-stress conditions in the field and to characterize their growing environments. The specific objectives of the study were:

1. To analyse yield-limiting weather conditions, particularly rainfall, in the grain legume growing ecoregions of Ethiopia to generate information useful for agricultural decisions making,
2. To compare the resource capture and utilization efficiency of the crops under water stress and well-watered conditions,
3. To determine and compare the influence of water deficit on growth, yield and yield components of the three species,
4. To examine each species' physiological response to drought during reproductive growth stages and
5. To evaluate the DSSAT grain legume crop simulation model in a semi-arid environment.

## CHAPTER 2

### Agroclimatic Potential of Selected Locations in Ethiopia: Analysis of Variability and Onset of Rainfall, Probability of Dry Spells and Length of Growing Season

#### 2.1. Introduction

Agriculture is always under the influence of different weather and climatic challenges. The degree of influence, however, depends on space, time and the type of agricultural commodity considered which make one weather element more important than another. For example, rainfall is the most important weather element that affects crop production in the semi-arid tropics (e.g. Virmani *et al.*, 1980). The rainfall in these regions is limited, variable in space and time, and unpredictable (Stewart and Hash, 1982; Sivakumar, 1992). The Eastern Horn of Africa is one of the regions where rainfall is extremely variable and unpredictable (Beltrando and Camberlin 1993; Beltrando, 1990; Ogallo, 1988). For example, in Ethiopia the rainfall is highly variable in amount and distribution both in space and time (NMSA, 1996).

Analysis of rainfall events in a short time scale is indispensable for agricultural decision making because of the fact that the seasonal rainfall distribution in the semi-arid tropical regions is variable and as a result recommendations based on annual totals are misleading (Simane and Struick, 1993; Virmani *et al.* 1980). Therefore, the start and end of the rains and their distribution (Stern *et al.* 1982a; Sivakumar, 1988), and the length, frequency and probability of dry spells (Sivakumar, 1992) in the growing season are key questions to be addressed in the planning and management of dryland agriculture.

Predicting the start of the growing season (onset of the rains) is the most risky business in agriculture because of the variability of the rainfall from year to year, from season to season and from region to region. A "false" start of the rainfall prompts the farmer to plant his crop early in the face of long dry spells after emergence. In most cases, this results in poor crop stand and/or complete crop failure. This situation is a common experience in many semi-arid tropical regions like Ethiopia. The subject has been the topic of many studies resulting in many different definitions. Some of them include:

- (1) the first occasion with more than 20 mm rainfall in one or two days after a certain selected date (Virmani, 1975),

- (2) the first ten-day period (decade) with more than 25 mm, provided that rainfall in the next decade exceeded half the potential evapotranspiration (Kowal and Knabe, 1972),
- (3) the first occasion when the 7 day total rainfall exceeds 25 mm and includes at least 4 rainy days (Raman 1974),
- (4) when rainfall is greater than  $0.35 ET_o$  (reference Evapotranspiration) (Houérou *et al.*, 1993),
- (5) the first occasion after a selected date when the rainfall accumulated over 2 days is at least 20 mm and when no dry spell (exceeding 10 days) occurs within the following 30 days (Stern *et al.* 1982a), and
- (6) the first occasion after a selected date when the rainfall accumulated over 3 days is at least 20 mm and no dry spell of length more than 7 days occurs within the following 30 days (Sivakumar, 1988).

Although the definitions used by the different authors do vary, they show the importance of analysing the start or onset of the rainfall in a given region so as to determine the potential and risks involved in either planting early or late in the season.

The end of the growing season is mainly dictated by stored soil water and its availability to the crop after the rain stops. In line with this, Stern *et al.* (1982a) defined the end of the season as the first date on which soil water is depleted. Simane and Struik (1993) used a threshold value of 20 mm total soil water to signify the end of the growing season.

Analysis of historical rainfall data to give information on the onset of rains, length of growing season, probability and frequency of dry spells is used as an input to assess cropping potential and risks in a given region. For example, in West Africa, where the rainfall is also variable, analysis of historical data has been used to assess the potential and risk of crop production in the region (Sivakumar, 1992; 1991; 1988). Except for a few studies by Simane and Struik (1993) and Simane *et al.* (1999) on some selected sites using decade (10 days) rainfall data and some reports by National Meteorology Service Agency (NMSA) using monthly data (e.g. NMSA, 1996), the rainfall patterns of Ethiopia and its agricultural implication has not yet been studied in detail using daily rainfall data.

The objectives are, therefore: (1) to analyse the pattern and spatial variability of rainfall at selected stations which are in the different agroecological zones of Ethiopia, (2) to determine the length of the growing season and to investigate the length and probability

of dry spells during the growing season, and (3) to evaluate the risk of planting with the first rains of the growing season at the various sites.

## 2.2. Methodology

### 2.2.1. Site description and data acquisition

Ten meteorological stations, which lie in the different parts of Ethiopia, were selected for the study. The choice of the stations was based on data availability, distribution of grain legume production and representativeness of agroecological settings in the country. Daily rainfall and temperature data were obtained from the National Meteorology Service Agency (NMSA). In order to fill some missing values and years, data was also collected from research stations at the respective locations as well as from the Ministry of Agriculture. The different stations used in the study, their geographical descriptions and the database considered are presented in Table 2.1 and Fig. 2.1.

**Table 2.1. Geographical description and rainfall database of ten stations used in the Study.**

Station	Latitude (°N)	Longitude (°E)	Altitude (m)	Data base period	Number of years	Source*
Alemaya	9.26	41.01	1980	1979-2001	23	NMSA
Awassa	7.05	38.29	1750	1970-1999	30	NMSA
Bahir Dar	11.36	37.25	1770	1970-1999	30	NMSA
Bako	9.07	37.05	1650	1970-1999	30	NMSA
Bole (A.A)	9.02	38.45	2408	1970-1999	30	NMSA
Debre Ziet	8.44	38.57	1900	1970-1999	30	NMSA/DZARC
Dire Dawa	9.36	41.51	1260	1970-1999	30	NMSA
Jijiga	9.20	42.47	1775	1970-1999	30	NMSA/SERP
Mekele	13.30	39.29	2070	1970-1988, 1991-1999	28	NMSA
Melkassa	8.24	39.19	1540	1977-1999	23	NMSA/EARO

\* EARO= Ethiopian Agricultural Research Organization, SERP = South East Rangeland Project, DZARC = Debre Zeit Agricultural Research Centre.

Soil data were obtained from a previous study (Eylachew, 1994) as well as onsite soil profile description, and analysis of samples collected from some of the sites (Awassa, Dire Dawa and Jijiga) at the National Soil Laboratory in Addis Ababa. Reference evapotranspiration ( $ET_0$ ) at 10-day intervals was taken from the NMSA report. Daily  $ET_0$  values were obtained by interpolation. Crop evapotranspiration (ET) of common bean (95 days maturing), chickpea (100 days maturing) and cowpea (100 days maturing) was calculated using crop coefficients (kc) obtained from Allen *et al.* (1998) and  $ET_0$  of the respective sites.

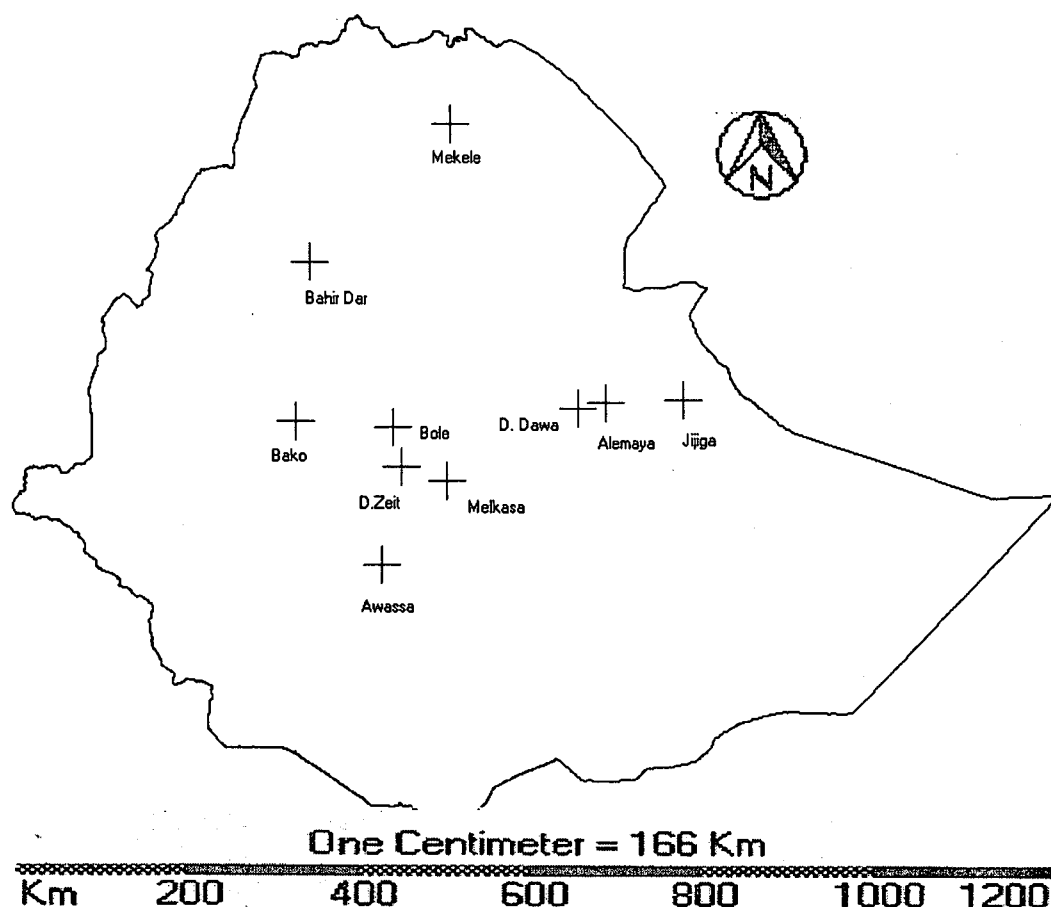


Figure 2.1. Map of Ethiopia showing the location of the meteorological station sites.

Daily  $kc$  values were determined using the following relationship as described in Allen *et al.* (1998).

$$kci = kc_{prev} + \left[ \frac{i - \sum(L_{prev})}{L_{stage}} \right] (kc_{next} - kc_{prev}) \quad (2.1)$$

Where  $i$  = day number within the growing season,  $kci$  = crop coefficient on day  $i$ ,  $L_{stage}$  = length of the stage under consideration (days),  $\sum(L_{prev})$  = sum of the length of all previous stages (days),  $kc_{next}$  = crop coefficient of the next stage,  $kc_{prev}$  = crop coefficient of the previous stage.

### 2.2.2. Analysis

The rainfall data were analysed using INSTAT Climatic Guide (Stern and Knock, 1998). This statistical package allows summarization of daily rainfall data and further processing of the data to obtain the starting date of planting, water balance calculation, determination

of the end of season, calculation of dry spell probabilities and length of growing season, etc., based on information provided by the user. It also allows fitting of gamma distribution and Markov chain probability models. For the purpose of comparing regions on long and equal period of time, a Markov chain model was fitted to generate 100 years data for each site for the calculation of onset of rains, end of season, and dry spell probabilities. The advantage of this method is described in detail in Stern *et al.* (1982b) and Stern and Coe (1982).

The annual, monthly and decadal patterns of the rainfall were examined for each site. The coefficient of variation (CV) was calculated as the ratio of the standard deviation to the mean rainfall. The annual rainfall trend was analysed using 5-year moving average for sites that have more than 25 years of data. The probabilities of getting a rainfall exceeding 0, 10 20, 30, 40, 50 100 and 150 mm were estimated for each of the 36 decades. Decade refers to the 10-day averaging periods of each month (WMO, 1966).

“Potential planting date” was defined as the first occasion with more than 20 mm rainfall in three days after a selected date. The onset of the rains, explained by Sivakumar (1988) as the first occasion after a selected date when the rainfall accumulated in 3 consecutive days is at least 20 mm and no dry spells of more than 7 days in the next 30 days, was used here as a “successful planting date”. This criterion is chosen as the successful planting date because it takes into account the potential dry spells at least in the following 30 days after planting as in contrast with the potential planting date. The risk of first planting (the failure of planting with first rains) was, therefore, calculated relative to the successful planting date.

The daily rainfall data was processed to give maximum dry spell lengths in the next 30-day periods from a starting date. Probabilities of the maximum dry spell lengths exceeding 5, 7, 10, 15 and 20 days over the next 30 days from the first decade of February (just before the start of the short rain period) to the last decade of November (end of the main growing season) were calculated to get an overview of the drought conditions throughout the year. The length of the dry spells (5-20 days) was selected in such a way that both drought sensitive and drought tolerant crops are considered in the growing season. Conditional dry spells (conditional on that the day before planting is rainy) were also calculated in order to see whether a break in dry spell affects the length of the following dry spells. Maximum and conditional dry spells were also calculated

starting from the onset of rains (successful planting date) to examine the probability of short and long dry periods during crop growth period.

A simple water balance calculation was conducted for each location using rainfall,  $ET_o$  (reference evapotranspiration) or  $ET$  (crop evapotranspiration) and soil water content at saturation. The water balance was calculated as described by Stern *et al.* (1982a) as follows:

$$S_n = S_{n-1} + P_n - ET \quad (2.2)$$

where  $S_n$  = soil water on day  $n$ ,  $S_{n-1}$  = soil water accumulated on previous day,  $P_n$  = rainfall on day  $n$  and  $ET$  = reference or crop evapotranspiration. Water holding capacity of the soil at saturation ( $\theta_s$ ) was determined from bulk density as described by Williams *et al.* (1992)

$$\theta_s = 0.93 * (1 - (\rho_b / \rho_s)) \quad (2.3)$$

where  $\rho_b$  is bulk density ( $\text{mg m}^{-3}$ ) and  $\rho_s$  is soil particle density ( $\text{mg m}^{-3}$ ) which is taken as 2.65 whenever measurements are not available. The calculated soil water balance was used to define the end of the growing season as the first date on which the soil water drops to  $10 \text{ mm m}^{-1}$  (i.e.  $<5.2 \text{ mm m}^{-1}$  available water) after a predetermined date. Available soil water was calculated as the difference between water content at drained upper limit (DUL) and permanent wilting point or lower limit (DLL). The soil water properties of each site are shown in Appendix 1A. Once the start and end of the season are known, the length of the growing season was obtained by subtraction.

## 2.3. Results and Discussion

### 2.3.1. Annual rainfall

The mean annual rainfall ranged from 601 mm (Mekele) to 1436 mm (Bahir Dar) and was highly variable from year to year and location to location (Table 2.2). The coefficient of variation (CV) ranged from 14% (Bako, Awassa) to 43% (Jijiga). Except for Jijiga, high rainfall variability was observed in the low annual rainfall areas which agree with previous reports (Brown and Cocheme, 1969, Simane and Struik, 1993, NMSA, 1996).

However, the high CV in Jijiga implies that such generalizations could be misleading, as the rainfall of a given region could be variable despite its annual amount. Table 2.2 also showed that the percentage of years with rainfall above  $X+SD$  ranged from 10 (Jijiga) to 22 % (Alemaya) and that of below  $X-SD$  ranged from 3 (Jijiga) to 23% (Dire Dawa).



**Table 2.2. Annual rainfall statistics of ten locations in the different ecoregions of Ethiopia for the period 1970-2001.**

Station	X <sup>*</sup> (mm)	Min (mm)	Max (mm)	SD (mm)	CV (%)	>X+SD (%)	<X-SD (%)	Mar.-May rainfall (%) <sup>a</sup>	Jun.-Sept. rainfall (%) <sup>b</sup>
Alemaya	791	569	1053	145	18	22	22	35	53
Awassa	965	725	1226	132	14	17	20	30	50
Bahir Dar	1436	900	2042	250	17	10	10	8	84
Bako	1207	964	1652	170	14	17	13	22	69
Bole	1081	817	1552	172	16	13	13	22	69
Debre Ziet	845	580	1123	145	17	13	17	19	74
Dire Dawa	612	357	965	157	26	17	23	39	44
Jijiga	682	389	1825	292	43	10	3	39	48
Mekele	601	293	918	140	23	14	14	15	81
Melkassa	789	512	1276	163	21	13	14	18	68

<sup>\*</sup>X= mean annual rainfall

Min= minimum recorded value of annual rainfall

Max = maximum recorded value of annual rainfall

SD= standard deviation

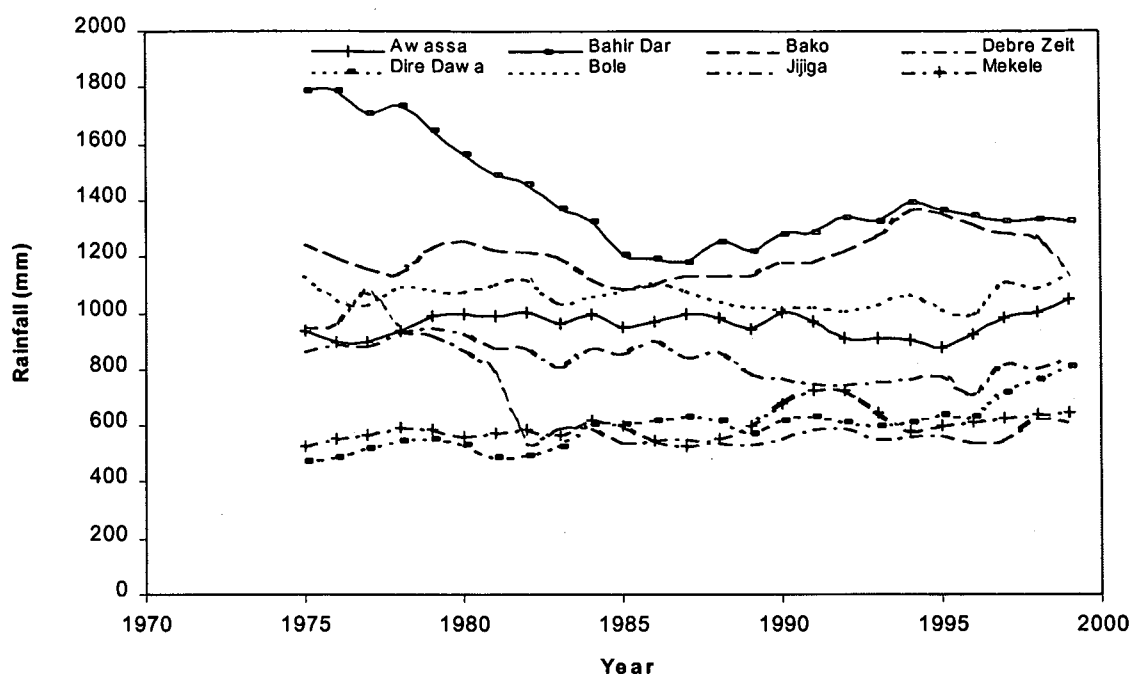
CV= coefficient of variability

>X+SD= percent of years with annual rainfall greater than X+SD

<X-SD = percent of years with annual rainfall less than X+SD

<sup>a</sup> short-rain period, <sup>b</sup> long-rain period

Analysis of annual rainfall (recorded at each station) using 5-year moving average for the period of 30 years showed a trend of both wet and dry years at most of the sites studied (Fig. 2.2). The rainfall at Bahir Dar was decreasing steadily from the 1970s to the middle of the 1980s (dry years). Nevertheless, it increased slightly again from that period to the middle of the 1990s (wet years). The rainfall at Bako followed the same trend after the middle of the 1990s. The trend at Jijiga was decreasing from the 1970s to the early 1980s but remained almost stable after this period. In Debre Zeit, the rainfall was steadily decreasing from the late 1980s to the early 1990s. On the other hand, the rainfall at Dire Dawa was slightly increasing starting from the early 1980s (Fig. 2.2). The rainfall was almost stable at Awassa and Bole from the 1980s to early the 1990s. Except Bahir Dar and Bako, the annual rainfall showed an increasing trend for all stations after the middle of the 1990s. Such variation among regions in long-term annual rainfall fluctuations suggest the need to make agricultural decisions region specific to exploit opportunities and minimize risks in each region.



**Figure 2.2. Trends of annual rainfall using 5-year moving average analysis in eight stations in Ethiopia for the year 1970-2000.**

### 2.3.2. Rainfall distribution

The rainfall is characterized by its seasonality in all the locations studied (Appendix 1B&C). The pattern of the rainfall in Bahir Dar, Bako and Awassa is unimodal. The rest of the locations studied have a bimodal or semi-bimodal pattern in which the rainfall has a small peak in April/May and maximum peak in August. About 50-84% of the total rainfall was received within four months (June-September) in all the locations except Dire Dawa and Jijiga (Table 2.2). In the true bimodal rainfall areas in the eastern part of the country (Alemaya, Dire Dawa, Jijiga), the first rainy season, which constitutes 35-39% of the annual rainfall, extends from March to May while the second extends from July to September (Table 2.2, Appendix 1C). The first (small) rain season in the bimodal regions is very short and it is highly characterized by inter-annual variation (Simane and Struik 1994, NMSA, 1996). The period when  $P$  exceeds 50%  $ET_0$  in the main (big) rain season extends from decade 19 to 29 in Alemaya, 9 to 29 in Awassa, 15 to 29 in Bahir Dar, 12 to 28 in Bako, 14 to 28 in Bole, 17 to 27 in Debre Zeit, 21 to 25 in Dire Dawa, 19 to 27 in Jijiga, 18 to 25 in Mekele and 17 to 26 in Melkassa. Awassa and Bako have the longest rainy periods followed by Bahir Dar and Bole (Appendix 1B&C). Similar to previous reports (Simane 1990, Kassam, 1977; Kowal and Kassam, 1978), the relation between  $P$

and 50%  $ET_0$  in the present study indicated a lower chance of false start of the rainfall once the rainfall exceeded half of the  $ET_0$  in the season.

Seasonal and annual rainfall variations in Ethiopia are results of the macro-scale pressure systems and monsoon flows which are related to the changes in the pressure systems (Haile, 1986; Beltrando and Camberlin, 1993; NMSA, 1996). The most important weather systems that cause rain over Ethiopia include Sub-Tropical Jet (STJ), Inter Tropical Convergence Zone (ITCZ), Red Sea Convergence Zone (RSCZ), Tropical Easterly Jet (TEJ) and Somalia Jet (SJ) (NMSA, 1996). The spatial variation of the rainfall is, thus, influenced by the changes in the intensity, position, and direction of movement of these rain-producing systems over the country (Tadesse, 2000). Moreover, the spatial distribution of rainfall in Ethiopia is significantly influenced by topography (NMSA, 1996; Tadesse, 2000). STJ, ITCZ, RSCZ, TEJ and the SJ cause rainfall in the bimodal and semi-bimodal areas. On the other hand, the rainfall in the unimodal areas is mainly the result of the movement of the ITCZ though some influences of the other weather systems still exist (NMSA, 1996).

### **2.3.3. Rainfall and evapotranspiration**

The periods when rainfall ( $P$ ) exceeds reference evapotranspiration ( $ET_0$ ) at 100, 50 and 35% are shown in Appendix 1B&C for the 10 locations. The period when  $P$  exceeds 35 %  $ET_0$  is considered as the minimum water requirement for start of growing season (Houérou *et al.*, 1993). The maximum number of decades when  $P$  exceeds 35%  $ET_0$  for three consecutive decades during the main rain season are 11 in Alemaya, 22 in Awassa, 15 in Bahir Dar, 19 in Bako, 21 in Bole, 11 in Debre Zeit, 7 in Dire Dawa and Mekele, 8 in Jijiga, and 10 in Melkassa (Appendix 1B&C). Comparison of monthly  $P$  and 100%  $ET_0$  indicated that in some regions the rainfall exceeded the evaporative demand of the sites for a period of as long as 4.7 months (Bako) whereas in other regions the rainfall could not meet the evaporative demand at all (Dire Dawa, Jijiga). Regions like Alemaya, Awassa, Bahir Dar, Bole, Debre Zeit, Mekele and Melkassa satisfy their evaporative demand for periods of at least 2 to 3 months. This period is the period of soil water accumulation in the respective sites. According to Troll's (1965) climatic classification, locations where rainfall exceeds reference evapotranspiration for 2 to 4.5 and 4.5 to 7 consecutive months are classified as dry semi-arid and wet-dry semi-arid, respectively. Areas where  $P$  exceeds  $ET_0$  for a period of less than 2 months are classified as arid

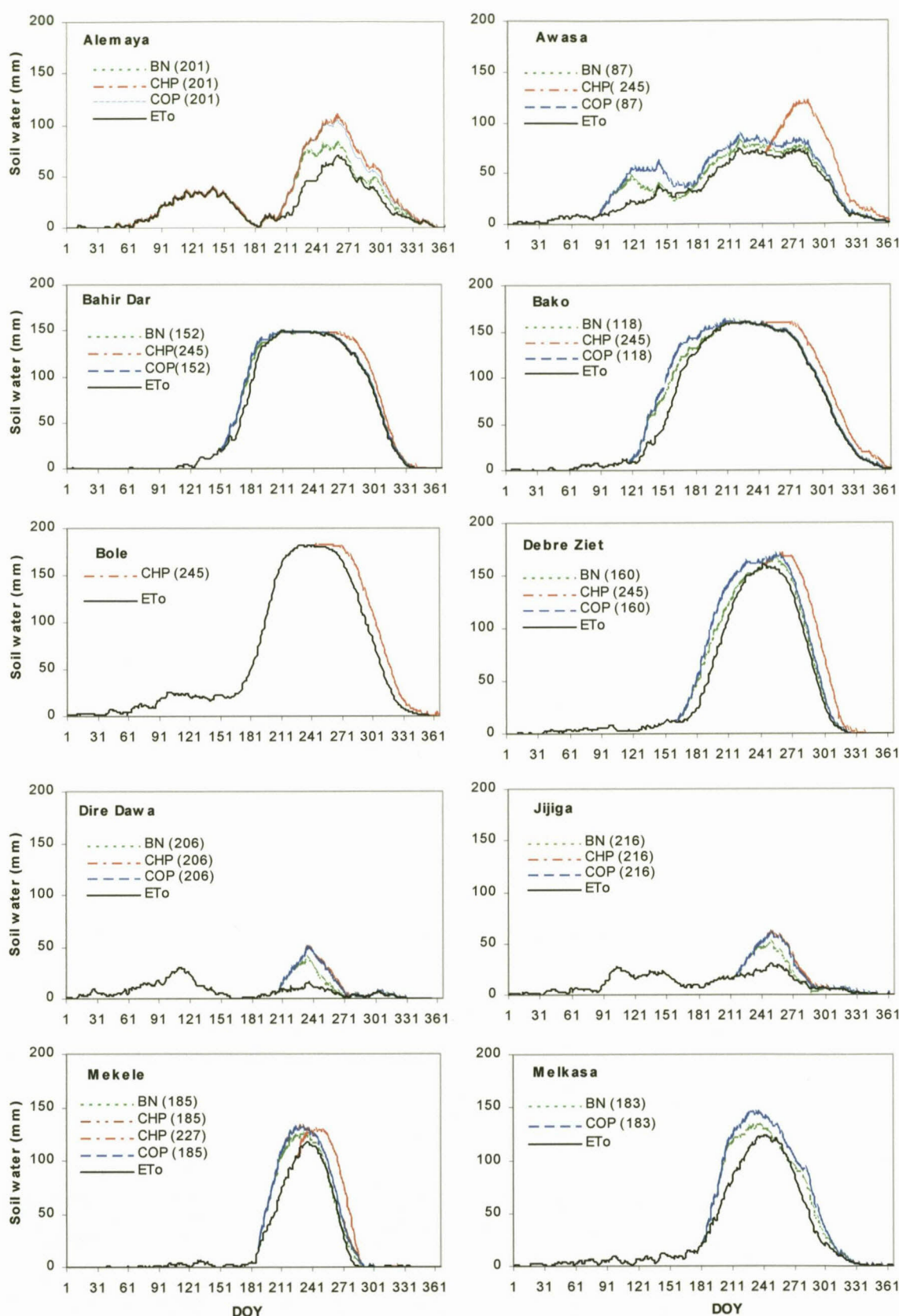
tropics. Accordingly, Alemaya, Awassa, Bahir Dar, Bole, Debre Zeit, Mekele and Melkassa are classified as dry semi-arid whereas Bako is classified as wet-dry semi-arid and Dire Dawa and Jijiga are classified as arid tropics.

#### **2.3.4. Soil water**

Results for the annual water balance studies using the long-term daily rainfall data are shown in Fig. 2.3. The maximum water stored in the soil during the main rain season ranged from 13 mm (Dire Dawa) to 176 mm (Bole). The period when soil water storage remained above 50 mm was the longest at Bako (16 decades) followed by Bahir Dar (13 decades), Bole (12 decades), Debre Zeit (10 decades), Melkassa (9 decades), Mekele (6 decades) and Alemaya (4 decades). The lowest soil water at Dire Dawa during the main rain season was mainly due to its low annual rainfall, high evaporative demand and low water holding capacity of the soil due to its sandy nature. The lower value at Jijiga is predominantly associated with its high evapotranspiration and erratic nature of the rainfall. In general, the results indicate the spatial variability of possible soil water accumulation as influenced by the rainfall, soil characteristics, and the evaporative demand of a given site (Huda, *et al.* 1990, Simane, 1990). The crop evapotranspiration tested in each site showed that soil water accumulation was influenced by the type of crop grown and its growing length (Fig. 3). Since the  $k_c$  is less than one for most of the growing period, the lower crop evapotranspiration resulted in a longer period of soil water accumulation than when using the reference evapotranspiration at all of the sites.

#### **2.3.5. Dependability of rainfall**

In most semi-arid regions, the start, end and continuity of the rainfall are not reliable. Therefore, information on probability of rainfall exceeding certain threshold values in a given period is more important than the average rainfall. The probabilities of receiving rainfall exceeding 0, 10, 20, 30, 40, 50, 100 and 150 mm per decade are shown in Fig. 2.4 for the 10 locations. The different rainfall values can be used as a threshold level for different crops with different maturity, drought tolerance and water logging resistance as well as for different soil types with different water holding capacities (Simane and Struik, 1993). In all the locations studied, the dependable rainfall (rainfall at 80% probability) is higher, and the season is longer at low than at high rainfall thresholds. However, the dependable rainfall is lower and the season is shorter in the bimodal rainfall areas (Alemaya, Dire Dawa, Jijiga) even at lower rainfall thresholds when compared to the

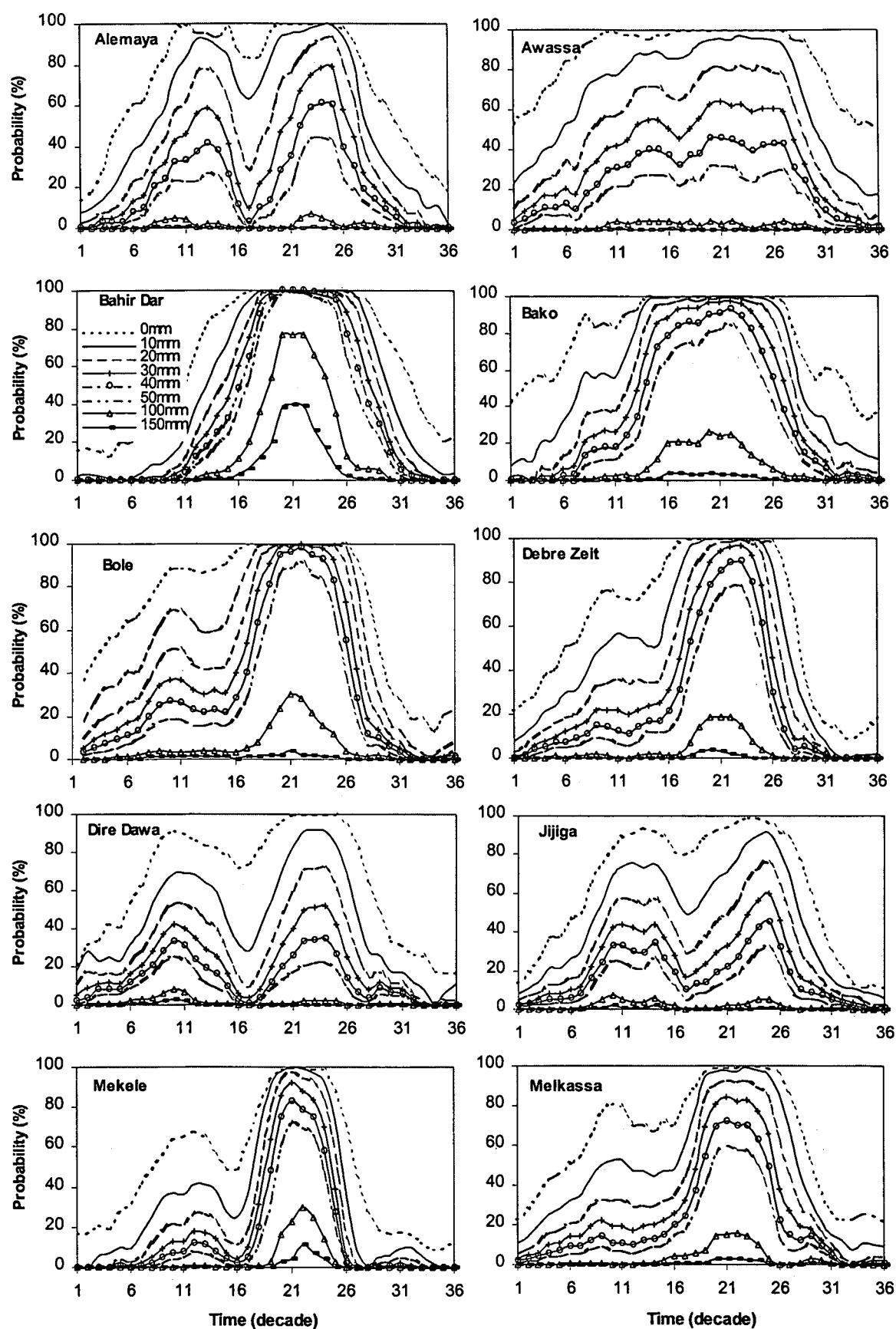


**Figure 2.3.** Seasonal soil water balance of 10 stations in Ethiopia using reference Evapotranspiration,  $ET_o$  (site water use) and maximum crop evapotranspiration (crop water use). Figures in parenthesis on the legend are days of planting (DOY) for the respective crops as practiced by the farmers. BN = beans, CHP = chickpea, COP = cowpea.

unimodal and semi-bimodal regions. Among the unimodal rainfall areas, the period of dependable rainfall at Mekele was very short (80 days). The length of the dependable rainfall in Awassa was exceptionally long at 0 and 10 mm thresholds (160-240 days) but very short at 20 mm threshold (60 days).

Investigation of the daily rainfall data shows a higher number of rainy days with low intensity of rainfall in the region. This nature of the rainfall may have significant impact on the agricultural activities of the region because of its high infiltration into the soil as well as its uniform distribution during the crop-growing season. The probability of receiving a decadal rainfall exceeding 100 and 150 mm reached 78 and 40%, respectively for three consecutive decades (21-23) at Bahir Dar. These high rainfall conditions necessitate the need to design alternative soil conservation practices and run-off protection strategies particularly on soils with low water holding capacity and also to design better drainage system in areas where the soil has high water holding capacity. There is also a 16 to 30% chance of receiving 100 mm rainfall in a decade at Debre Zeit, Bole, Mekele and Melkassa during August. This high rainfall is problematic especially at Bole and Debre Zeit where the soil has Vertic properties (high clay content) leading to water logging conditions that hinder agricultural activities such as sowing, weeding, fertilizer application etc., and also affects crop growth and development. The chance of receiving rainfall exceeding 150 mm in a decade is very low in all regions except Bahir Dar.

There is a good chance of getting high rainfall (100 mm per decade) in Mekele during the month of August such that a water harvesting technique can be practiced to capture the rainfall, which can then be used later in the season to lengthen the growing period. According to the study of Rockström and Falkenmark (2000), on average 30-40% of seasonal rainfall is lost as runoff and deep percolation in many semi-arid cropping systems of sub-Saharan-Africa. Harvesting and storing this water in reservoirs could help in prolonging the crop growth period and also averting the effect of dry spells if applied as supplemental irrigation (Barron *et al.*, 1999; Rockström, 2001).



**Figure 2.4.** Probabilities of receiving rainfall exceeding 0, 10, 20, 30, 40, 50, 100 and 150 mm per decade at ten locations in Ethiopia.

### **2.3.6. Length of dry spells**

#### **2.3.6.1. Probability of dry spells computed on a calendar day basis**

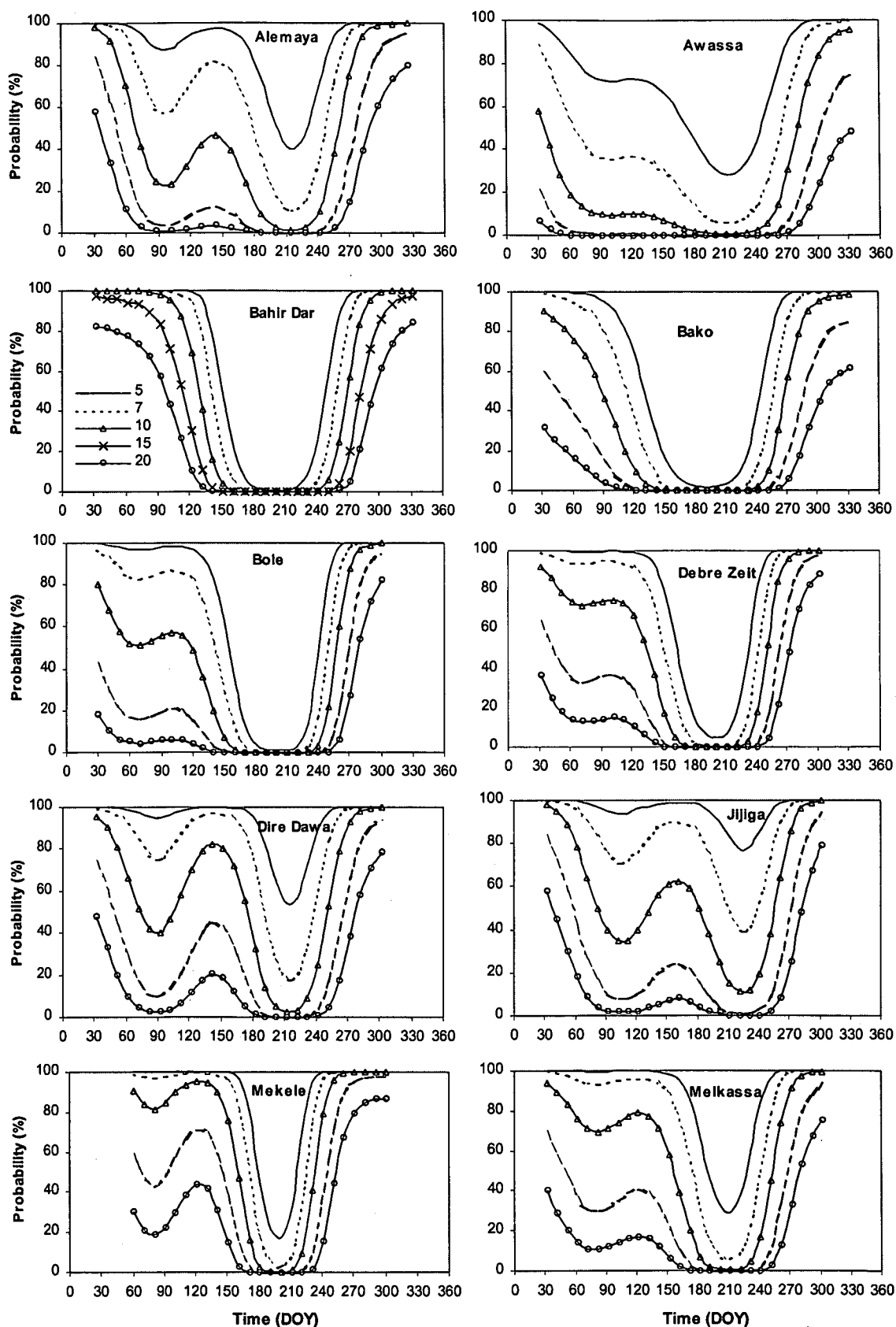
The probabilities of maximum dry spells exceeding 5, 7, 10, 15 and 20 days within a 30 day period after a specified starting date at the 10 locations is shown in Fig. 2.5. Dates are presented from the beginning of February to the last decade of November to provide a quick overview of the drought risks during the year at each location. In the bimodal rainfall areas (Alemaya, Dire Dawa, Jijiga), the probability of maximum dry spell lengths of 7 days or more never fall below 60% during the first rainy season (DOY 60-151). Conditional dry spell probabilities (Appendix 1D) also showed the same trend but had lower values than the maximum probabilities indicating the influence of early rain on shortening the length of subsequent dry spells.

The probability of dry spells of 5 days or more remained above 30% at Awassa during the main rain season. On the other hand, the maximum and conditional probabilities exceeding 15 and 20 days were below 5% from March to late September (DOY 60-262) at the same site. The maximum dry spell probabilities decrease rapidly after DOY 180 (Jun 28) in Alemaya, Dire Dawa and Jijiga, DOY 130 (May 9) in Awassa, DOY 122 (May 1) in Bahir Dar, DOY 150 (May 29) in Debre Zeit, Mekele and Melkassa. This shows that the period after the indicated dates in each region is the period when there is minimum risk to the emergence, establishment and subsequent growth of annual crops. On the contrary, the probability of longer dry spell lengths (>20 days) increased rapidly after DOY 256 (September 12) in Alemaya, DOY 272 (September 28) in Awassa, Bahir Dar and Bako, DOY 260 (September 16) in Bole, DOY 252 (September 8) in Dire Dawa, Debre Zeit and Melkassa, and DOY 232 (August 19) in Mekele. In all of the regions studied except Awassa, the maximum and conditional dry spells with a length of 10 days or more are above 60% after end of September (DOY 274) suggesting that standing crops after this time will face increasingly greater risk of water shortage, particularly in areas where the soil water holding capacity is low.

#### **2.3.6.2. Dry spells computed on crop calendar basis**

Because of the changing nature of sowing dates with the rainfall distribution of each year, computations of dry spells on a calendar day basis have limited significance for specific application in crop production (Sivakumar, 1992). Therefore, it is necessary to calculate





**Figure 2.5. Probabilities of maximum dry spells exceeding 5, 7, 10, 15 and 20 days within 30 days after starting date (DOY 32) at 10 locations in Ethiopia.**

the probabilities of dry spells after onset (successful planting dates) are established. The probabilities of dry spells after onset of rain were computed for each station and are shown in Fig. 2.6. The probability of long dry spells (15 and 20 days) increase rapidly 60 days after sowing (DAS) in Alemaya, 200 DAS in Awassa, 140 DAS in Bahir Dar, 160 DAS in Bako, 110 DAS in Bole, 100 DAS in Debre Zeit, 50 DAS in Dire Dawa, 40 DAS in Jijiga, 60 DAS in Mekele, and 70 DAS in Melkassa. Although dry spell lengths of 15 days or more commence as early as 100 and 110 DAS in Debre Zeit and Bole respectively, standing crops will not be affected easily because of high water stored in the soil during the peak rain months (Fig. 2.3). The soil of these regions is classified as Vertisol and has high water holding capacity as compared to the rest of the regions studied (Appendix 1A). Bahir Dar and Bako also have high soil water storage capacity that can prolong the growing period by a significant length.

Dry spell analysis helps in identifying the type of crop (short, medium or long maturing, drought tolerant or susceptible, etc.) and management practices (supplemental irrigation, fertilizer and insecticide application, etc.) (Sivakumar, 1992; Simane and Struik, 1993) that is appropriate to the respective regions. For example, it is necessary to choose a terminal drought tolerant variety if one wants to plant a crop variety with a maturity length of more than 100 days at Mekele and 120 days at Alemaya and Melkassa as longer dry spells prevail after this period at these sites. Besides serving as a tool in the choice of a suitable crop variety for a given site, this type of dry spell analysis could also be used as a guide for breeding varieties of various maturity durations for the different locations (Sivakumar, 1992).

An example of this application is shown for Dire Dawa for which crop varieties that mature within 70 days are required whereas varieties which have a maturity period of 200 days or more are required for Awassa and Bako in order to fully utilize the regions' resources. As pointed out by Sivakumar (1992), dry spell analysis could also be used as a tool to study mismatches of phenology of a new crop to the rainfall regime of a given area as well as to answer 'what if' questions in decision-making. For example, one may ask "what is the chance of dry spells longer than 15 days after 80 days of planting my crop?" and get answers from the dry spell analysis like the one shown in Fig. 2.6. The length of dry spell probabilities closely follows the annual rainfall amount in all the locations studied except Jijiga.

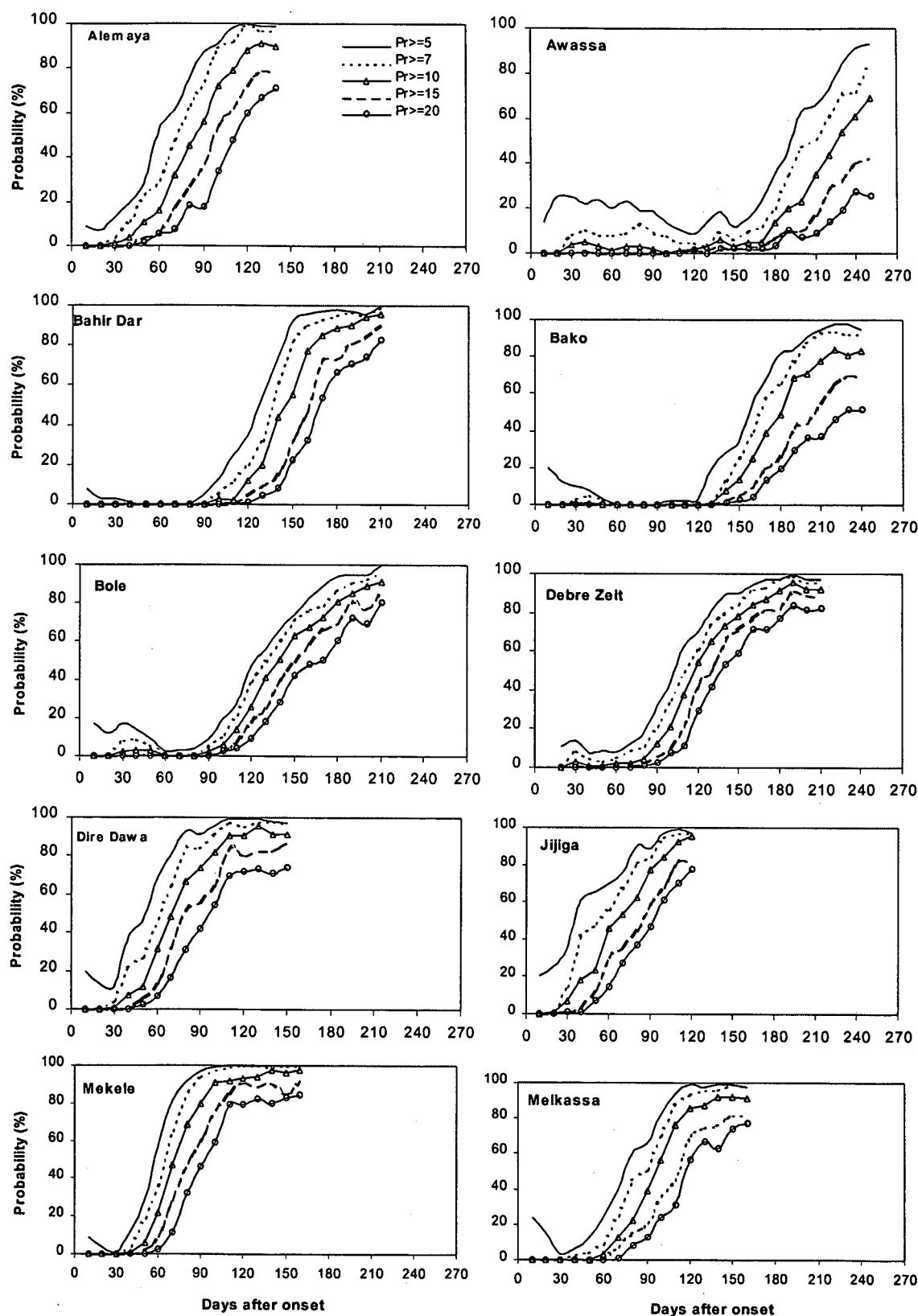


Figure 2.6. Probability of dry spells exceeding 5, 7, 10, 15, and 20 days after onset (sowing) at ten locations in Ethiopia.

In general, analysis of dry spells on calendar day basis provides an overview on the frequency and distribution of dry spells in a given region. This is important to understand the probability of different length of dry spells for the specific regions so as to make appropriate recommendations such as time of planting, and also to match crop phenology to the period of water availability. Moreover, the dry spell analysis after sowing dates are established is an important step in addressing issues like: Which crop/variety is best for which site? What is the probability of long dry spells on a certain day after planting the crop in question? Is supplemental irrigation (if there is that option) needed and when should it be applied? What kind of crop management should be practiced and during which period?

### **2.3.7. Length of growing season**

The average potential planting dates (PPD), risk of planting with early rains, the average successful planting dates (SPD), dates of end of season (ES) and length of growing season (LGS) calculated for the rainy seasons are shown in Table 2.3. Assuming normal distribution of the 100 years data, the average SPD ranged from DOY 95 (April 4) in Awassa to DOY 216 (August 3) in Jijiga. Thus, average SPD may start as early as April and could be delayed until August 3 in the regions studied. The 20, 50 and 80 percentiles of SPD, ES and LGS are shown in Table 2.4. The median successful planting dates (50%) are similar to the average successful planting dates shown in Table 2.3 indicating the normal distribution of the data. Compared to potential planting dates (PPD), average SPDs were delayed by a range of 2 (Bako) to 35 (Debre Zeit) days. Cumulative probability curves shown in Fig. 2.7 were also constructed for the potential and successful planting dates. The choice of any value on the cumulative probability curves depends on the level of risk to be taken on the one hand and the length of the growing season needed on the other. This in turn depends on the crop's drought sensitivity (particularly during the early season) and its length of maturity (duration of total growth period).

The risk of potential planting dates was calculated with reference to the successful planting dates. The risk ranged from 6% (Bako) to 68% (Debre Zeit) indicating high chance of "false start" of the rainfall at Debre Zeit followed by Jijiga and Bole (Table 2.3). The 95% confidence interval shows that the risk of "false start" can vary from 2% (Bako) to 80% (Jijiga) (Table 2.3).

**Table 2.3. Average potential (PPD) and successful (SPD) planting dates, dates of end of season calculated using ET<sub>o</sub> of site (ES<sub>o</sub>) and ET of crops planted on day numbers indicated in parenthesis (ES<sub>c</sub>), length of growing season (LGS) and risk of first planting for the first (if any) and the second rainy seasons for ten locations in Ethiopia.**

Location	First rainy season						Second rainy season					
	PPD <sup>a</sup> (DOY)	SPD (DOY)	Risk of PPD (%)*	ES <sub>o</sub> (DOY)	ES <sub>c</sub> <sup>b</sup> (DOY)	LGS (days)	PPD <sup>a</sup> (DOY)	SPD (DOY)	Risk of PPD (%)*	ES <sub>o</sub> (DOY)	ES <sub>c</sub> <sup>b</sup> (DOY)	LGS (days)
						ES <sub>o</sub> ES <sub>c</sub>						ES <sub>o</sub> ES <sub>c</sub>
Alemaya	87(Mar1)	121	52(43-64)	133	145 (97)	-    -	199(Jun21)	203	14(7-20)	304	311 (197)	101    114
Awassa							82 (Mar1)	95	29(22-38)	304	315 (115)	209    200
Bahir Dar							142 (May1)	152	34 (26-46)	319	319 (152)	167    167
Bako							116 (Apr1)	118	6 (2-13)	331	331 (109)	213    222
Bole							112 (Apr1)	139	61(51-71)	321	321 (245)	182    76
Debre Zeit							119 (Apr1)	154	68 (58-77)	310	320 (254)	156    66
Dire Dawa	81 (Mar1)	141	74 (66-84)				199 (Jun21)	208	32 (24-44)	285	283 (207)	77    76
Jijiga	83 (Mar1)	135	76 (68-85)				190 (Jun21)	216	63 (61-80)	215	268 (191)	4    77
Mekele							181(Jun1)	185	19 (10-27)	277	280 (185)	92    95
Melkassa							170 (Jun1)	183	46 (37-58)	285	297 (183)	102    114

<sup>a</sup> dates in parenthesis refer to starting dates of rainy season, \* values in parenthesis are 95% confidence intervals of risk of potential planting date.

<sup>b</sup> numbers in parenthesis refer to dates of planning (DOY) of a 95-100 day maturing chickpea (Bole and Debre Zeit) and bean (the rest eight sites) following the local farmers practice.

In some of the study areas like Bako, Alemaya and Mekele, the chance of dry spells of 7 days or more was minimum after the rain had started. This is shown by the narrow gap between PPD and SPD cumulative probability curves in Fig. 2.7.

**Table 2.4. Successful planting dates (SPD), dates of end of season (ES) and length of growing season (LGS) at 20, 50 and 80 percentiles expressed in day of year (DOY).**

Station	SPD			ES			LGS		
	20%	50%	80%	20%	50%	80%	20%	50%	80%
Alemaya	189	201	217	290	305	317	81	100	121
Awassa	70	87	113	278	314	326	177	213	247
Bahir Dar	139	152	165	312	319	326	154	168	181
Bako	102	118	133	323	330	340	194	214	230
Bole	110	143	165	316	321	326	157	179	213
Debre Zeit	133	160	176	305	310	316	133	151	180
Dire Dawa	191	206	220	272	287	300	63	82	100
Jijiga	196	216	233	214	215	230	-	4	37
Mekele	177	185	194	274	277	282	82	93	104
Melkassa	168	183	198	275	291	302	85	109	128

The analysis made to assess the potential of the first rain season (March-May) for crop production in the bimodal rainfall areas (Alemaya, Dire Dawa, Jijiga) is shown in Fig. 2.7. It was found that the rain during this period started early so that potential planting was possible during the last week of March. However, the rain season ends before successful planting dates were established. For example, the average risk of potential planting was 52% in Alemaya, 74% in Dire Dawa and 76% in Jijiga (Table 2.3). The 95% confidence interval ranged from 43-85% for the same period. This shows that this season is very risky and is not suitable for crop production purposes unless crops are selected that can resist long and frequent dry spells. If this season has to be used for production purpose in areas like Alemaya, crops are required that can resist a dry spell length of more than one month (June and early July) and continue growth during the second season without severe damage. Sorghum is the only crop currently serving this purpose at Alemaya. In some areas like Jijiga, where livestock rearing is predominant, the rain during the first season may be used for growing pasture and grass for animal feed.

The end of the season was calculated using  $ET_0$  of the respective sites and ET of the pulse crops that are being grown at each site. The average dates of end of season are shown in Table 2.3, and the cumulative probability curves are shown in Fig. 2.7.

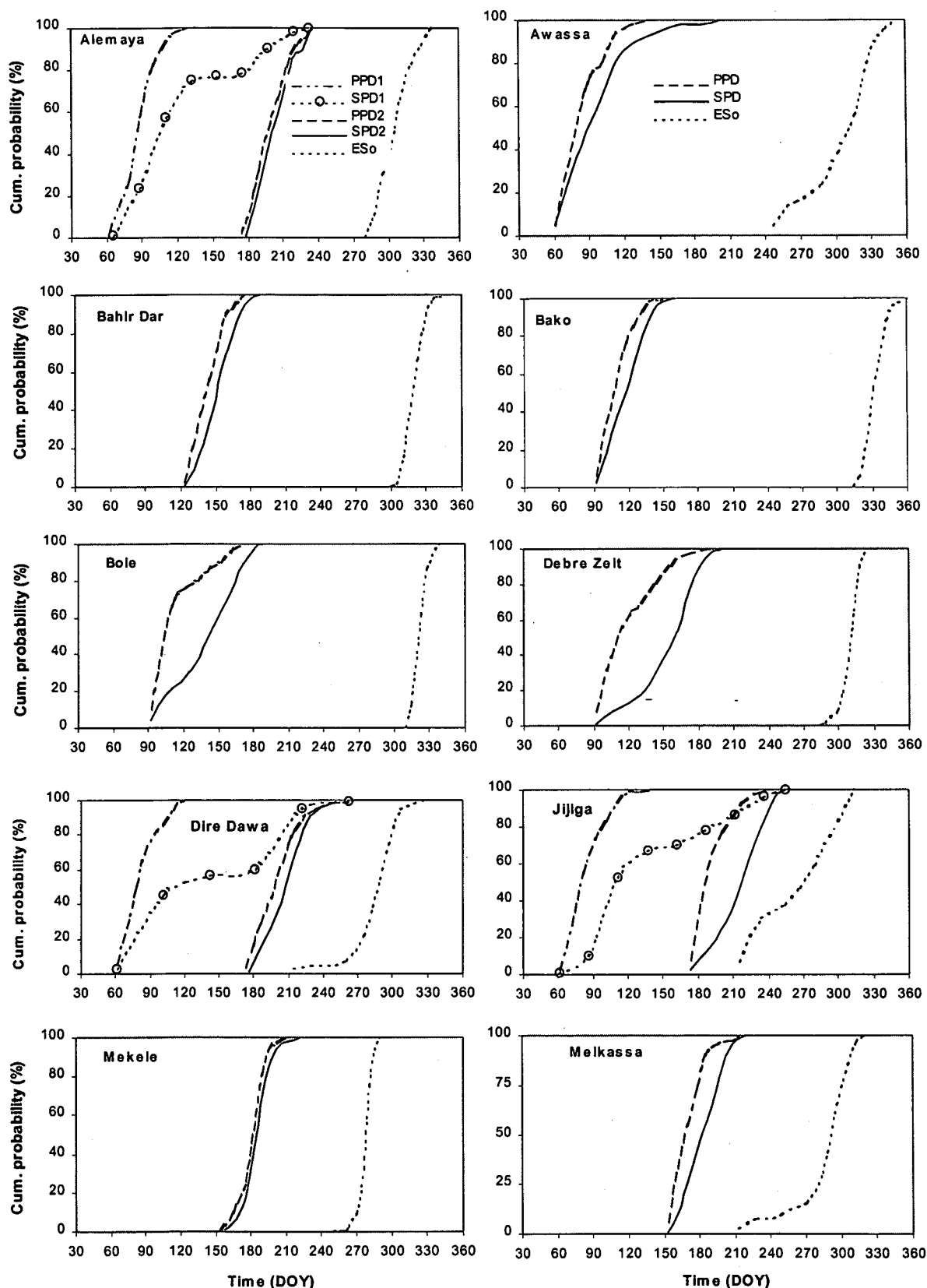


Figure 2.7. Cumulative probabilities of potential (PPD) and successful (SPD) planting dates and end of season (ESo) of the growing seasons at 10 locations in Ethiopia. PPD1, PPD2 and SPD1, SPD2 at the bimodal stations refer to potential and successful planting dates for the first and second rainy seasons, respectively.

Using crop ET, the average date of end of the growing season ranged from DOY 288 (September 26) at Jijiga to DOY 331 (November 26) at Bako (Table 2.3). On the other hand, the end of the growing season ranged from DOY 263 (September 19) at Jijiga to DOY 331 (November 26) at Bako using  $ET_o$  of the respective sites (Table 2.3). In areas like Alemaya, Awassa, Debre Zeit, Melkassa as well as Jijiga, the ET resulted in longer growing period as compared to  $ET_o$  of the respective sites suggesting that growing of grain legumes can extend the growing season of the sites by reducing soil surface evaporation (lower actual water use than potential demand). On the other hand, a 100 days maturing legume could not utilize the available water in the high rainfall areas like Bako and hence soil water depletion (end of season) is determined by evaporative demand of site.

Very strong association was found between onset of the rains and LGS and LGS and  $ES_o$  (Table 2.5). As expected, early plantings and late end of season result in longer growing season. Using the sites' evaporative demand for calculating dates of end of season, the median LGS ranged from 4 days (Jijiga) to 213 days (Bako) (Table 2.4). When crop ET was used during the growing season, the LGS was found to range from 66 days (Debre Zeit) to 222 days (Bako). The ET of common bean (95 days maturing), chickpea and cowpea (100 days maturing) were used in this study assuming that the crops were planted on dates currently practiced by the local farming community. It was found that in some of the locations studied (Dire Dawa, Jijiga, Debre Zeit, Bole), the crops were prone to early and late season drought in areas like Jijiga and to terminal drought in Dire Dawa, Debre Zeit, and Bole due to the current planting practice and wrong choice of cultivars in terms of maturity length. Therefore, it is advisable to choose the appropriate crop variety that can best fit the actual length of the growing season in areas like Jijiga and Dire Dawa whereas in areas like Bole and Debre Zeit, where heavy water logging conditions prevent early sowing, it is essential to choose chickpea varieties which can mature within 70-80 days or varieties that can tolerate terminal droughts.

Awassa, Bako, Bole and Bahir Dar have one long growing period (longer than 5 months) which is suitable for late maturing crops. Grain legume crops, which usually mature in less than 150 days, would not fully utilize the soil water in these regions. Therefore, unless intercropped with other late maturing cereal crops like maize and



sorghum, sole cropping of grain legumes should not be recommended for these sites. On the other hand, Alemaya and Melkassa were found suitable for grain legumes that mature within 110 days and Mekele was found appropriate for grain legumes crops that mature between 90 and 95 days.

**Table 2.5. Correlations between successful planting date (SPD), date of end of season (ES<sub>0</sub>) and length of growing season (LGS).**

Station	SPD vs ES <sub>0</sub>	SPD vs LGS	ES <sub>0</sub> vs LGS
Alemaya	-0.05	-0.75	0.70
Awassa	0.02	-0.71	0.69
Bahir Dar	0.02	-0.85	0.50
Bako	-0.02	-0.88	0.61
Bole	-0.16	-0.98	0.37
Debre Zeit	-0.09	-0.96	0.37
Dire Dawa	-0.02	-0.76	0.67
Jijiga	-0.10	-0.85	0.61
Mekele	-0.16	-0.89	0.59
Melkassa	-0.24	-0.67	0.88

The cumulative probability curves in Fig. 2.7 indicate that in 80% of the years, the season ends before day 340 (December 5) in the high rainfall areas (Awassa, Bahir Dar, Bako and Bole) and before day 317 (November 12) in the low to intermediate rainfall areas (Alemaya, Debre Zeit, Melkassa, Dire Dawa, Mekele and Jijiga).

## 2.4. Summary and Conclusion

Ethiopia's economy is highly dependent on subsistence agriculture. More than 85% of the population is engaged in this sector of which the majority are involved in rainfed crop production. Because of tremendous variability of the rainfall from year to year and season to season, the country becomes vulnerable to recurrent droughts. Therefore, analysis of historical rainfall data in conjunction with soil factors can be used in assessing cropping potential and risks in different regions so as to make appropriate recommendations for crop planning and disaster prevention schemes. The role of such studies in planning agricultural development is indicated in many reports (Dennet *et al.*, 1984; Peacock and Sivakumar, 1986; Simane and Struik 1993; Stern *et al.*, 1982a, 1982b; Virmani *et al.*, 1980).

The current study has revealed the existence of broad regional differences in water supply. In some areas like Bahir Dar, Bako and Bole, management of excess water is the major concern unlike some other areas (Jijiga and Dire Dawa) where water supply is limited and hence maximizing water use and water use efficiency are crucial. This

means that there is a need to adopt different management strategies for optimum resource use for each region. The variability in mean annual rainfall between and within regions and seasons means that farming practice recommendations should be region and season specific.

Information on the length and frequency of dry spells is crucial in adjusting crop and cropping practices to the environment and to some extent in adjusting the micro-environment to the crop (e.g. irrigation, mulching and drainage). Grain legume crops are more susceptible to drought than cereal crops like sorghum, millet and wheat in the semi-arid tropics. Therefore, the information generated on probability of dry spells in the present study is important to facilitate agricultural decision making to sustain the production of grain legumes under these variable and fragile environments.

The onset of the rains is an important factor in determining agricultural activities such as sowing, choice of crop and division of labour. The study indicated strong association between onset of rains and length of growing season. As shown by the strong negative correlations, early sowing resulted in longer growing season and *vice versa*. Therefore, relatively longer duration varieties can be used when the rain starts early whereas short maturing varieties are needed whenever the onset is delayed from the expected period. Sivakumar (1988) reported similar results in West Africa. This again implies the need to adjust tactical decisions following the onset of the rains in the current Ethiopian rainfed crop production system. In a given rain season, false start of rainfall is less likely in all the regions once the decade precipitation exceed half of the decade evapotranspiration. Therefore, this relationship between rainfall and reference evapotranspiration can be used as a general guide in planning sowing dates at the respective locations.

The dependability of first rains varied across locations. In many of the locations studied such as Bahir Dar, Bole, Debre Zeit, Dire Dawa, Jijiga and Melkassa, the chance of false start is very high resulting in high risk for early planting. At the other locations (Alemaya, Bako and Mekele), the delay in successful planting after the potential planting date is very narrow and hence the risk of first planting was very low suggesting the reliability of the season once the rain has started. Regional differences were observed for the length of growing season. Bako, Awassa, Bole and Debre Zeit have a long growing season that is suitable for crops which have a maturity length of

5 to 7 months. Alemaya, Melkassa and Mekele have an intermediate growing season which can support a crop maturing within 3 to 3.5 months. Dire Dawa has a relatively short growing season. There was not any successful start of the season in 75% the years at Jijiga and the median length of the growing season was only 4 days. Therefore, this region is unsuitable for crop production despite the current practice of growing many crop species, which often fail.

In the current Ethiopian agriculture system and its rainfall condition, matching of crop phenology to the water availability period seems to be the best option to promote pulse crop production in the country. A similar conclusion was reached by Simane and Struik (1993) with respect to wheat production in the same country. Selection of crop species/varieties for the drought prone areas (Jijiga, Dire Dawa, Mekele) should be done with great caution so that farmers could get reasonable yields even in dry years. For such regions, species/varieties that are drought-tolerant and adaptable to the erratic nature of the rainfall are deemed necessary. Moreover, developing an appropriate land use system is imperative for utilization of a given site to its full capacity. For example, Jijiga is more suitable for livestock than crop production implying that many of the impacts of drought events in the different parts of the country are results of not only natural calamities but also improper land use system. This has led to deforestation (for the sake of charcoal making to bake daily bread), bush encroachment, and finally degradation of natural resources, which in turn affected the climate of the respective regions. Studies like this one are believed to have immense contribution to develop suitable land use system in the country. Moreover, the information generated from this study will have valuable contribution in advising the farmer, extension agent, agronomist and other groups involved in crop production.

## CHAPTER 3

### Phenology, Growth and Dry Matter Allocation in Three Grain Legume Species Grown Under Three Water Regimes in a Semi-Arid Environment

#### 3.1. Introduction

Grain legumes are a major source of plant protein in the developing and developed world (Duranti and Gius, 1997). Being the only source of protein for a number of poor farming communities in the semi-arid tropics (Singh, 1997a), these crops are given the nickname, 'poor man's meat' (Duranti and Gius, 1997). In the semi-arid tropical regions, the crops are traditionally grown under rainfed conditions in marginal environments, and their growth and development is usually affected by drought, which can occur at any time during the growing period (Adams *et al.*, 1985; Rachie, 1985; Graham and Ranalli, 1997).

Phenology plays an important role in plant growth and productivity. Under drought conditions, it affects plant productivity through various simple or complex pathways (Blum, 1996). Drought may hasten or delay phenological periods depending on the time it occurs, its severity, rate of onset of stress and type of species involved (Blum, 1996). For example, in wheat, mild water stress caused advanced flowering (Angus and Moncur, 1977) while severe water stress caused delayed flowering (Dwyer and Stewart, 1987). Phenology is one of the major factors that control water use, duration of exposure to stress, leaf area development and its duration, tissue juvenility, and also the degree of stomatal response in plants (Blum, 1996; Turk and Hall, 1980a; Turk *et al.*, 1980b).

Plants have a suite of morphological and physiological adaptations that allow them to survive water stress (Monneveux and Belhassen, 1996). The degree of adaptation, however, varies greatly within genera and species (Torrecillas *et al.*, 1996). Patterns of biomass allocation between different plant organs have been used to explain the response of plants to variations in resource availability (Ninkovic, 2003). Allocation of photosynthate among various plant parts is a mechanism by which plants modify their growth in response to environmental conditions in a way that maximizes growth. Therefore, when water supply is variable in the growing season, dry matter is partitioned to plant parts depending on the time in the life cycle (Boyer, 1996). The redistribution of assimilates accumulated during the vegetative and early reproductive periods to the seed

during the seed-filling period is considered as a potential source of yield stability in terminal drought environments (Turner *et al.*, 2001). Dry matter reallocation to grain has been reported for a number of grain legumes including chickpea (Saxena, 1984; Singh, 1991; Leport *et al.*, 1999), mungbean (Bushby and Lawn, 1992), groundnut (Wright *et al.*, 1991), and soybean (Westgate *et al.*, 1989) under water deficit conditions. The commonly observed rapid senescence and abscission of leaves in grain legumes under water deficit is suggested to be a means of reallocating carbon and nitrogen from the senescing leaves to the seed (Turner *et al.*, 2001). Therefore, it is important to be able to calculate some type of index of assimilate partitioning in order to relate yield and dry matter allocation under water deficit conditions.

Information on pattern of growth and dry matter partitioning between various plant parts is an essential step in the development of crop growth simulation models (Royo and Blanco, 1999; Sheng and Hunt, 1999). Moreover, data on growth and its partitioning would allow better interpretation of results within the context of processes and resource exploitation (Williams *et al.*, 1996). However, such information is sparse for grain legumes particularly under water deficit conditions in the field. The objective is, therefore, to study the growth, phenology and dry matter allocation of common bean (*Phaseolus vulgaris* L.), chickpea (*Cicer arietinum* L.) and cowpea (*Vigna anguiculata* L.) grown under water stress and non-stress conditions in a semi-arid environment in the field.

### 3.2. Materials and Methods

#### 3.2.1. Field experiments

Three field experiments were conducted at the fruit farm and research centre of Alemaya University in Dire Dawa, Ethiopia (latitude 9°6'N, longitude 41°8' E, altitude 1197 m above sea level) during the periods from early December 2001 to late March 2002 (first season), late March until the end of Jun 2002 (second season) and from mid-October 2002 to early February 2003 (third season). The station lies in the semi-arid belt of the eastern rift valley escarpment with a long-term average rainfall of 612 mm. The soil is classified as Eutric Regosol with a gentle slope (3-8%) (Amede, 1998). The texture and structure of the topsoil (0-30 cm) are sandy loam and sub angular blocky, respectively. The soil has an average pH (H<sub>2</sub>O 1:2.5) of 8.52 and organic matter content of 1.18% (Appendix 6D).

Seeds of common bean (cv. Roba-1), Kabuli chickpea (cv. ICC-4958,) and cowpea (cv. Black eye bean) were planted on 7 December 2001, 27 March 2002 and 17 October 2002 for the first second and third seasons, respectively. All cultivars had semi-indeterminate growth habit. Roba-1 is an improved bean variety released by the Institute of Agricultural Research, Ethiopia ten years ago. Blackeye bean is a well-adapted cowpea variety used as a check by the lowland Pulse Improvement Research Program at Alemaya and Melkasa research stations. ICC-4958 is a registered drought resistant chickpea cultivar (Saxena *et al.*, 1993) currently grown in Ethiopia.

Nitrogen and phosphorus fertilizers were applied to the soil before planting in the form of urea and di-ammonium phosphate at a rate of 30 kg ha<sup>-1</sup> each. Hand weeding was done throughout the growing periods to keep the plots free of weeds. Sumathion (20 ml ai/10 L water) and Maneb (10g ai/10 L water) were applied twice during each season to control insect pests and fungal diseases, respectively.

### 3.2.2. Experimental design

The experiments had two water deficit treatments (referred here after as water stress treatments) and a well-watered control treatment as shown in Table 3.1. The experimental treatments, each replicated three times, were arranged in a randomized split plot design using the water regimes as main plot and the crop species as sub-plot. The total experimental area was 22.8 m x 40.2 m.

**Table 3.1a. Soil water regimes applied in the experiments and the lowest available soil water (ASW) maintained at a depth of 300-600 mm before irrigation in each water regime.**

Water regime	Stress period **	Minimum ASW at re-watering
Mid-season stress (MS)	Flowering	23-25%
Late season stress (LS)*	Pod filling until maturity	23-35%
Control (C)	No water stress	>60%

**Table 3.1b. Duration of stress periods for the water stress treatments in each species during the three seasons.**

Water regime	Species	Seasons		
		2001/2002	2002	2002/2003
MS	Beans	52-66	45-56	45-62
	Chickpea	52-66	45-56	42-57
	Cowpea	63-77	45-56	53-72
LS	Beans	62 to maturity	58-71	62 to maturity
	Chickpea	62 to maturity	58-71	62 to maturity
	Cowpea	64 to maturity	58-71	62 to maturity

\* Treatment received no water after the stress was induced unless rain occurred. <sup>o</sup>DAP= days after planting.

Each sub-plot (4m x 6m) had 10 rows, and the inter- and intra-row spacing was 0.4 m and 0.1 m, respectively (25 plants m<sup>-2</sup>). The 4 m length of the central four rows in each plot were used for final yield determination whereas the other rows were used for destructive measurements excluding the outer rows.

### 3.2.3. Irrigation schedule

Plots were irrigated (33.3 mm) immediately after planting to ensure uniform seedling establishment. A measured amount of water from a 1000 m<sup>3</sup> capacity water tank was applied to each furrow using a 100 m long plastic hose. The tank was recharged each time from a nearby well. Non-stressed treatment plots received irrigation whenever available soil water at 30 cm depth (58 mm) reached 60-70%. Stress was imposed in the MS treatment by withholding irrigation and rainfall until the available soil water depletion reached 23-25% (Table 3.1). In the LS treatment, plots were not irrigated and also protected from rainfall for the period from pod filling to maturity. A simple rain shelter, constructed on site from transparent plastic (Gundle-plastall, South Africa) and wooden poles, was used to protect stress plots from rainfall during the stress periods. The stress plots were covered with the shelter only during an event of rainfall. Lateral movement of water between plots was prevented by a polythene plastic sheet buried in the soil to a depth of 1.2 m. The soil water content at 300-600 mm soil depth was monitored every day throughout the growing period using Time Domain Reflectometry (TDR) (Soil Moisture Equipment Corp., CA, USA).

### 3.2.4. Experimental measurements

Leaf area was measured throughout the growing period destructively using a portable leaf area meter (Model CI-202, CID, Inc., USA) from five randomly selected plants (0.2 m<sup>2</sup> area) in a plot at an interval of 10 days starting at 35, 17 and 20 days after planting (DAP) for the first, second and third experiments, respectively until physiological maturity. Above ground dry matter (ADM) was determined from the same five plants for the same interval of time. The plant samples were separated into leaf, stem, pod and seed, and then dried in an oven for 72 hours at 60°C to determine mass of dry matter. Final harvest was done from March 1 to April 6, May 30 to Jun 26 and January 13 to February 5 in the first, second and third seasons, respectively, according to maturity dates of the crops in the different treatments.

### 3.2.4.1. Phenology

#### Calendar days and thermal time

Date of emergence, flowering, pod initiation and maturity were recorded whenever 50% of plants in a plot show the character. Time to each phenological stage was determined starting from the date of planting. Daily thermal time ( $t_T$ , °C d) was calculated as:

$$t_T = \left( \frac{T_{\max} + T_{\min}}{2} - T_b \right) * \Delta t \quad (3.1)$$

where  $T_{\max}$  and  $T_{\min}$  are daily maximum and minimum temperatures (°C),  $T_b$  is base temperature (°C) and  $\Delta t$  is time interval (day). The base temperatures used in the calculation were 10 °C for beans (Guyer and Kramer, 1952; Hardwick, 1988b) and 8 °C for both chickpea (Singh, 1991) and cowpea (Craufurd *et al.*, 1997). The daily  $T_{\max}$  is made equal to 30 °C if it is above this threshold (Cross and Zuber, 1972; Mauromicale *et al.*, 1988). Thus, the thermal time accumulated (GDD) for a given time interval ( $\Delta t$ ) was calculated as:

$$GDD = \sum_{i=1}^t \left( \frac{T_{i\max} + T_{i\min}}{2} - T_b \right) * \Delta t_i \quad (3.2)$$

### 3.2.4.2. Growth

#### 3.2.4.2.1. Comparison of dry matter production

Because of ontogenic differences between the species, data on total above ground dry matter (ADW) was compared after fitting the data with a Richards function. The Richards Function (Richards, 1959) is expressed as:

$$y = \frac{a}{1 + \exp(b - cx)^{(1/d)}} \quad (3.3)$$

where  $y$  is ln-transformed dry matter,  $x$  is time and  $a$ ,  $b$ ,  $c$  and  $d$  are constants. 'a' represents the upper asymptote of the curve while 'd' controls inflection and its position on the curve.

Second or third degree polynomial functions were fitted to leaf dry matter (LDM) and stem dry matter (SDM) while linear, logarithmic or exponential functions were fitted to pod dry matter (PDM) depending on the water stress treatments. The curve fitting process was conducted using Curve Expert Version 1.37 curve fitting system (<http://home.comcast.net/~curveexpert/>).



### 3.2.4.2.2. Specific leaf area (SLA)

Specific leaf area (SLA,  $\text{m}^2 \text{g}^{-1}$  or  $\text{cm}^2 \text{g}^{-1}$ ) was calculated as explained by Hunt (1982) and Causton and Venus (1981) as shown below:

$$SLA = \frac{LA}{LDM} \quad (3.4)$$

The mean seasonal SLA of the species was calculated as the slope of the linear regression between leaf area and leaf dry matter.

### 3.2.4.2.3. Leaf area duration (LAD)

Leaf area duration (LAD, days) was calculated as follows:

$$LAD_{t_1-t_2} = \int_{t_1}^{t_2} LAI dt \quad (3.5)$$

where LAI is leaf area index calculated as the ratio of leaf area to the area of ground, and  $dt$  is the change in time.

### 3.2.4.2. Dry matter allocation

The dry matter allocation among the shoot components was calculated by the method of Borrell *et al.* (1989) as follows:

$$AR_{part} = \frac{dw_{part}/dt}{dw_{total}/dt} \quad (3.6)$$

where AR is allocation ratio,  $dw$  is the change in dry mass and  $dt$  is the change in time. This ratio enables one to assess the relative sink strength of the leaf, stem and pod by comparing the growth rate of each part with the whole plant shoot growth rate.

### 3.2.5. Statistical analysis

Analysis of variance and mean separation (LSD) were conducted for the phenological data using MSTATC program (Michigan State University, Michigan). Regression analysis, t-tests and Kolmogorov-Smirnov (KS) tests were made using NCSS 2000 (Number Cruncher Statistical Systems; Hintze, 1997). The Pearson correlation coefficients were obtained using MINITAB for windows (Minitab Inc.).

### 3.3. Results and Discussion

#### 3.3.1. Weather conditions

Daily maximum ( $T_{\max}$ ) and minimum ( $T_{\min}$ ) temperatures and monthly weather conditions during the three seasons are shown in Fig. 3.1 and Table 3.2, respectively. Both  $T_{\max}$  and  $T_{\min}$  were higher after 30 DAP in the second season than in the first and third seasons.

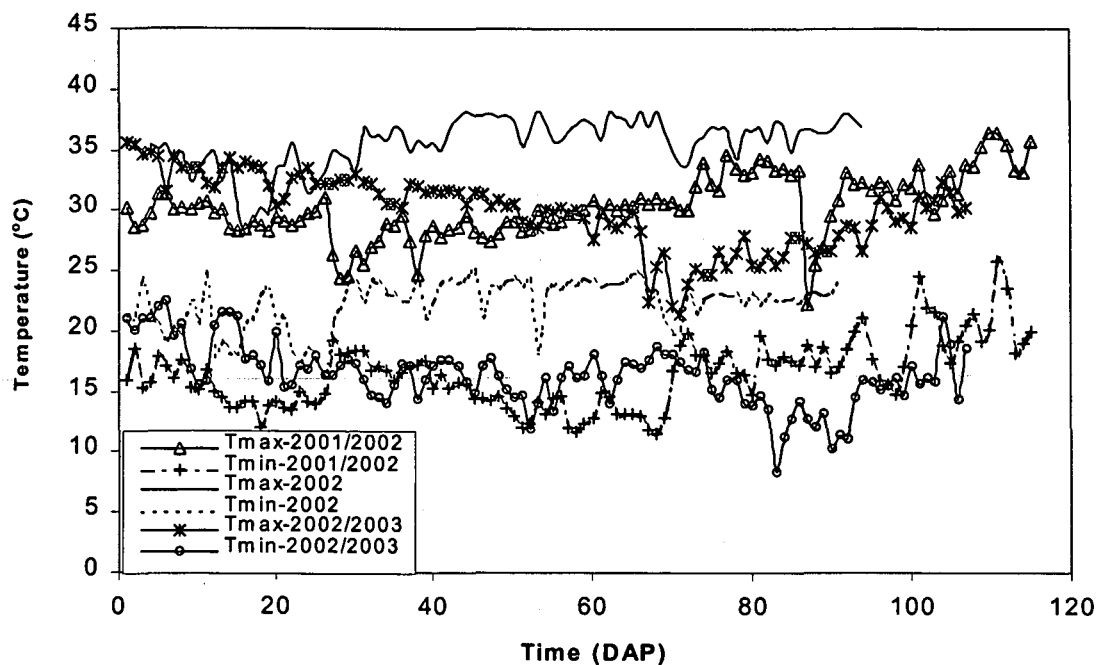


Figure 3.1. Daily maximum ( $T_{\max}$ ) and minimum ( $T_{\min}$ ) temperatures during the three seasons (2001/2002, 2002 and 2002/2003).

Table 3.2. Monthly weather conditions of the three seasons at Dire Dawa, Ethiopia.

Month	$T_{\max}$ (°C)		$T_{\min}$ (°C)		RH (%)		SR (MJ m <sup>-2</sup> d <sup>-1</sup> )		Rainfall (mm)
	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Total
<b>2001/2002</b>									
Dec.	28.2-31.7	29.8	12.1-18.5	15.0	32-70	52	12.8-20.7	19.4	6.0
Jan.	24.4-31.0	28.0	12.0-19.2	15.7	35-89	64	7.8-21.7	17.1	34.8
Feb.	29.8-34.6	31.6	11.6-19.8	15.4	25-65	51	8.9-23.0	21.2	0.0
Mar.	22.3-36.4	32.0	14.8-25.9	19.2	34-88	57	7.5-24.0	20.0	80.9
<b>2002</b>									
Apr.	28.0-36.7	33.4	16.5-24.8	20.6	33-71	52	14.0-25.5	21.4	83.1
May	34.8-38.1	36.8	18.0-25.2	23.5	20-59	39	16.7-25.6	23.0	33.3
Jun.	33.8-38.2	36.4	19.8-24.8	22.9	21-55	38	12.1-24.5	22.1	9.7
<b>2002/2003</b>									
Oct.	30.0-36.8	34.1	16.5-22.5	19.5	16-47	26	13.2-23.1	20.5	19.0
Nov.	30.2-34.1	32.0	14.0-19.8	16.4	16-42	26	16.2-22.0	20.7	0.0
Dec.	21.4-31.4	27.9	11.9-18.7	16.2	48-89	65	3.5-21.4	15.8	12.4
Jan.	25.3-32.4	28.3	8.3-21.2	14.5	38-73	60	10.0-22.7	19	19.8

The third season had higher  $T_{\max}$  and  $T_{\min}$  than the first season in the first half of the season but lower  $T_{\max}$  and  $T_{\min}$  in the second half of the season. As shown by the relative humidity (RH) values, the second season was less humid than the first but both seasons received higher rainfall than the third season. Solar radiation (SR) was similar for all the seasons. The length of the growing period was shorter in the second (94 days) than in the first and third seasons (107 to 115 days).

### 3.3.2. Phenology

#### 3.3.2.1. Calendar days

The phenological data is presented in Table 3.3 and 3.4. Cowpea had a mean emergence period of 3-5 days in all the seasons, which was significantly shorter than both beans (6-9 days) and chickpea (7-9 days). Chickpea flowered 8-10 days earlier than beans and 10-12 days earlier than cowpea in 2001/2002 and 2002/2003 seasons.

However, the time from emergence to flowering was similar for the three species in 2002 due to the high temperature condition in this season, which hastened early flowering in beans and cowpea. Chickpea also started pod formation earlier than the other species by an average of 3 days. Early pod set in chickpea is considered as a prime strategy for avoiding drought stress in environments prone to end of season water stress (Sedgley *et al.*, 1990). As stated by Kumar *et al.* (1996), development of early maturing varieties of chickpea that escape drought can increase productivity and facilitates the production of this crop in more drought prone areas.

The importance of earliness for better adaptation in drought prone environments has also been shown for cowpea, pea and other grain legume crops (Hall and Patel, 1985; Sharma and Khan, 1997). The number of days to pod initiation between beans and cowpea were similar in 2001/2002 and 2002 but significantly different in 2002/2003 (Table 3.3). When considered across seasons, the time to pod initiation was shorter in 2002 (48-50 days) followed by 2002/2003 (50-57 days) and 2001/2002 (59-64 days). Higher temperature hastened both the time to flowering and podding in 2002. The rate of progress towards flowering in crop plants usually increases with increases in temperature up to an optimum temperature (Summerfield *et al.*, 1991; Roberts and Summerfield, 1987; Squire, 1990). However, the period to pod initiation was not significantly affected by the MS treatment (Table 3.3 and 3.4).

**Table 3.3. Time to emergence (TE), flowering (TF), pod initiation (TP) and maturity (TM), and pod filling period (PFP) in the 2001/2002 and 2002/2003 seasons.**

S <sub>P</sub> <sup>++</sup>	W <sub>R</sub>	Time (days)									
		2001/2002					2002/2003				
		TE	TF	TP	TM	PFP	TE	TF	TP	TM	PFP
Beans	C	9	58	62	93	31	6	49	54	102	48
	MS	9	57	64	81	17	6	50	55	102	47
	LS	9	58	63	77	14	6	48	54	84	30
Chickpea	C	9	47	60	91	31	7	42	51	105	54
	MS	8	48	60	78	18	7	42	50	106	56
	LS	8	48	59	78	19	7	42	51	85	34
Cowpea	C	6	61	64	90	26	4	53	57	104	47
	MS	5	60	64	78	14	4	52	56	95	39
	LS	5	59	64	78	14	4	51	55	84	29
LSD (P<0.05)	W <sub>R</sub>	n.s	n.s	n.s	5.84**	6.07**	n.s	n.s.	n.s	3.47***	3.19***
	S <sub>P</sub>	0.703***	2.73***	1.04***	n.s	3.28*	0.10**	2.21***	0.98	n.s	4.57**
	W <sub>R</sub> x S <sub>P</sub>	n.s.	n.s.	n.s	n.s.	n.s	n.s.	n.s.	n.s	n.s	n.s.
CV (%)		10.7	4.8	1.6	3.0	15.5	0.00	4.5	1.8	4.3	10.4

\*\*\*, \*\*, \*: Treatment differences significant at 0.1, 1 and 5% probability level respectively, n.s: treatment not significant at 5% probability level., ++ S<sub>P</sub> = species, W<sub>R</sub> = water regime.

**Table 3.4. Time to emergence (TE), flowering (TF), pod initiation (TP) and maturity (TM), and pod filling period (PFP) in the 2002 season.<sup>δ</sup>**

S <sub>P</sub>	W <sub>R</sub>	Time (days)				
		TE	TF	TP	TM	PFP
Beans	C	6	43	48	89	41
	MS	6	43	48	80	32
	LS	6	43	48	73	25
Chickpea	C	7	41	46	90	44
	MS	7	41	46	65	19
	LS	7	41	46	76	30
Cowpea	C	3	43	50	91	41
	MS	3	43	50	80	30
	LS	3	43	50	76	26

<sup>δ</sup> measurements were not replicated.

There was no significant difference among species in the length of time from planting to physiological maturity (Table 3.3 and 3.4) in any of the seasons. Nevertheless, the length of time to physiological maturity was significantly affected by the water stress treatment in all the seasons. The time to maturity in the C treatment was significantly longer than both the MS and LS treatments in 2001/2002 and 2002 seasons and the LS treatment in 2002/2003. There was no significant difference between the MS and LS treatments in the time to reach physiological maturity in 2001/2002 and 2002. However, in 2002/2003, the MS treatment had similar length of time to mature to the C treatment (except in cowpea)

and was significantly different from the LS treatment in which plants matured 17 days earlier. The longer maturity period in the MS treatment in 2002/2003 was due to favourable temperature conditions ( $<32^{\circ}\text{C}$ ) after re-watering that promoted the growth of juvenile vegetative organs. The period after re-watering of the MS treatment in 2002 was characterized by high temperatures ( $>34^{\circ}\text{C}$ ) resulting in lack of vegetative re-growth of organs in any of the species, and thus the length of maturity significantly reduced from the C. Therefore, water deficit during the pod filling period significantly reduced the length of time to physiological maturity whereas the effect in the MS treatment is dependent on the temperature conditions after re-watering. Generally, the present results indicated that water stress during the reproductive stage of grain legumes significantly reduced the period of physiological maturity, particularly when it was coupled with high temperatures. This is in line with the observation made by many authors for many crops including chickpea (Singh, 1991), beans (Tedeschi and Zerbi, 1984), cowpea (Hall and Patel, 1985), and wheat (Simane *et al.*, 1993). Since it occurs towards the end of the rainy season, end of season drought is usually associated with increasing temperature (Calcango and Gallo, 1993; Singh, 1997b; Kumar and Abbo, 2001). Therefore, the mechanism of shorter development period under late season water deficit has been related to increases in leaf or canopy temperature (Slatyer, 1969; Sandhu and Horton, 1978). On the contrary, severe water deficit is reported to delay developmental events in many cereal crops because of the inhibition of growth resulting from the stress (see Blum, 1996).

Pod filling period (PFP) was shorter in 2001/2002 while it was longer in 2002/2003. When daily temperatures were not too high (e.g. in 2001/2002 and 2002/2003), chickpea had significantly longer PFP than cowpea in the first season and both beans and cowpea in third season (Table 3.3). Cowpea had the shortest PFP during the same period (2001/2002 and 2002/2003). Pooled over the species, the PFP in the C treatment was significantly longer (13-15 days) than the MS and LS treatments in 2001/2002 and 2002 and the LS treatment (19 days) in 2002/2003. Except in 2002/2003, the MS and LS had the same PFP when pooled over the species. Previous reports indicate that the duration of pod filling varies greatly according to field conditions and growth type (Jeuffroy and Ney, 1997). For example, seed filling under different environmental conditions ends when remobilizable nitrogen in the plant is exhausted (Munier-Jolani *et al.*, 1996; Jeuffroy and Ney, 1997). Similar to the observation in this study, water shortage during the

reproductive stage has shortened the period of seed filling in many other grain legumes (e.g. Korte *et al.*, 1983; Turc, 1995). There was no significant interaction between water regime treatments and species for period of podding, physiological maturity and PFP in the present study (Table 3.3) indicating similar response of the crops to the timing of water stress for these characters.

### 3.3.2.2. Thermal time

Thermal time is an important phenological variable widely used in crop growth simulation modelling. Therefore, determination of the thermal time of a certain growth stage in field crops such as grain legumes is essential to develop models for a given site and crop and/or calibrate existing models to suit a new environment. The thermal time from planting to emergence (E), from emergence to flowering (E-F), from flowering to pod initiation (F-P), from pod initiation to maturity (P-M) and from flowering to maturity (F-M) was determined for beans, chickpea and cowpea for all three seasons, and the data are presented in Fig. 3.2 and Appendix 3A&3B. Chickpea had longer thermal time requirement (average of 132 °Cd with a base temperature of 8 °C) to emerge than beans and cowpea in all the seasons. Cowpea needed an average of 76 °Cd for emergence in three seasons using a base temperature of 8 °C while beans needed an average of 101 °Cd using a base temperature of 10 °C (Fig. 3.2). According to Squire (1990), differences in the rate of germination at any temperature could be attributed to differences in optimum and maximum (ceiling) temperatures in many determinate growth grain legumes. Rapidly germinating seeds have a higher ceiling temperature than the slowly germinating ones (Squire, 1990). Thus, the fast emergence of cowpea seeds would possibly shows a higher ceiling temperature for germination in cowpea than in beans and chickpea. Early germination is associated with early vigour and ground cover which are valuable drought resistance traits in drought prone areas (Subbarao *et al.*, 1995).

The average thermal time elapsed between emergence and flowering ranged from 600-608 °Cd in beans, 568-570 °Cd in chickpea and 745-755 °Cd in cowpea (Fig. 3.2). As expected, there was no significant difference in thermal time between the treatment plots before flowering. Compared to the control, the MS treatment in chickpea shortened the period between flowering and pod initiation by an average of 13 °Cd while the difference between the C and MS for the same period was less than 5 °Cd in beans and cowpea in 2002/2003 (Appendix 3A). However, there was no significant difference when data was

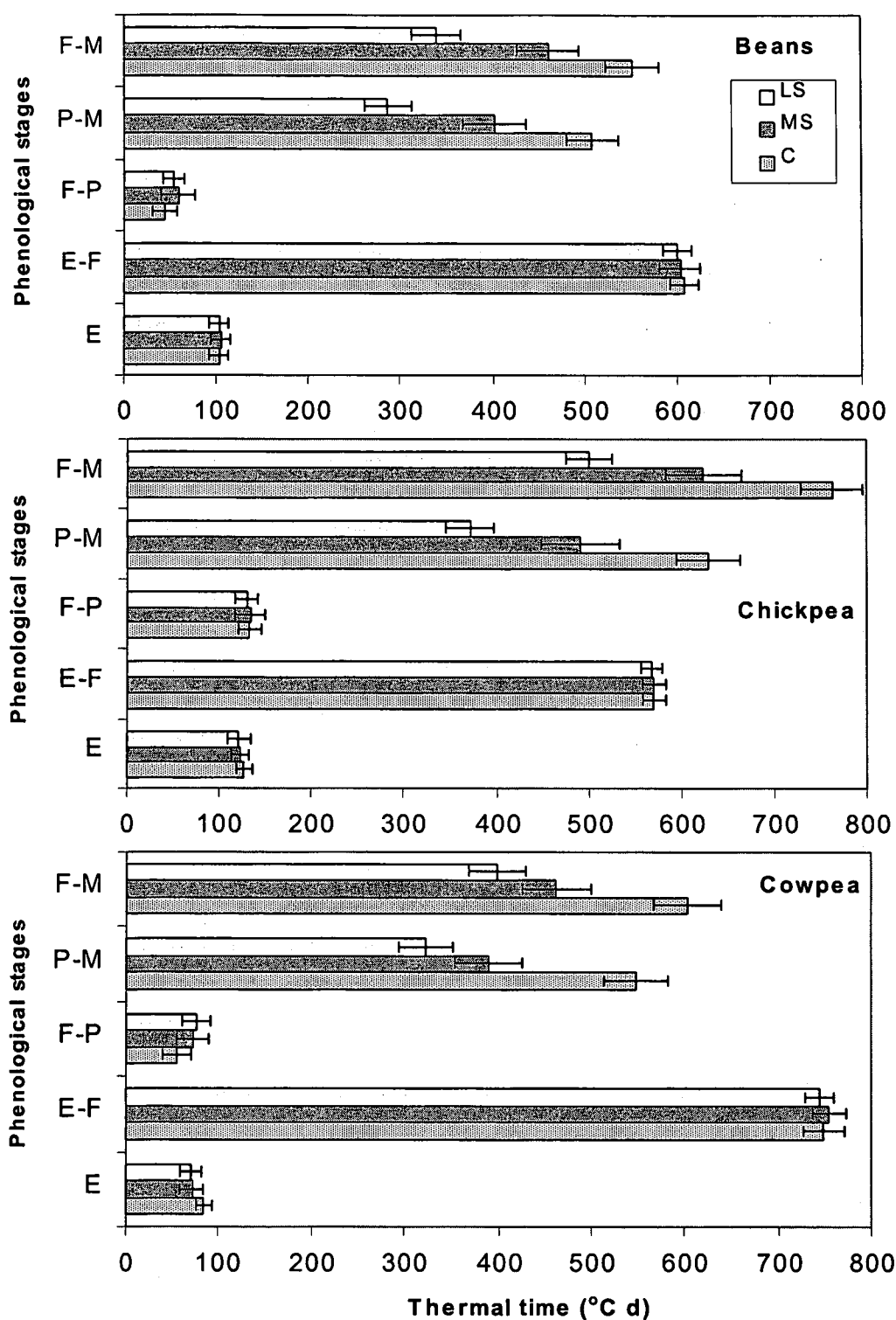


Figure 3.2. Thermal time from planting to emergence (E), from emergence to flowering (E-F), from flowering to podding (F-P), from podding to maturity (P-M) and from flowering to maturity (F-M) for three grain legumes grown under well-watered (C) and mid-season (MS) and late season (LS) water stress in three seasons. (Data are pooled over three seasons with  $n=7$ : three replications for each of the two seasons (2001/2002 and 2002/2003) and one replication for one season (2002)). Horizontal bars refer to standard error of means.

pooled over seasons (Fig. 3.2). Significant differences were observed among the water regime treatments for the thermal time elapsed between pod initiation and maturity and between flowering and maturity (Appendix 3A). Compared to the C, the LS treatment significantly reduced the thermal time required between pod initiation and maturity and between flowering and maturity in all species while the effect of the MS treatment was not consistent across seasons because of vegetative re-growth upon re-watering, which was mainly influenced by the temperature conditions after re-watering. The average thermal time elapsed between pod initiation and maturity was 509, 630 and 548 °Cd in the C treatment, 403, 491, 322 °Cd in the MS treatment and 286, 372 and 322 °Cd in the LS treatment for beans, chickpea and cowpea, respectively. On the other hand the average thermal time elapsed between flowering and maturity was 553, 763 and 604 °Cd in the C, 461, 624 and 462 °Cd in the MS, and 340, 501 and 399 °Cd in the LS for beans, chickpea and cowpea, respectively (Fig. 3.2).

Generally, beans had lower thermal time than chickpea and cowpea. This may be related to the higher base temperature used in the calculation for beans compared to the other two species. Despite the same base temperature used for the two species, cowpea and chickpea showed variability in thermal time requirements at different phenological stages. For example, cowpea had higher thermal time requirement for the period between emergence and flowering while it had lower requirements for the rest of its phenological stages unlike chickpea which had lower thermal time requirements for the period between emergence and flowering and higher requirements for the rest of its phenological stages. Knowledge of such important differences is, thus, important for modelling the growth of these crops for semi-arid areas. The use of thermal time to describe responses of plants has been emphasized (Squire, 1990) and has been widely used to describe the progress of crop development in grain legumes and other crops (Wilhelm and McMaster, 1995; Jeuffroy and Ney, 1997).

### 3.3.3. Comparison of dry matter production

Besides the seeds which are used as a source of human and animal food, residues of grain legumes are an important source of animal feed and nitrogen-rich fertilizer for the farmer (e.g. Jayasundara *et al.*, 1998) in many developing countries. Therefore, high dry matter production is as important as the seed production for the subsistence farmer in sub-Saharan Africa. In this study, therefore, the dry matter production of the three grain legumes was compared both under well-watered and water stress conditions.



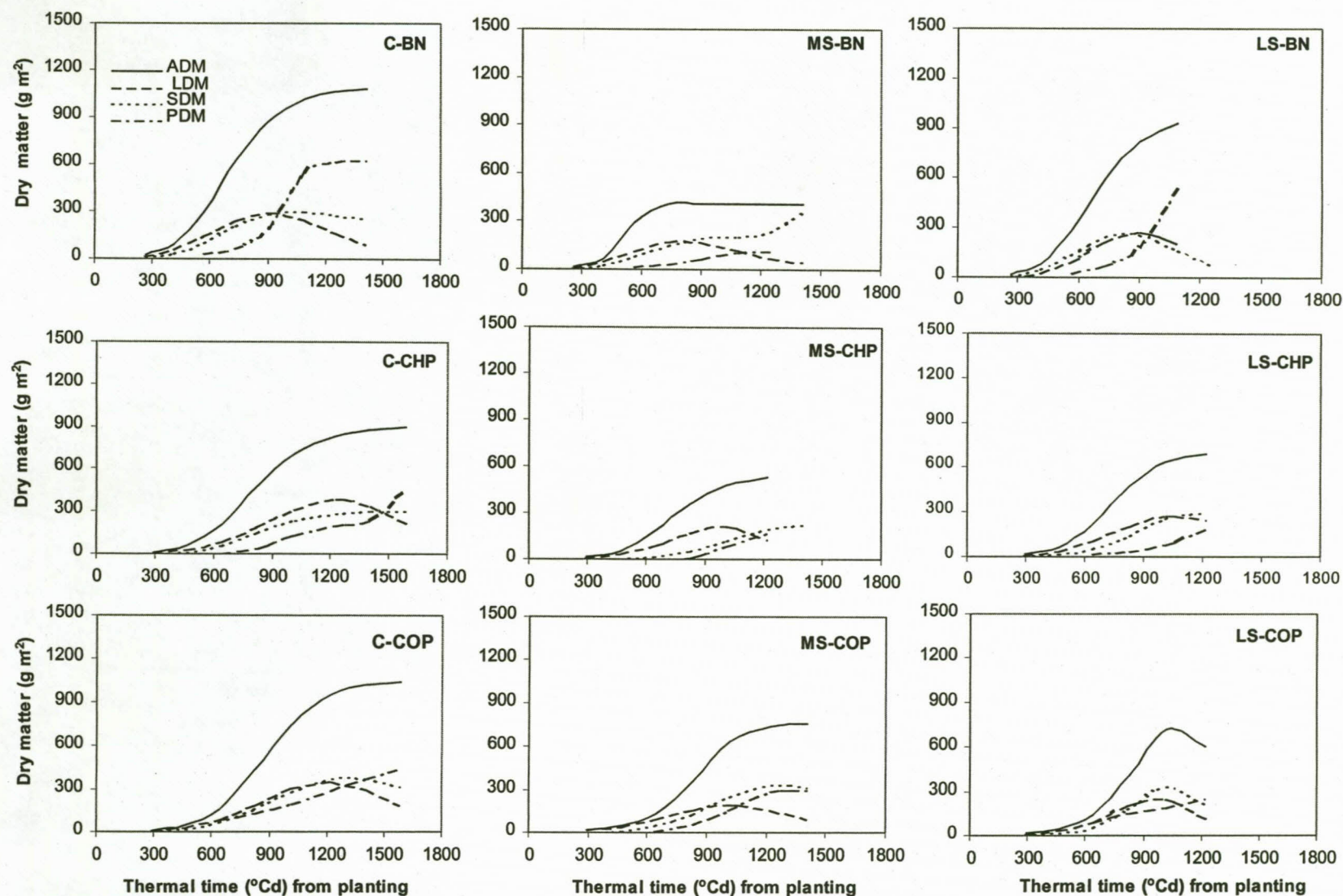


Figure 3.3. The seasonal course of total above ground dry matter (ADM), leaf dry matter (LDM), stem dry matter (SDM) and pod dry matter (PDM) in beans, chickpea and cowpea under water stress (MS, LS) and non-stress (C) conditions in 2002 (BN = bean, CHP = chickpea, COP = cowpea). Thermal time to flowering was 651, 790 and 867 °C d for BN, CHP and COP, respectively.

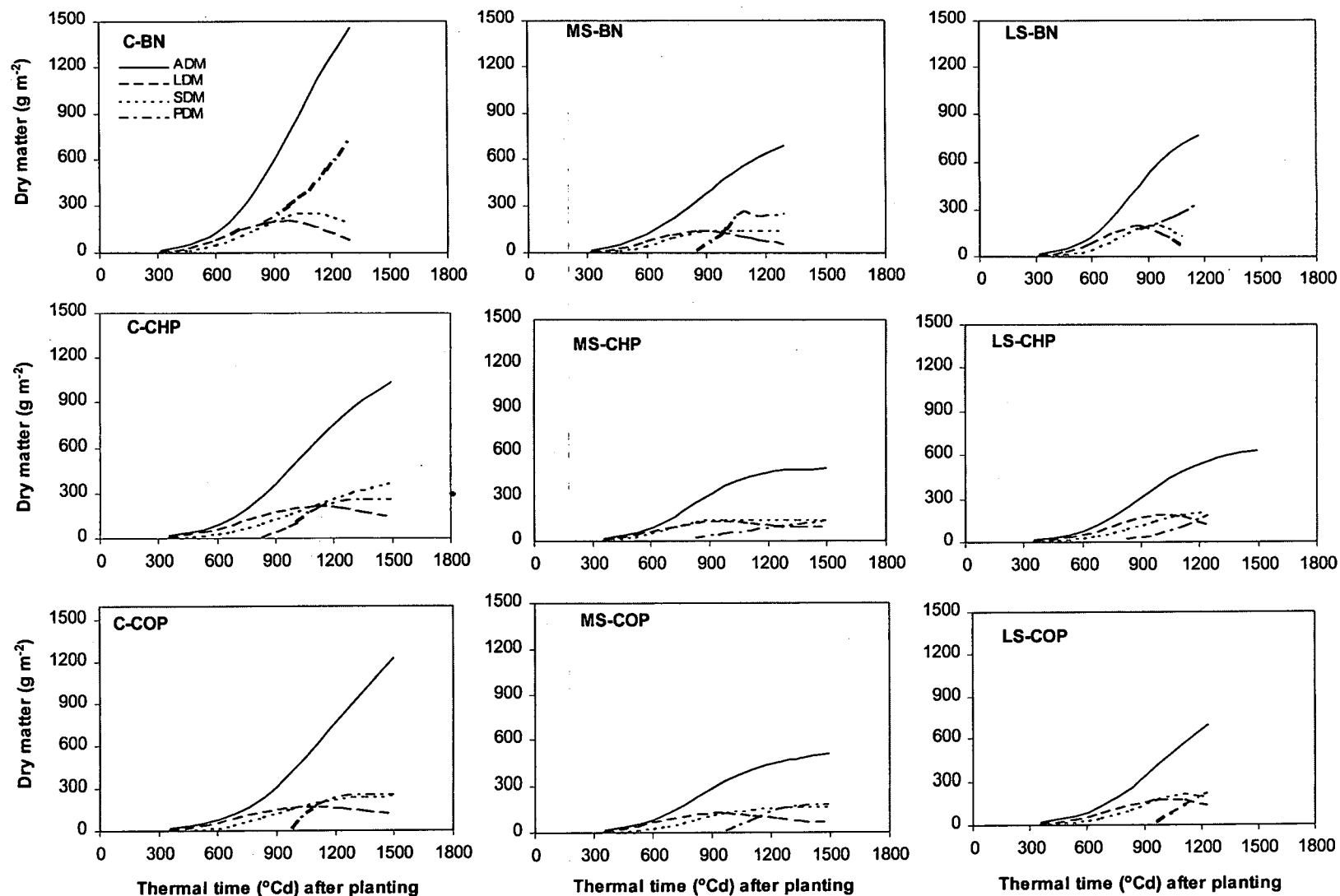


Figure 3.4. The seasonal course of total above ground dry matter (ADM), leaf dry matter (LDM), stem dry matter (SDM) and pod dry matter (PDM) in beans, chickpea and cowpea under water stress (MS, LS) and non-stress (C) conditions in 2002/2003 (BN = bean, CHP = chickpea, COP = cowpea). Thermal time to flowering was 749, 711 and 854 °Cd for BN, CHP and COP, respectively.

Under well-watered conditions, beans had faster growth than chickpea; and chickpea had faster growth than cowpea during all the seasons (Fig. 3.3 and 3.4). Chickpea had the lowest final dry matter in the C treatment under the relatively higher temperature season (2002) but had the highest dry matter in the relatively milder temperature season (2001/2002, data not shown). This shows the sensitivity of chickpea to high temperatures which agrees with the report of Summerfield *et al.* (1981) that the reproductive growth of chickpea suffered considerably more in hot (35/18 °C, day/night) environments compared with that in a milder environment (30/10 °C, day/night).

In 2001/2002, bean accumulated the highest dry matter under the MS treatment because of its long period of growth after re-watering followed by chickpea and cowpea in that order. In this season, no significant differences were observed among water regime treatments (Table 3.5).

In 2002, cowpea produced higher total dry matter than beans and chickpea (Fig. 3.3 and 3.4) indicating its better performance under high temperature conditions. Cowpea has been considered to be one of the crop species most adapted to high temperatures and grows better in hot environments such as the Sahel (Ntare, 1992; Ehlers and Hall, 1997). In beans and chickpea, post-flowering dry matter production was significantly reduced by mid-season water stress in 2002 whereas it was not significantly affected in cowpea (Table 3.5, Fig. 3.3).

In 2002/2003, bean had the highest dry matter whereas chickpea and cowpea produced equal amount of final dry matter. Dry matter in the MS treatment was significantly lower than the C in all species in the 2002/2003 season.

The t- and KS- tests for differences in above ground dry matter production for the period after flowering are shown in Table 3.5 for each season, species and water regime. Both tests showed no significant differences in ADM among the water regime treatments in all species in 2001/2002. The absence of significant difference between the C and MS treatments in this season was due to vegetative re-growth in the MS treatments after re-watering while senescence was accelerated in the C treatment. The tests showed a different scenario in the other two seasons in which the MS treatment significantly reduced post-flowering dry matter in beans and chickpea in 2002 and in all species in 2002/2003.

**Table 3.5. Comparisons of total above ground dry matter (ADM), leaf dry matter (LDM), stem dry matter (SDM) and pod dry matter (PDM) production and leaf area (LA) expansion during the post-flowering period using two-sample t-test (t) and Kolmogorov-Smirnov test (KS) for three seasons.**

Species	Water Regime*	ADM		LDM		SDM		PDM		LA	
		t	KS	t	KS	t	KS	t	KS	t	KS
2001/2002											
Bean	C	a	a	a	a	a	a	a	a	a	a
	MS	a	a	a	ab	a	a	a	a	a	a
	LS	a	a	a	ac	a	a	a	a	a	a
Chickpea	C	a	a	a	a	a	a	a	a	a	a
	MS	a	a	a	ab	a	a	b	b	b	b
	LS	a	a	a	b	a	a	a	a	b	b
Cowpea	C	a	a	a	a	a	a	a	a	a	a
	MS	a	a	ab	ab	a	a	b	a	a	a
	LS	a	a	b	b	a	a	b	a	a	a
2002											
Bean	C	a	a	a	a	a	a	a	a	a	a
	MS	b	b	a	a	a	a	b	b	b	b
	LS	a	a	a	a	a	a	ab	ab	a	ab
Chickpea	C	a	a	a	a	a	a	a	a	a	a
	MS	b	b	a	a	a	a	b	b	b	b
	LS	a	a	a	a	a	a	b	b	ab	ab
Cowpea	C	a	a	a	a	a	a	a	a	a	a
	MS	a	a	a	a	a	a	a	a	a	a
	LS	a	a	a	a	a	a	a	a	a	a
2002/2003											
Bean	C	a	a	a	a	a	a	a	a	a	a
	MS	b	b	b	b	b	b	b	b	a	a
	LS	ab	ab	a	a	ab	ab	ab	ab	a	a
Chickpea	C	a	a	a	a	a	a	a	a	a	a
	MS	b	b	b	b	b	a	b	b	b	b
	LS	ab	b	a	a	a	a	ab	ab	a	ab
Cowpea	C	a	a	a	a	a	a	a	a	a	a
	MS	b	b	b	b	b	b	a	b	a	a
	LS	a	a	a	a	a	a	a	ab	a	a

\* Water regime treatments designated by the same letter within a species are not significantly different from each other at 5% t-test and the respective D values of the KS test.

The significant difference between the two treatments in the two seasons was because of lack of re-growth of vegetative parts in the MS treatment after re-watering in 2002 and 2002/2003 because of high temperature and high VPD experienced by the plants after re-watering, respectively.

On many occasions, alleviation of water stress is followed by a rapid rise in leaf water potential and recovery of turgor (Simpson, 1981). The extent of recovery, however, depends on the duration of stress, species involved, and subsequent environmental conditions (Simpson, 1981). Except one case in chickpea, no significant differences were observed between the C and LS treatments in post flowering dry matter production across

all species and seasons (Table 3.5). This is explained by the fast maturity of plants in the LS treatment before a significant reduction in dry matter could occur.

Compared to beans and cowpea, chickpea was relatively sensitive to late season stress in terms of dry matter production. Reduction in total dry matter of chickpea towards end of season drought was also observed in other studies (Leport *et al.*, 1999). According to the KS-test, significant differences in post-flowering leaf dry matter production were observed between the C and LS in chickpea and cowpea, and between LS and MS in beans in 2001/2002, and between the C and MS treatments in 2002/2003 in all species (Table 3.5). No significant differences were observed in 2002 among any of the water stress treatments because of the depressing effect of high temperature on leaf growth, particularly in chickpea and beans. In general, the results show the sensitivity of leaf dry matter production to late-season water supply in chickpea and cowpea, and to mid-season water supply in all species (Fig. 3.3 & 3.4). However, extremely high temperature throughout the growing period, as observed in 2002, affected leaf dry matter accumulation in all treatments and hence masked difference among the water regimes. Besides temperature and species differences, leaf dry matter production during late season water stress is also influenced by varietal differences. For example, Leport *et al.* (1999) observed reduction of leaf and stem dry matter from 27-60% in many of the desi chickpea genotypes while there was no reduction in the kabuli variety in a Mediterranean-type environment.

A decrease in stem dry matter (SDM) production was observed towards the end of the growing season in the C and LS treatments in beans and cowpea in all the seasons (Fig. 3.3&3.4). In chickpea, however, decline in stem dry matter production towards the end of the season was not observed in any of the water regime treatments. A continuous increase in stem dry matter was also observed for beans and cowpea in the MS treatment. There was no significant difference in post-flowering stem dry matter production among the water regime treatments and species except the C and MS treatments in beans and cowpea in 2002/2003 (Table 3.5).

Maximum pod dry matter (PDM) was recorded in the C treatment followed by the LS treatment in all species and seasons (Fig. 3.3 & 3.4). The MS treatment resulted in the lowest PDM in all species and seasons. Among species, bean had the highest PDM while chickpea and cowpea had similar PDM in all seasons under well-watered conditions.

PDM production by the species in the MS treatment was variable among seasons and as a result there was no particular trend observed (Fig. 3.3&3.4). The KS test showed a significant difference between the C and MS treatments in all species in 2002 and 2002/2003 and between the C and LS in chickpea in 2002 (Table 3.5). Since re-watering resulted in growth of new leaves in most of the cases, the low PDM in the MS treatment could be due to sink limitation rather than source limitation. As observed on many occasions, early reproductive stage water stress (MS treatment) affects flowering through inhibition of floral induction and development (Simpson, 1981; Saini and Westgate, 2000) and possibly flower drop. The stage of meiosis is believed to be the most stress sensitive period of reproduction in a number of crops (Saini and Westgate, 2000), and damage at this stage can limit the subsequent yield of the crop, particularly in determinate plants (Simpson, 1981). As observed in chickpea in the present study, drought stress at seed filling (LS treatment) can also limit yield despite favourable water condition earlier in the development period (Simpson, 1981).

Leaf area growth was faster in beans than in chickpea and cowpea (Appendix 3C to 3E). A decline in green leaf area was observed after pod initiation in all species, water regimes and seasons except in the MS treatment of beans in 2001/2002. However, the rate of decline was variable among species, water regimes and seasons. Rapid rate of total leaf area decline was observed in the LS treatment in all species and seasons, and in the MS treatment in chickpea. An increase in total leaf area was observed in beans after re-watering of the MS treatment in 2001/2002 and 2002/2003 seasons. As shown in Table 3.5, significant differences in post flowering total leaf area were observed in chickpea between the C and MS treatments in all the seasons and in beans in 2002. Reductions in leaf expansion and subsequent decline in total dry matter production are associated with the effect of water stress on cell expansion and division, which are usually reduced before photosynthesis is affected (Hsiao, 1973; Simpson, 1981; Jeuffroy and Ney, 1997). According to Blum (1996), the reduction in leaf area index and intercepted radiation under water stress before flowering are largely the result of impaired leaf expansion and changes in leaf display whereas the reduction after flowering is mainly due to early leaf senescence. The same effect of water stress on leaf growth was observed in this study in chickpea in all seasons and in beans only in the high temperature season. No significant difference was observed among the water regimes in cowpea during any of the seasons indicating its ability to maintain high total leaf area under different water supply and

temperature conditions. This agrees with previous reports that cowpea is less sensitive to mild water deficit, and also has both drought avoiding and tolerating attributes (Grantz and Hall, 1982; Squire, 1990).

Since leaf area is determined by phenology, stem morphology (e.g. stem length), rate of leaf emergence and potential leaf size, the effect of drought on these factors also affects leaf area (Blum, 1996). Therefore, lack of significant differences in the course of post-flowering total leaf area among the water regime treatments in beans (2001/2002 and 2002/2003) and cowpea could be explained by the shorter stress accelerated maturity time in the LS treatment (i.e. before many of the leaves senescence), and an increase in leaf area in the MS treatment upon relief from the stress. Differences among species in sensitivity of leaves to water stress are common (Simpson, 1981), and the current differences in leaf area maintenance among the species indicate the differential response of the crops to reproductive period water stress. Therefore, as observed in the present study and in many other reports (e.g. Blum, 1996 and references there in), plasticity in leaf area is an important mechanism by which crops under drought stress regulates water use.

#### **3.3.4. Leaf area duration (LAD) and final dry matter production**

Three seasons' pooled data for LAD and final dry matter is presented in Fig. 3.5. The results showed the dependence of dry matter production on green LAD in all the three species. The LAD explained 75, 72 and 64% of the final dry matter variability in beans, chickpea and cowpea, respectively. A t-test indicated that the slope of the regression line in chickpea was significantly lower than that of beans and cowpea. Being the photosynthetic site and primary source of assimilates, the leaf determines the performance and productivity of plants in a given environment. Photosynthetic capacity of the leaf (net assimilation rate, NAR) and its duration (LAD) are related to final yield (Hunt, 1982). Similar to the present study, other workers also noted a positive correlation of longer green leaf area duration with final yield in many legume crops (e.g. Kumudini *et al.*, 2001, Thomson and Siddique, 1977). As observed in this study in the LS treatment, accelerated leaf senescence and reduced leaf growth are the major causes of final dry matter reduction under drought environments. Therefore, species or cultivars that maintain green leaf area under variable water supply, as observed in cowpea, could also maintain yield under drought prone environments. It should also be noted that LAD is

influenced by temperature, ontogeny and nutrient availability besides water supply (Squire, 1990).

In all species and seasons, much of the dry matter was allocated to the leaf until the plants reach flowering when allocation to stems increased (Appendix 3F&3G). This is in agreement with the observations made by Siddique *et al.* (1998) in lentil in a Mediterranean-type environment. The dry matter allocation after flowering was influenced by species, water regime treatments and seasons.

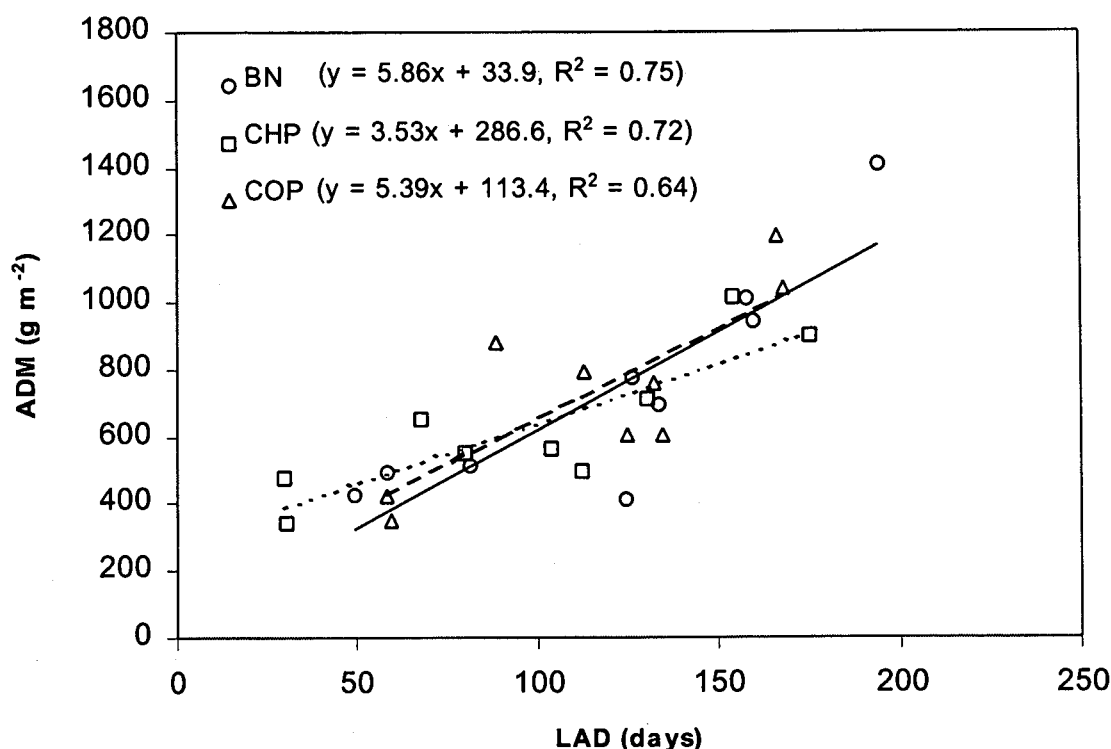


Figure 3.5. The relationship between leaf area duration (LAD) and above ground dry matter at maturity (ADM) in beans (BN, —), chickpea (CHP, ----) and cowpea (COP, ----) for data over three water regimes and three seasons ( $n = 9$ ).

### 3.3.5. Dry matter (biomass) allocation

#### 3.3.5.1. Dry matter allocation in 2002

The seasonal course of dry matter allocation ratio (AR) in 2002 is shown in Appendix 3F. In this season,  $AR_{pod}$  was increasing while  $AR_{leaf}$  and  $AR_{stem}$  were decreasing in beans and cowpea under the C treatment. In chickpea, however, allocation to the pod and stem increased slightly at the expense of allocation to the leaf in the same treatment. In the MS treatment, allocation to the pod and stem increased while allocation to the leaf remained



constant (beans) or declined (chickpea). In cowpea,  $AR_{pod}$  reached maximum of 1.21 (Appendix 3F) during the period of MS stress but declined after re-watering and attained a value of 0.37 at maturity (Table 3.6). Regardless of species,  $AR_{pod}$  in the LS treatment increased until maturity whereas  $AR_{leaf}$  and  $AR_{stem}$  decreased. The  $AR_{leaf}$  decreased much faster than  $AR_{stem}$  in all species under late season stress.

**Table 3.6. Allocation ratio (AR) calculated just before physiological maturity in three grain legume species grown under three water regimes in 2002 and 2002/2003 seasons.**

Species	Plant part	Seasons and water regimes					
		2002			2002/2003		
		C	MS	LS	C	MS	LS
Beans	$AR_{leaf}$	-0.93	-0.49	-0.82	-0.25	-0.45	-1.28
	$AR_{stem}$	-0.77	0.96	-0.62	-0.24	0.00	-0.66
	$AR_{pod}$	0.10	1.78	3.07	0.88	0.24	1.11
Chickpea	$AR_{leaf}$	-2.54	-1.77	-0.50	-0.31	-0.36	-0.85
	$AR_{stem}$	0.28	0.65	0.75	0.39	0.01	0.30
	$AR_{pod}$	0.71	1.79	1.82	0.03	1.30	1.17
Cowpea	$AR_{leaf}$	-0.36	-3.64	-0.94	-0.13	-0.52	-0.27
	$AR_{stem}$	-2.13	-1.36	0.36	0.03	0.12	-0.17
	$AR_{pod}$	3.02	0.37	0.61	0.00	0.19	0.98

At around maturity, the  $AR_{pod}$  in the LS treatment were 3.07, 1.82 and 0.61 for beans, chickpea and cowpea respectively whereas the  $AR_{leaf}$  were -0.82, -0.50 and 0.04 and  $AR_{stem}$  was -0.62, 0.75 and 0.36 for beans, chickpea and cowpea, respectively (Table 3.6). The  $AR_{pod}$  in the C treatment was 0.01, 0.71 and 3.00 for beans, chickpea and cowpea, respectively for the same period (Table 3.6). Results show that under terminal drought, crops allocate most of the assimilates to reproductive development whereas under C, there is a tendency to distribute them to different above ground parts.

### 3.3.5.2. Dry matter allocation in 2002/2003

The seasonal course of AR among above ground parts in 2002/2003 is shown in Appendix 3G. Unlike 2002,  $AR_{pod}$  under the C treatment in 2002/2003 increased with time in beans whereas it decreased in chickpea and cowpea suggesting that allocation of dry matter to the pod was also influenced by other environmental factors (like temperature) besides water supply. Allocation of biomass to different plant parts usually depends on species, growth habit (determinate vs. indeterminate), ontogeny and environmental conditions such as temperature and water supply (Poorter and Nagel, 2000; Squire, 1990). The MS treatment decreased  $AR_{stem}$  in all species in this season,

particularly in beans and cowpea. The pattern of leaf, stem and pod AR in the LS treatment was similar to that of the 2002 season. The  $AR_{pod}$  at maturity was 1.11, 1.17 and 0.98 in the LS treatment and 0.88, 0.03 and 0.00 in the C treatment for beans, chickpea and cowpea, respectively (Table 3.6). The seasonal AR in 2001/2002 was similar to that of the 2002/2003 season (data not shown).

The contribution of post-flowering stem reserves to final grain yield is shown in Table 3.7. The reduction of stem dry matter at maturity relative to its maximum in the three seasons ranged from 13-47%, 2.7-3.2% and 0-23% in the C and 26-76%, 20-32% and 10-34% in the LS treatments in beans, chickpea and cowpea, respectively. Such reduction of stem dry matter towards the end of the growing season was not observed in the MS treatment in any species or season except for cowpea in 2002 (Table 3.7). The contribution of stem dry matter to the final grain yield in the three seasons ranged from 9-37% in beans, 0-5% in chickpea, and 0-32% in cowpea in the C treatment and 19-64% in beans, 28-40% in chickpea and 14-33% in cowpea in the LS treatment (Table 3.7).

**Table 3.7. The contribution of post-flowering stem and leaf reserves to grain yield in beans, chickpea and cowpea under well-watered (C) conditions and mid-season (MS) and late season (LS) water stress in three seasons.**

Calculated parameters*	Seasons and water regimes								
	2001/2002			2002			2002/2003		
	C	MS	LS	C	MS	LS	C	MS	LS
<b>Beans</b>									
1	86.4	-	80.5	38.3	-	71.0	71.9	-	64.9
2	47%	-	76%	13%	-	26%	28%	-	32%
3	37%	-	64%	9%	-	19%	22%	-	26%
4	93.0	-	88.8	198.4	97.8	186.0	127.7	84.7	128.2
5	54%	-	85%	69%	56%	71%	60%	59%	63%
<b>Chickpea</b>									
1	6.94	-	28.8	-	-	76.7	9.2	-	39.0
2	3.2%	-	27%	-	-	32%	2.7%	-	20%
3	3%	-	30%	-	-	40%	5.2%	-	28%
4	53.0	-	14.4	162.3	85.6	29.1	65.9	38.0	68.4
5	26%	-	14%	42%	40%	11%	31%	28%	54%
<b>Cowpea</b>									
1	53.7	23.2	24.6	51.1	24.0	112.4	-	5.2	21.1
2	23%	18%	17%	14%	7%	34%	-	3%	10%
3	32%	35%	33%	13%	13%	48%	-	4%	14%
4	15.1	-	20.8	166.0	97.0	134.6	57.3	60.0	38.4
5	9%	-	19%	47%	50%	54%	32%	45%	21%

\* 1. Decreases in stem mass between period of its maximum and maturity ( $g\ m^{-2}$ )

2. Decreases in stem mass as percentage of maximum total stem mass

3. Decreases in stem mass as percentage of final grain mass (GY)

4. Decreases in leaf mass between period of its maximum and maturity ( $g\ m^{-2}$ )

5. Decreases in leaf mass as percentage of maximum total leaf mass

The reductions in leaf mass between its maximum and maturity in the three seasons ranged from 54-69%, 26-42% and 9-47% in the C treatment, 0-59%, 0-40% and 0-50% in the MS treatment and 63-85%, 11-54%, and 19-54% in the LS treatment for beans, chickpea and cowpea, respectively (Table 3.7). This indicated that the leaf had also contributed a high percentage of its dry matter to the pod in each of the water regimes. The current quantification of dry matter loss in stem and leaves to the grain is a gross estimate and the calculated values seems to be higher because of the fact that the observed reduction in dry mass was not adjusted for losses in respiration. In other crops like wheat, for example, Borrell *et al.* (1989) used a factor of 0.33 (from a previous report) to account for the loss of dry matter to respiration. However, if actual data is not available for a given crop at a given site, the use of reported values might create further complication. Therefore, the use of gross dry matter loss from a plant part as an index to determine the magnitudes of assimilate translocation from a given organ, and to compare species/varieties for a given purpose is preferable.

#### **3.3.5.3. Relationship between leaf, stem and pod dry matter with total above ground dry matter**

For practical applications of assimilate translocation between plant organs in crop growth simulation models, a quantitative relationship between leaf, stem, pod and root growth has to be established. Although root growth was not determined in the present study because of measurement difficulties under field conditions, the relationship between leaf, stem and pod dry matter with the total above ground dry matter was determined using a least square regression by combining the data of the three seasons as shown in Fig. 3.6, 3.7 and 3.8. Lower degree polynomial functions were found to be appropriate to explain the partitioning of dry matter to the leaf and stem in all species and water regimes. On the other hand, pod dry matter accumulation was explained by a power function in beans and chickpea under all water regimes (Fig. 3.6 and 3.7) and by a linear function in cowpea under the MS and LS treatments (Fig. 3.8).

The regression equations in Fig. 3.6 indicated that much of the dry matter of beans translocated to the pod was from the leaves under the C and LS treatments, and that the translocation was higher in the LS than in the C in beans. Except PDM in the MS treatment, the fitted equations were able to explain more than 70% of the observed variability in LDM, SDM and PDM accumulation of beans (Fig. 3.6).

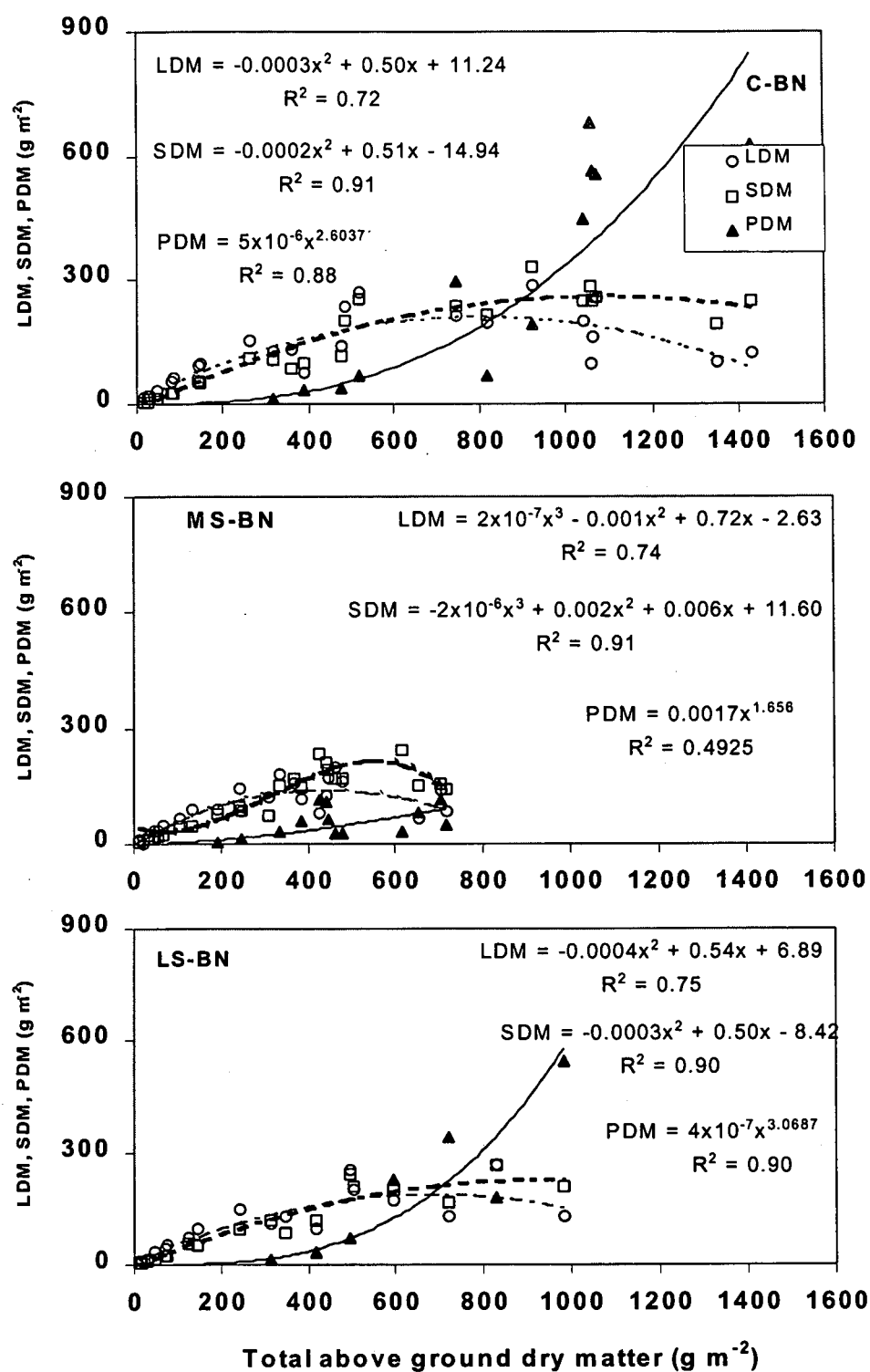


Figure 3.6. Dry matter allocation between leaf (LDM, ---), stem (SDM, ---) and pod (PDM, —) in beans for data combined over three seasons under well-watered conditions (C) and mid-season (MS) and late-season (LS) water stress ( $n = 24, 24$  and  $18$  for leaf and stem dry matter and  $13, 13, 7$  for pod dry matter in the C, MS and LS treatments, respectively).

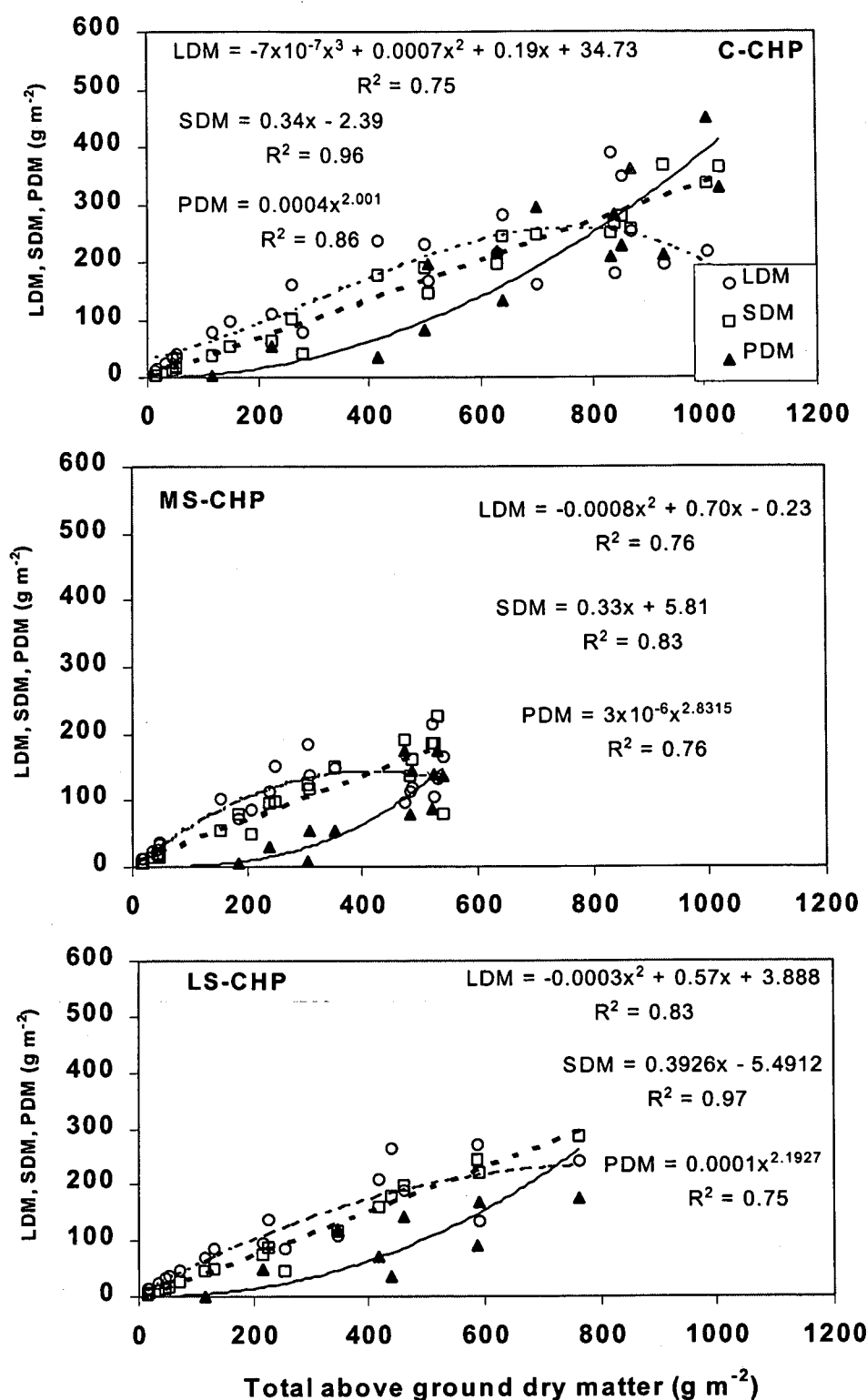


Figure 3.7. Dry matter allocation between leaf (LDM, ---), stem (SDM, ---) and pod (PDM, —) in chickpea for data combined over three seasons under well-watered conditions (C) and mid-season (MS) and late-season (LS) water stress ( $n = 24, 21$  and  $18$  for leaf and stem, and  $16, 12, 9$  for pod in the C, MS and LS treatments, respectively).

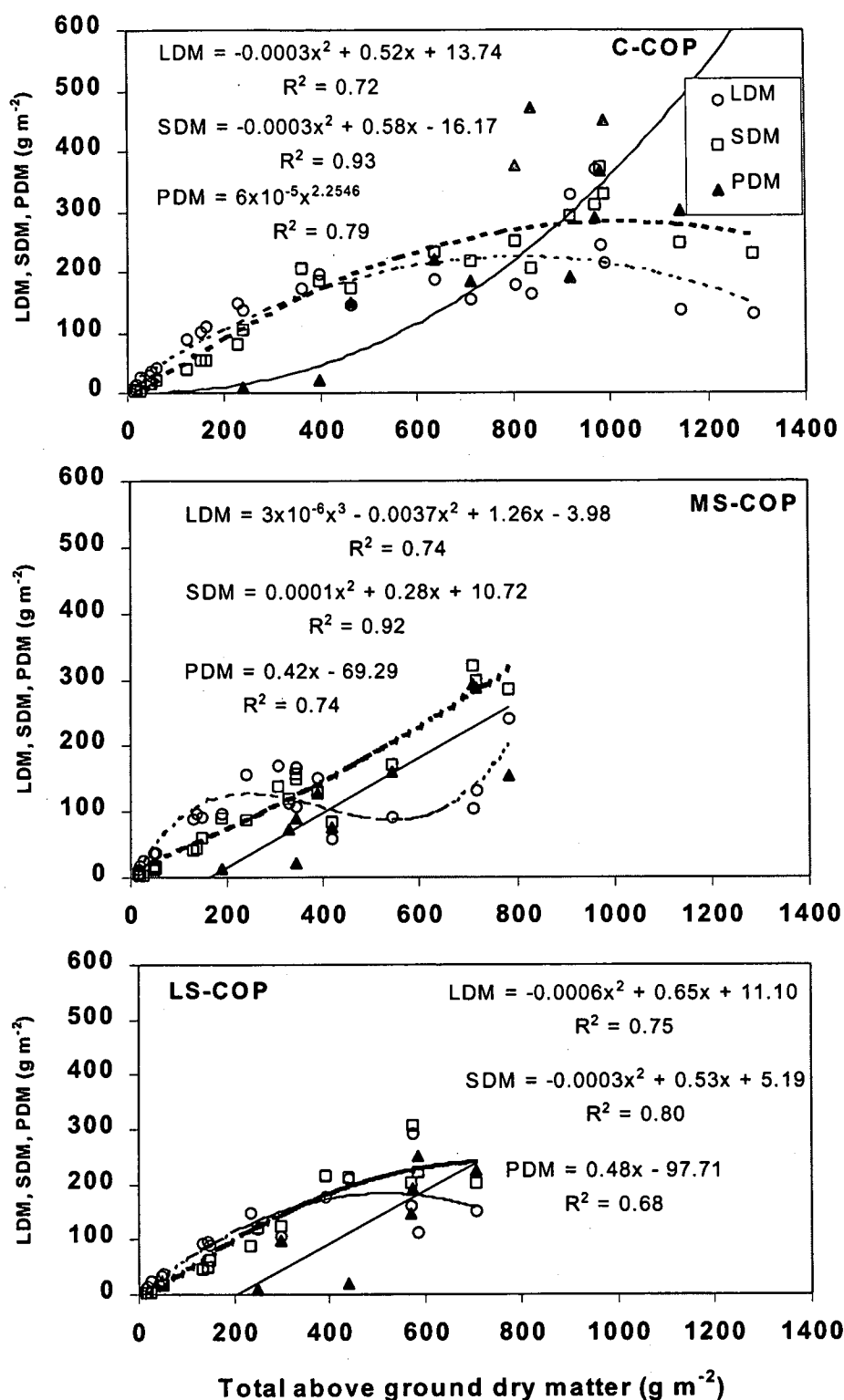


Figure 3.8. Dry matter allocation between leaf (LDM, ---), stem (SDM, ---) and pod (PDM, —) in cowpea for data combined over three seasons under well-watered conditions (C) condition and mid-season (MS) and late-season (LS) water stress ( $n = 24, 21$  and  $18$  for leaf and stem, and  $13, 11, 8$  for pod in the C, MS and LS treatments, respectively).

Regression of above ground parts on total dry matter in chickpea indicated a linear growth of SDM in all water regimes (Fig. 3.7), and the PDM was best explained by the power function under all water regimes ( $R^2 > 0.75$ ). Unlike beans and cowpea where leaf re-growth was observed after re-watering, the regression equation in chickpea indicated higher dry matter allocation to the pod under mid-season water stress which was translocated only from the leaves (Fig. 3.7). The regression equations also showed higher leaf dry matter translocation to the pod in the LS than in the C treatment. In chickpea, the equation explained more than 75% of the variability in LDM, SDM and PDM under all water regimes.

The regression equations in cowpea indicated that dry matter allocation between leaf and stem was similar under well-watered conditions while allocation to- and translocation from- the leaf was higher than the stem under late season water stress (Fig. 3.8). The growth of PDM was explained by a linear function ( $R^2 > 0.67$ ) in both the water stress treatments while it was explained by the power function ( $R^2 = 0.79$ ) under well-watered condition. The equations under water stress conditions indicated that PDM growth was higher in the LS than in the MS treatment in cowpea. The regression coefficients for SDM in the MS were positive suggesting that dry matter was not translocated from the stem to the pod in cowpea under mid-season water stress.

Generally, the regression coefficients in the three species indicated that dry matter translocation between above ground parts was higher under conditions of late season water stress followed by well-watered conditions similar to the data shown in Table 3.7. Under these conditions, much of the translocation goes to pod growth, and the translocation from the leaf is higher than from the stem in most cases. Under mid-season water stress, translocation from the leaf to the pod was observed in chickpea whereas the translocation in beans and cowpea was minimal. Regression of the three seasons combined data indicated that dry matter translocation from the stems to the pods under MS condition was unlikely in all species.

When water supply is variable in the growing season, dry matter is partitioned differently to the different parts of the plant in a way that maximizes growth (Boyer, 1996; Ninkovic, 2003; Poorter and Nagel, 2000). This translocation of assimilates, which enables the plant to capture more of the resources that limit growth most, is considered as an adaptive

mechanism (Poorter and Nagel, 2000). Leaves, stems, roots and nodules are the major sinks for assimilate produced prior to pod initiation in grain legumes (Singh, 1991).

Water stress after flowering resulted in allocation of greater proportion of assimilates to pods than water stress during the whole growth phases in chickpea and most of the translocation of assimilates to pods was reported to come from leaves (Singh, 1991). About 15-20% of assimilates produced prior to pod initiation was translocated to pods in chickpea (Singh, 1991; Saxena 1984) and the amount of translocation was directly proportional to the intensity of water stress during pod and seed growth (Singh, 1991). This fully agrees with the present result observed in chickpea. Leport *et al.* (1999) observed higher redistribution of above ground dry matter during seed filling in Desi chickpea than in Kabuli chickpea. Despite higher total dry matter, the latter produced the lowest yield. Therefore, final grain yield is determined by total biomass production and the proportion allocated to grain in both legume (Muchow *et al.*, 1993; Leport *et al.*, 1999) and cereal crops (Squire, 1990; Van den Boogaard *et al.*, 1997). Among grain legumes, the translocation of reserves in chickpea is reported to be higher than faba bean, lentil and field pea (Wery *et al.*, 1993). Chickpea, however, had the lowest AR in the present study as compared to beans and cowpea which could be due to varietal differences. In line with the present study, allocation of dry matter from vegetative parts to the reproductive organs under water stress has been reported for many grain legumes including lupins (French and Turner, 1991), mungbean (Bushby and Lawn, 1992), peanut (Wright *et al.*, 1991), soybean (Westgate, *et al.*, 1989) and pigeonpea (Robertson *et al.*, 2001). As observed in the present study and also stated by Squire (1990), the effect of drought on partitioning of assimilate depends on its severity, stage of crop development, sink type and duration of sink growth.

### **3.3.6. Specific leaf area (SLA) and its relation with WUE**

SLA plays a significant role in the growth and development of a given crop species. Easier and less expensive measurements make it a desirable parameter in crop physiology studies (Nageswara Rao and Wright, 1994). The seasonal mean SLA was determined for the three grain legumes by regressing leaf area against leaf dry mass. In 2001/2002, the highest SLA was recorded in the MS for bean and in the LS for chickpea and cowpea (Table 3.8). In 2002, SLA was highest in the LS treatment for all species (Table 3.8).



The SLA in 2002 ranged from 125-219 in beans, 99-144 in chickpea and 90-216  $\text{cm}^2 \text{g}^{-1}$  in cowpea. SLA was generally higher and less variable among treatments in 2002/2003 than the previous two seasons (Table 3.8). The highest SLA was observed in the MS treatment in chickpea and cowpea in 2002/2003. The values ranged from 155-182 in beans, 114-136 in chickpea and 155-172  $\text{cm}^2 \text{g}^{-1}$  in cowpea. Pooled over water regime treatments, bean had the highest SLA followed by chickpea in the first two seasons and by cowpea in the third season.

**Table 3.8. Specific leaf area (SLA,  $\text{cm}^2 \text{g}^{-1}$ ) of three grain legumes obtained from a linear regression of leaf area vs. leaf dry matter for three seasons.**

Species	Water regime	2001/2002			2002			2002/2003		
		SLA	$R^2$	n	SLA	$R^2$	n	SLA	$R^2$	n
Beans	C	42 ± 26.8	0.83	7	183 ± 21.0	0.93	8	182 ± 13.1	0.96	9
	MS	168 ± 38.3	0.76	8	125 ± 62.4	0.45	7	155 ± 8.2	0.98	9
	LS	83 ± 64.3	0.29	5	219 ± 14.1	0.98	6	170 ± 5.9	0.99	7
Chickpea	C	63 ± 12.9	0.83	7	112 ± 13.5	0.92	8	119 ± 7.0	0.98	9
	MS	54 ± 14.3	0.82	5	99 ± 35.5	0.66	6	136 ± 4.3	0.99	9
	LS	103 ± 8.1	0.99	4	144 ± 34.7	0.81	6	114 ± 11.2	0.95	6
Cowpea	C	69 ± 17.5	0.79	6	90 ± 28.3	0.63	8	172 ± 15.0	0.95	9
	MS	50 ± 40.2	0.25	6	169 ± 24.4	0.91	8	183 ± 12.4	0.97	9
	LS	98 ± 22.5	0.86	5	216 ± 15.3	0.98	6	155 ± 9.7	0.98	7

**Table 3.9. Specific leaf area (SLA,  $\text{cm}^2 \text{g}^{-1}$ ) of three grain legumes based on a linear regression of leaf area vs. leaf dry matter for all three seasons data combined.<sup>a</sup>**

Species	Water regime	SLA	$R^2$	n	P
Beans	C	169 ± 15.8	0.84	24	0.000
	MS	150 ± 22.2	0.68	24	0.000
	LS	208 ± 13.7	0.93	19	0.000
Chickpea	C	114 ± 8.4	0.89	24	0.000
	MS	107 ± 16.1	0.71	20	0.000
	LS	143 ± 16.0	0.83	18	0.000
Cowpea	C	114 ± 12.3	0.81	22	0.000
	MS	160 ± 15.1	0.86	21	0.000
	LS	186 ± 10.9	0.88	19	0.000

<sup>a</sup> SD = standard deviation of the regression line, n = number of observations, P = probability level.

Data was combined over three seasons in order to get a representative SLA for each species and water regime. An example of the regression analysis for the combined data is shown in Fig. 3.9 and the SLA for each water regime and species is presented in Table 3.9. When data was combined over the three seasons, the correlation (r) between LW and SLA was greater than 0.90 in the C and LS treatments and greater than 0.80 in the MS treatment (Table 3.9). The pooled data showed that SLA was significantly higher in the

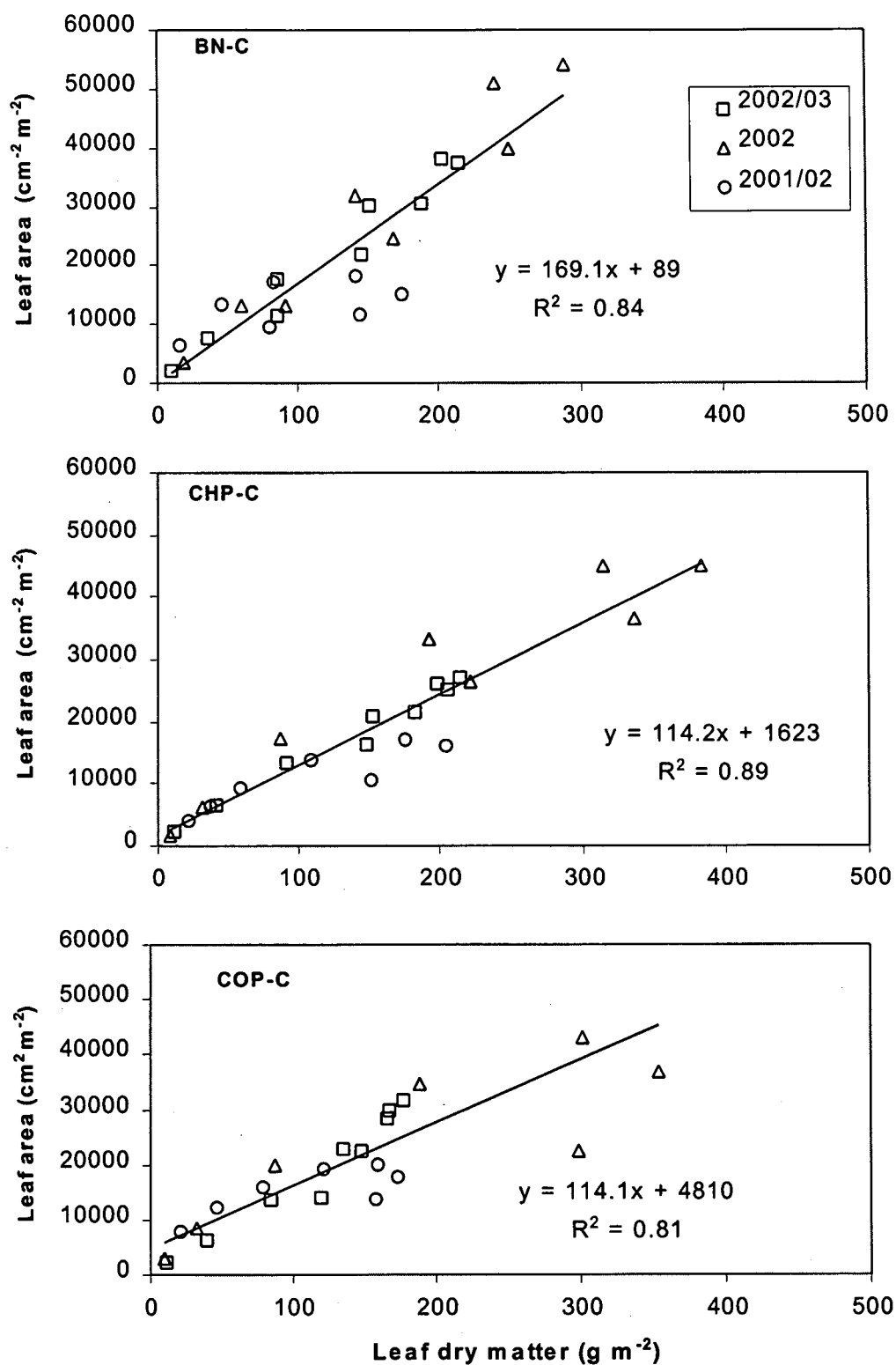


Figure 3.9. An example of specific leaf area (SLA) determination by regression of leaf area vs. leaf dry matter in beans (BN), chickpea (CHP) and cowpea grown under well-watered (C) conditions for data combined over three seasons.

LS than the other two treatments in all species, and bean had the highest SLA followed by cowpea. Higher SLA in the LS shows thinner leaves which is indicative of dry matter translocation from leaves to reproductive organs.

The relation of SLA with water use efficiency (WUE, see Chapter 4) under well-watered and mid-season stress conditions for the 2002 and 2002/2003 seasons is presented in Fig. 3.10 and 3.11, respectively. SLA was strongly negatively correlated with WUE in the C treatment in all species in both seasons and the MS treatments in beans in 2002/2003.

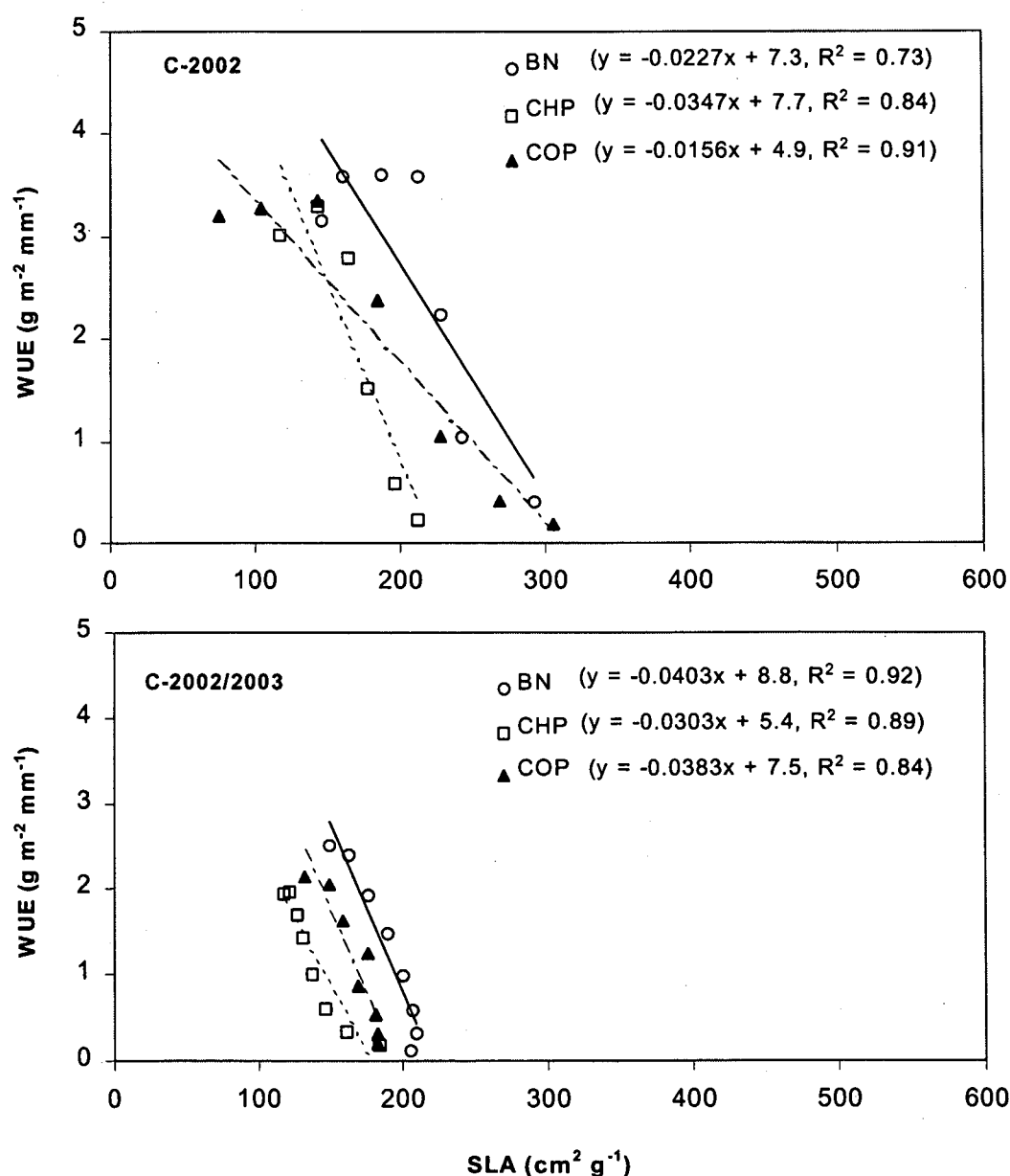
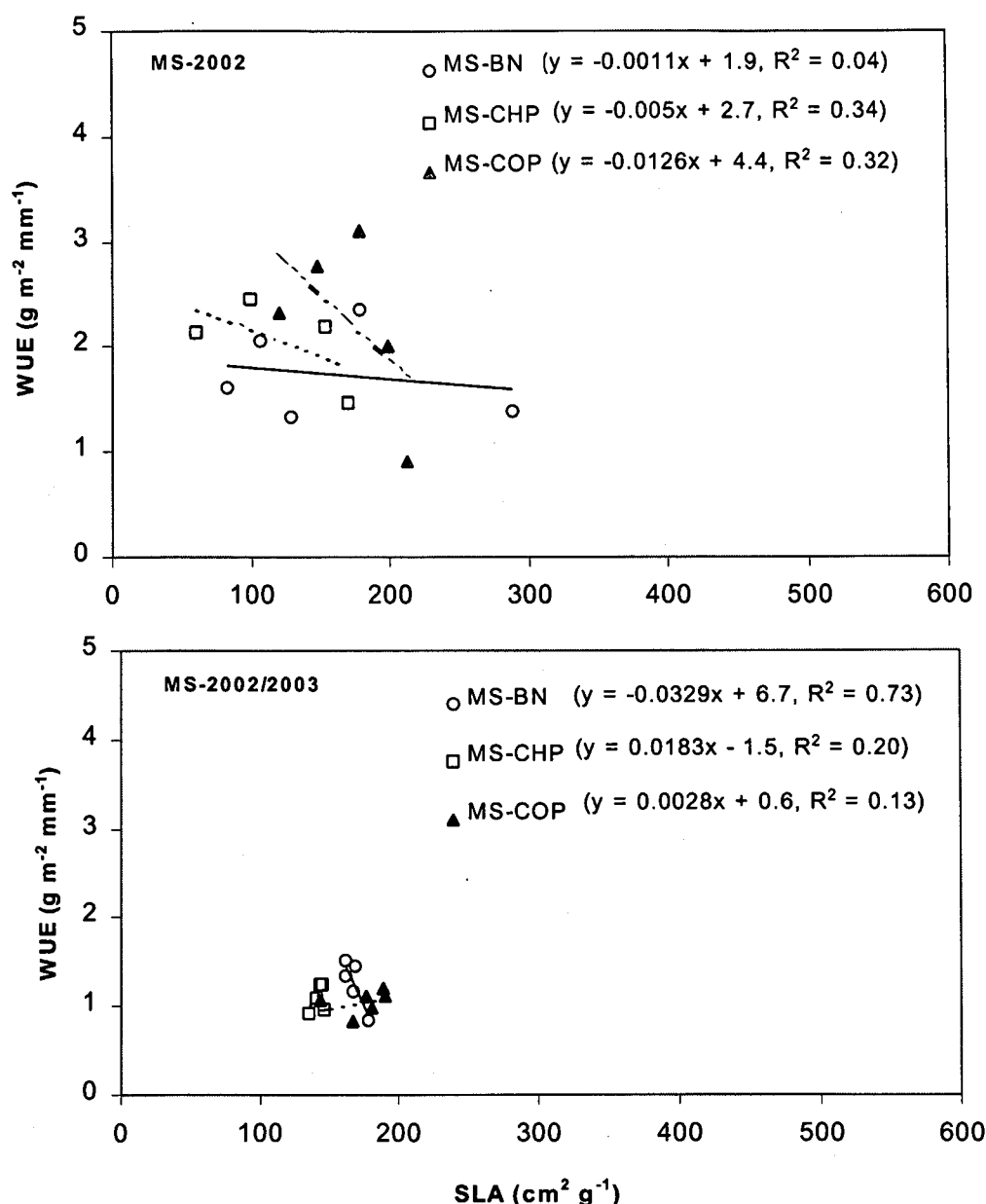


Figure 3.10. The relationship between water use efficiency (WUE) and specific leaf area (SLA) in beans (BN), chickpea (CHP) and cowpea (COP) under well-watered conditions in two seasons ( $n = 6$  and  $8$  for 2002 and 2002/2003 seasons, respectively).



**Figure 3.11.** The relationship between water use efficiency (WUE) and specific leaf area (SLA) in beans (BN), chickpea (CHP) and cowpea (COP) under mid-season water stress (MS) during the reproductive period in two seasons ( $n = 5$  for each season). The data considered was only for the period after flowering during the time of water stress.

Leaf area and leaf dry matter, from which SLA is derived, are closely related to radiation interception, photosynthesis, transpiration, growth rate and final yield (Ma *et al.* 1992). SLA determines the physiological cost of producing leaf area (Dingkuhn, *et al.*, 2001). High SLA is a major factor for early ground cover and high radiation interception and hence determines the growth of plants in many situations (Dingkuhn *et al.*, 2001). SLA is an important component of crop growth simulation models as it relates dry matter

production to leaf area expansion, and consequently to radiation interception and photosynthesis (Gray *et al.*, 1993; Manschadi *et al.*, 1998b). A sugarcane variety with greater SLA showed a more rapid leaf area expansion and growth, and as a result SLA was recommended as an index for improving the early growth of sugarcane (Terauchi *et al.*, 2001). Therefore, the high SLA in beans and cowpea in the present study suggests better performance of the species in the utilization of resources such as radiation and water. The highest and lowest SLA values observed in the LS and MS treatments respectively suggest thinner leaves in the former (possible mobilization of assimilates from the leaves) and thicker leaves in the latter (accumulation of high leaf mass).

As reported by Wright *et al.* (1994) and Nageswara Rao and Wright (1994), SLA is positively correlated to carbon isotope discrimination ( $\Delta$ ) and negatively to WUE (based on transpiration) in peanut. It was also found to be stable across genotypes and environments (Nageswara Rao and Wright, 1994). Therefore, SLA can be used as a surrogate for  $\Delta$  to identify genotypes with high WUE and total biomass (Hubick *et al.*, 1986; Wright *et al.*, 1994; Nageswara Rao and Wright, 1994). A strong negative correlation between WUE (based on evapotranspiration) and SLA was also observed in the present study under well-watered conditions in all species (Fig. 3.10) suggesting the potential use of the character as selection criteria for high field water use efficiency. However, the relation under mid-season water stress was neither strong nor consistent between seasons and species (Fig. 3.11) indicating the limitation of using SLA as indicator of high field WUE under conditions of high soil surface evaporation.

### 3.4. Summary and conclusion

Information on phenology, pattern of growth and dry matter partitioning under different environmental conditions is essential for agricultural decision-making and in the development and/or calibration of crop growth simulation models. The phenology, growth and dry matter partitioning behaviour of three grain legumes were investigated in this study. Compared to the control, late season water stress significantly shortened the time to maturity of the three grain legumes in all seasons while the effect of the mid-season stress was season dependent. The thermal time requirement of the different phenological stages of the species were determined under water stress and non-stress conditions so that these values could be used to predict the phenological stages for management decisions and in crop simulation models.

Leaf area growth and above ground dry matter production were significantly reduced by mid-season water stress but not by late season stress. Re-growth of vegetative parts such as leaves was observed in beans and cowpea upon re-watering after mid-season stress. However, the degree of re-growth and its duration after stress relief was affected by temperature conditions. High temperature conditions inhibited re-growth. LAD is highly correlated with final dry matter yield in all species suggesting that radiation based crop growth models can be effective in simulating the dry matter production of these grain legume crops.

Allocation of assimilates among aboveground parts was influenced by both the timing of water supply and species. Allocation of dry matter to the pod was higher under the late season water stress followed by the well-watered condition in all species. Both the leaves and stem contributed to the growth of the pods although much of the dry matter was translocated from the former. Allocation of dry matter under the MS stress was observed only from the leaves and it was small when compared to the one in the LS and C treatments. Among the species, beans had higher dry matter allocation to the pod than chickpea and cowpea under C and LS conditions, whereas chickpea had higher pod allocation than beans and cowpea under the MS conditions. Allocation of dry matter to the pods under well-watered conditions seems to be season dependent in beans and cowpea. Under milder temperature conditions, bean tend to allocate more dry matter to its pod at the expense of allocation to its stem and leaf whereas cowpea allocate dry matter to all parts with no preference. This condition reversed at high temperature conditions. The combined data over the three seasons indicated that dry matter allocation among aboveground parts was best explained by 1<sup>st</sup> to 3<sup>rd</sup> degree polynomial functions for the stem and leaf growth and by a power function for the pod growth. The regression fit was excellent and the coefficients determined can be used in calibrating existing crop growth models as well as to develop new ones.

SLA was significantly negatively correlated with WUE under well-watered conditions in all the species in both seasons, and, thus, it could be used as a selection criterion for high WUE in high rainfall environments. However, the relationship under mid-season water stress conditions was not strong suggesting further investigation in the stability of the relationship between the two parameters under field conditions.

Generally, differences between chickpea on the one hand and cowpea and beans on the other are wider than difference between cowpea and beans for many of the characters studied. This kind of information is, therefore, essential to facilitate crop choice for a given environment and also adjust to management practices.

## CHAPTER 4

### Resource Utilization of Three Grain Legume Species in A Semi-Arid Environment. I. Water Use and Water Use Efficiency

#### 4.1. Introduction

Dry matter production of a crop depends on the amount of water used and its efficiency of use (Black and Ong, 2000). Plant water use depends mainly on water supply and evaporative demand of a given environment. Therefore, crop water use is determined by the prevailing atmospheric evaporative demand of the environment under well-watered conditions and by both evaporative demand and crop factors under water deficit conditions (Baldocchi *et al.*, 1985; Singh *et al.*, 1990; Black and Ong, 2000). Among crop factors, regulation of canopy size can be more important than leaf conductance in controlling water use during sustained drought (Ong *et al.*, 1996). Therefore, based on the type of water deficits (transient or long), water use at canopy level is controlled by long- and short-term regulatory mechanisms in which reductions in transpiration at any level results in reduced assimilation and growth (Blum, 1996; Black and Ong, 2000).

Water use efficiency (WUE) can be defined as the amount of dry matter (DM) produced per unit of evapotranspiration (ET) (Sinclair *et al.*, 1984; Cooper *et al.*, 1988; Turner, 1997). Both the numerator and denominator of this ratio are defined in many different ways. The numerator could be expressed as the mass of CO<sub>2</sub> that enters the stomata, or the total dry matter produced by the crop, or the above ground dry matter or the grain yield of the crop, and the denominator as the amount of water leaving the stomata (transpiration) or the amount lost as evapotranspiration from the crop and soil (Cooper *et al.*, 1988). As it can be predicted readily from physiological principles and is relatively conservative for a given location, the ratio of mass of CO<sub>2</sub> fixed as carbohydrate to mass of water transpired from leaves, which is commonly termed as transpiration efficiency (TE), is a useful quantity to evaluate crop performance (Tanner and Sinclair, 1983; Copper *et al.*, 1988). While the ratio of dry matter to transpiration shows the total biomass productivity relative to water used by the plant, the ratio of dry matter to evapotranspiration shows the agronomic yield of the system relative to total water use (Loomis, 1983).



WUE is influenced by many factors including water supply, saturation vapor pressure deficit of the air, CO<sub>2</sub> concentration in the air, air temperature, plant factors (carbon metabolism, stomatal behavior, canopy size and structure) and soil properties (Stanhill, 1986; Copper *et al.*, 1988). Therefore, unlike TE, which is conservative within a given species, WUE is affected by management practices. Environmental factors (e.g. drought) that lower the leaf area and thereby increase soil surface evaporation ( $E_s$ ) are known to reduce the WUE (Tanner and Sinclair, 1983). Comparisons of plant species show that the WUE values for tropical C4 cereals are more than twice that of C3 species under similar conditions, although drought tolerant C3 species (e.g. cowpea and cotton) show similar WUE values as drought sensitive cultivars of C4 species such as maize and sorghum (Squire, 1990; Black and Ong, 2000).

Supply of water is a major constraint in the semi-arid environments, and the pattern of water deficit during the season varies across locations and years and with soil types (Singh *et al.*, 1990; Turner *et al.*, 2001). Grain yield is a combined result of many physiological and biochemical processes. Therefore, the study of yield determining processes provides a better mechanistic assessment of the performance of a given cultivar or environment than yield *per se*. Passioura (1977) expressed cereal yield in the dry environments as shown in equation 1.7. Based on this relationship, the study of W, WUE and HI has been used in assessing the adaptation and yield of a number of cereal crops (Turner *et al.*, 2001) and recently grain legumes (Siddique *et al.*, 2001). The components of this model can, therefore, be used to study the performance of grain legumes under the semi-arid regions where water shortage is prevalent.

As reported in many studies (e.g. French and Schultz, 1984; Perry, 1987; Loss *et al.*, 1997; Siddique *et al.*, 2001), the efficiency of water use by a crop can be used as a benchmark for evaluating crop performance as well as for comparing environments. Accordingly, the water use and WUE of many grain legumes have been studied individually under various environments (e.g. Copper *et al.*, 1988; Pannu and Singh, 1993; Silim *et al.*, 1993a; Loss *et al.*, 1997; Ashok, *et al.*, 1999; Collino *et al.*, 2000; Siddique *et al.*, 2001). However, there is little information available on the comparative water use and WUE of grain legumes under water-stress and non-stress conditions in the low rainfall semi-arid areas of Ethiopia. The objective of this study was, therefore, to compare water use and WUE of common bean (*Phaseolus vulgaris* L.), chickpea (*Cicer*

*arietinum* L.) and cowpea (*Vigna anguiculata* L.) grown under different water regimes in a semi-arid region.

## **4.2. Materials and Methods**

### **4.2.1. Field experiments**

Details of experimental site, material and design, cultural practices and irrigation schedule are given in Chapter 3 and will be explained here in brief. Three field experiments were conducted at Dire Dawa, Ethiopia during the periods from early December 2001 to late March 2002 (first season), from late March to early July 2002 (second season) and from mid October 2002 to early February 2003 (third season). Seeds of common bean (cv. Roba-1), chickpea (cv. ICC-4958) and cowpea (cv. black eye bean) were planted on December 7, 2001, March 27, 2002 and October 17, 2002, for the first, second and third seasons, respectively. The experiments had three water regime treatments as shown in Table 3.1. The experimental treatments, replicated three times, were arranged in a randomized split plot design using the water regime treatments as main plot and the crop species as sub-plot. The total experimental area was 22.8m x 40.2m.

### **4.2.2. Experimental measurements**

The soil water content to a depth of 300 mm in 2001/2002 season and 600 mm in 2002 and 2002/2003 seasons was monitored every day throughout the growing period using Time Domain Reflectometry (TDR) (Soil Moisture Equipment Corp., CA, USA). Above ground dry matter (ADM) was measured from five plants (0.2 m<sup>2</sup> area) per plot at intervals of 10 days starting on 35, 17 and 20 days after planting (DAP) for the first, second and third experiments, respectively until physiological maturity. The plant samples were separated into leaf, stem, pod and seed and dried in an oven for 72 hours at 60°C for dry matter determination. Based on the maturity period of plants in the different water regimes, the final harvest was done from March 1 to April 6, from June 7 to July 4 and from January 13 to February 5 in the first, second and third seasons, respectively.

### **4.2.3. Calculations**

#### **4.2.3.1. Seasonal evapotranspiration (ET)**

The ET was calculated on a daily basis using the water balance equation as follows:

$$ET = P + Ir - R - D \pm \Delta S. \quad (4.1)$$

where P is rainfall, Ir is irrigation, R is runoff, D is deep percolation/drainage, and  $\Delta S$  is change in soil water stored within in 600 mm depth (300 mm for the first season). Since water was applied to reach field capacity during irrigation and there was no heavy rainfall during the experimental periods, R and D were considered negligible in this experiment. ET was calculated for different periods: (i) pre-flowering ( $ET_b$ ), (ii) post-flowering ( $ET_a$ ) and (iii) seasonal total ( $ET_s$ ).

#### 4.2.3.2. Water use efficiency

The WUE was calculated using total above ground dry matter at different stages for the pre-flowering period ( $WUE_b$ ), post-flowering period ( $WUE_a$ ), whole season ( $WUE_d$ ) and for grain yield at harvest ( $WUE_g$ ) as follows:

$$WUE_b = \frac{ADM_b}{ET_b} \quad (4.2)$$

$$WUE_a = \frac{ADM_a}{ET_a} \quad (4.3)$$

$$WUE_d = \frac{ADM}{ET_s} \quad (4.4)$$

$$WUE_g = \frac{Y}{ET_s} \quad (4.5)$$

where  $ADM_b$ ,  $ADM_a$  and  $ADM$  refer above ground dry matter ( $\text{kg ha}^{-1}$ ) before flowering, after flowering and at harvest, respectively, Y is grain yield ( $\text{kg ha}^{-1}$ ).

#### 4.2.3.3. Transpiration (T)

Transpiration was calculated from DM using the following relationship (Tanner and Sinclair, 1983; Singh *et al.*, 1990; Squire, 1990).

$$T = \frac{DM}{e_w} (e_s - e_a) \quad (4.6)$$

where T is transpiration ( $\text{kg m}^{-2}$ ), DM is total dry matter ( $\text{g m}^{-2}$ ),  $e_s$  and  $e_a$  are mean daytime saturation and actual vapour pressure of the air respectively (kPa) and  $e_w$  is crop specific transpiration efficiency coefficient ( $\text{g kPa kg}^{-1}$ ). The  $e_w$  values ( $\text{g kPa kg}^{-1}$ ) used were 4.8 for chickpea (ICRISAT, 1988; Singh *et al.*, 1990; Singh and Sri Rama, 1989),

4.2 for beans (Ogindo and Walker, 2003) and 3.5 for cowpea (Barnard *et al.*, 1998; Ashok *et al.*, 1999). Because root dry matter was not measured, the total dry matter was estimated using top/root ratio of 5:1 for the well-watered treatment as shown for soybeans (Barnard *et al.*, 1998) and 4:1 for the water stress treatments because of increased root density and dry matter allocation to roots during water deficit (e.g. Husain *et al.*, 1990; Manschadi *et al.*, 1998a). Transpiration efficiency for grain yield at harvest ( $TE_g$ ) was calculated as the ratio of grain yield (Y) to seasonal transpiration ( $T_s$ ). Seasonal soil surface evaporation ( $E_s$ ) was calculated as the difference between seasonal evapotranspiration ( $ET_s$ ) and  $T_s$ . Harvest index (HI) was calculated as the ratio of grain yield to total above ground try matter at harvest.

#### 4.2.3.4. Vapour pressure (e)

Saturation vapour pressure ( $e_s$ ) was calculated as described by Allen *et al.* (1998) as follows:

$$e^o(T_{\max}) = 0.6108 \exp\left(\frac{17.27T_{\max}}{T_{\max} + 237.3}\right) \quad (4.7)$$

$$e^o(T_{\min}) = 0.6108 \exp\left(\frac{17.27T_{\min}}{T_{\min} + 237.3}\right) \quad (4.8)$$

$$\text{Thus, } e_s = \frac{e^o(T_{\max}) + e^o(T_{\min})}{2} \quad (4.9)$$

$$e_a = \frac{e^o(T_{\min}) * \frac{RH_{\max}}{100} + e^o(T_{\max}) * \frac{RH_{\min}}{100}}{2} \quad (4.9)$$

$$VPD = e_s - e_a \quad (4.11)$$

$T_{\max}$ ,  $T_{\min}$ ,  $RH_{\max}$ ,  $RH_{\min}$  refers to daytime maximum temperature, minimum temperature ( $^{\circ}\text{C}$ ), maximum relative humidity and minimum relative humidity (%), respectively and VPD is mean daytime vapour pressure deficit of air (kPa).

### 4.3. Results and Discussion

#### 4.3.1. Seasonal irrigation and water use

Because of the shallow depth of soil water measurement in the first season, detail results are presented only for the second and third seasons. Cumulative ET was higher in the

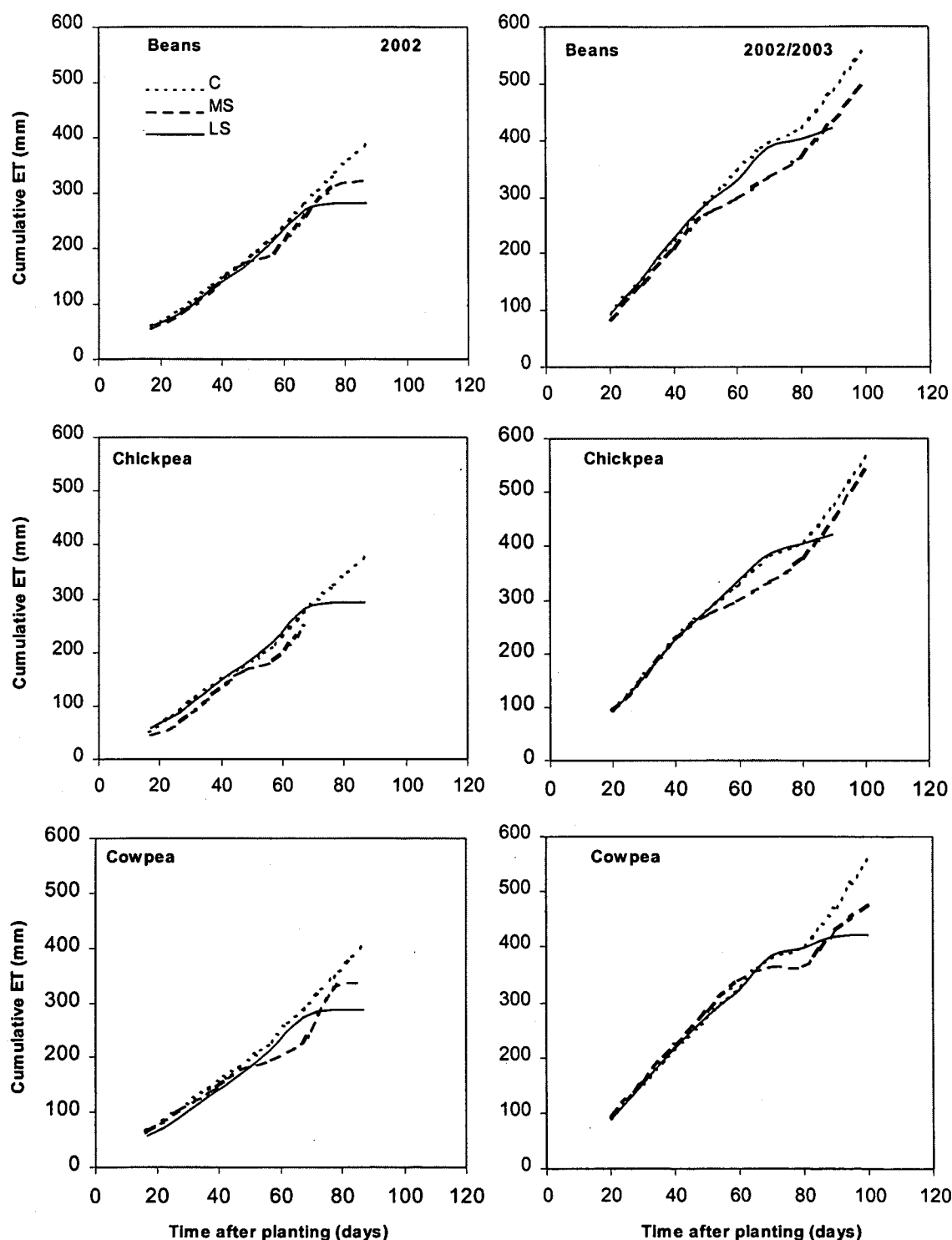
third season than in the second because of longer growing period in the 2002/2003 season (Fig. 4.1). However, the rate of water use (data not shown) was higher in the second than in the third season. This could be due to higher vapour pressure deficit (VPD) of the air in the second season as compared to the third one (Table 4.1). As reported on many occasions (e.g. Bierhuizen and Slatyer, 1965; Tanner and Sinclair, 1983; Stanhill, 1986; Squire, 1990), the VPD of the air is the most important driving force that controls the rate of water vapour exchange between a plant canopy and its boundary layer. Irrigation and water use were the highest in the C treatment followed by the MS treatment in both seasons in all the species (Fig. 4.1 and 4.2). The cumulative water use in the MS and LS treatments was lower than the C treatment during the respective treatment periods and remained below the control for the rest of the season (Fig. 4.1). As shown in the same figure, an increase in water use was observed in the MS treatment upon re-watering. The first season has lower water use (Appendix 5) compared to the other two seasons, which could be due to low VPD of the season (Table 4.1) and/or shallow soil water measurement.

#### 4.3.2. Comparison of pre-flowering, post-flowering and seasonal water use

Significant differences in total seasonal water use were observed among the water stress treatments and among the species in both seasons (Table 4.2). The LS treatment had lower seasonal water use ( $ET_s$ ) than the MS and the difference in  $ET_s$  between the MS and LS treatments was significant ( $P < 0.05$ ) in both seasons (Table 4.2). Significant differences ( $P < 0.05$ ) were also observed among the species.

Under well-watered conditions, cowpea had the highest  $ET_s$  (403 mm) compared to the lowest in chickpea (375 mm) in the second season whereas the three species had similar  $ET_s$  values (422-430 mm) in the third season (Table 4.2). Chickpea had the lowest  $ET_s$  and  $E_s$  in the second season while it had the highest in the third season. This seasonal difference in  $ET_s$  was, therefore, mainly due to differences in leaf area growth (Chapter 3) which affected percent ground cover and soil surface evaporation. Beans had the lowest  $ET_s$  under the LS treatment in both seasons while chickpea and cowpea had similar values (Table 4.2). Similar to the present study, a significant difference in seasonal water use was also reported for chickpea (Siddique and Sedgley, 1987) and faba bean over four sowing dates (Loss *et al.*, 1997) in the low rainfall Mediterranean environments. On the other hand, Siddique *et al.* (2001) did not find any significant difference in seasonal water

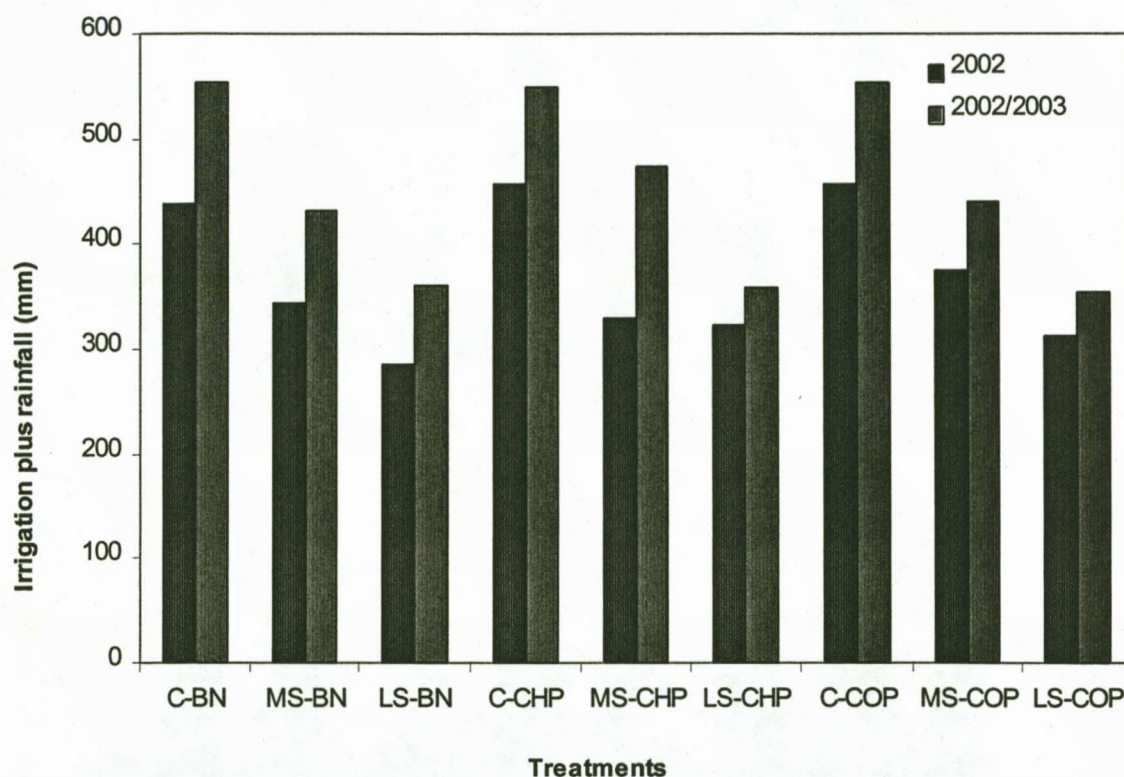
use in a range of erect and prostrate grain legumes under rainfed conditions in the Mediterranean environment which agreed with the present observation under well-watered conditions.



**Figure 4.1.** Seasonal cumulative ET of three grain legumes species under water stress (MS, LS) and non-stress (C) conditions in 2002 (left) and 2002/2003 (right) seasons.

**Table 4.1. Daytime mean vapour pressure deficit (kPa) above the canopy of three grain legumes grown under three water regimes in three seasons for the period between emergence to maturity.**

Season	Water regime	Beans	Chickpea	Cowpea
2001/2002	C	1.60	1.62	1.61
	MS	1.74	1.75	1.64
	LS	1.56	1.75	1.67
2002	C	2.15	2.15	2.14
	MS	2.11	2.02	2.09
	LS	2.10	2.09	2.07
2002/2003	C	1.76	1.75	1.77
	MS	1.76	1.75	1.82
	LS	1.83	1.82	1.85



**Figure 4.2. Seasonal irrigation plus rainfall received by each of the three water regimes (C = well-watered, MS = mid-season water stress, LS = late season water stress) and three grain legumes (BN= beans; CHP = chickpea, COP = cowpea) in 2002 and 2002/2003 seasons in a semi-arid environment.**

There was no significant difference ( $P > 0.05$ ) among species for pre-flowering water use ( $ET_b$ ) in all seasons (Table 4.2 and Appendix 5A) suggesting that vegetative stage water use is similar for the three species under well-watered conditions. On the other hand, differences in post-flowering water use ( $ET_a$ ) among the water regime treatments were significant ( $P < 0.05$ ) in all seasons (Table 4.2 and Appendix 5A). The C and LS

treatments had the highest and the lowest post-flowering water use, respectively. The corresponding values for the second and third seasons were 237.1 and 220.4 mm in the C treatment and 139.6 and 123.7 mm in the LS treatment, respectively. The large variation in post-flowering water use between the water regime treatments is mainly due to the effect of water deficit on canopy development and water availability in the stressed treatments which influence soil cover by leaves and root water uptake, respectively (Chapter 3 of this document; Siddique and Sedgley, 1987). Moreover, water stress hastened physiological maturity in the LS treatment and resulted in lower seasonal water use. The difference in post-flowering water use among species was significant ( $P < 0.05$ ) in the first and second seasons but not in the third season (Table 4.2 and Appendix 5A). Pooled over water regimes, cowpea had the highest (189.1 mm) post-flowering water use in the second season followed by beans (186.5 mm), whereas chickpea had the highest (185.2 mm) in the third season followed by cowpea (174.4 mm). The lowest  $ET_a$ , however, was recorded for chickpea (162.2 mm) in the second season and for beans (165.7 mm) in the third season. This shows the inconsistency of post-flowering water use by the species over seasons which is mostly due to differences in canopy ground cover among species which varied with season.

Water use by crops can be influenced by the stage of crop development and, thus, information on water use for a given phenological period is important to adjust water supply and other management practices (e.g. Simane, 1993). This study attempted to determine the water use for vegetative and reproductive periods in three grain legume species under three water regimes. Significant variation in the ratio of pre- to post-flowering water use ( $ET_b:ET_a$ ) was observed among water regime treatments but not among species in both seasons (Table 4.2). The ratio ranged from 0.61 to 1.11 in the second season and from 0.93 to 1.73 in the third season. The ratio was the highest in the LS treatment (1.04 in the second and 1.66 in the third seasons) while it was the lowest in the C treatment (0.64 and 0.94 in the second and third seasons, respectively).

The lack of significant difference among species for pre- and post-flowering water use under the C treatment indicate the similarity of the species potential to use the same amount of water under non-limiting water supply conditions. However, the ratios of pre- to post-flowering water use indicate that post-flowering water use in terminal drought



**Table 4.2. Seasonal ( $ET_s$ , mm), pre-flowering ( $ET_b$ , mm), post flowering ( $ET_a$ , mm) and ratio of pre- to post flowering water use ( $ET_b:ET_a$ ) and seasonal transpiration ( $T_s$ , mm) and soil evaporation ( $E_s$ , mm) of three grain legume species for 2002 and 2002/2003 seasons.<sup>a</sup>**

Water Regime ( $W_R$ )	Species ( $S_P$ )	2002						2002/2003					
		$ET_s$	$ET_b$	$ET_a$	$ET_b:ET_a$	$T_s$	$E_s$	$ET_s$	$ET_b$	$ET_a$	$ET_b:ET_a$	$T_s$	$E_s$
C	BN	388.5	147.4	241.1	0.61	341.3	47.2	421.9	203.8	218.1	0.93	264.5	157.5
	CHP	375.3	146.4	228.9	0.64	201.5	173.8	430.1	207.4	222.7	0.93	226.4	203.7
	COP	402.6	161.2	241.4	0.67	364.0	38.7	426.2	205.7	220.6	0.97	246.5	179.7
MS	BN	321.1	138.5	182.6	0.76	94.1	227.1	354.2	196.4	157.7	1.43	173.7	180.5
	CHP	244.9	128.8	116.1	1.11	125.8	119.1	416.5	203.1	213.2	1.03	165.1	251.5
	COP	332.6	148.1	184.5	0.80	164.9	167.7	381.1	206.9	174.2	1.27	255.8	125.4
LS	BN	278.9	143.1	135.8	1.10	245.8	33.2	287.2	196.2	121.3	1.63	193.7	93.4
	CHP	288.9	147.4	141.5	1.04	160.7	128.3	321.3	201.5	119.8	1.73	202.9	118.4
	COP	283.9	142.4	141.5	1.01	164.1	119.8	326.3	197.9	128.4	1.60	196.6	129.7
LSD ( $P \leq 0.05$ )	$W_R$	14.3**	n.s.	13.5**	0.01**	33.9**	33.9**	36.5**	n.s.	38.3**	0.39*	17.4**	32.3**
	$S_P$	10.2**	n.s.	10.7*	n.s.	25.6**	23.6**	26.4*	n.s.	n.s.	n.s.	n.s.	36.1*
	$W_R \times S_P$	n.s.	n.s.	n.s.	n.s.	40.8**	40.8**	n.s.	n.s.	n.s.	n.s.	5.25*	62.5*
CV (%)		10.0	5.5	10.0	0.84	11.1	19.6	6.9	6.7	10.6	14.4	13.8	21.9

\*, \*\*: Significant at 5 and 1% probability level respectively; <sup>a</sup>: Soil water was measured to a depth of 60 cm. BN: beans; CHP: chickpea; COP: cowpea.

conditions was much lower than the one under favorable water supply conditions in all species in both seasons as expected. Although  $ET_a$  is slightly higher than  $ET_b$  in the high temperature season (the second season), the  $ET_b$  to  $ET_a$  ratio of the three species was generally closer to unity under well-watered conditions indicating similar water use in the vegetative and reproductive growth stages of the species. Higher values of the ratio in 2002/2003 than in 2002 season indicate that post-flowering water use is dependent not only on water supply but also on other environmental conditions of the season such as air temperature and humidity. In the Mediterranean environment, the ratio of pre- to post-flowering water use was found to be 1.3 or less for early sown faba bean (Loss *et al.*, 1997), and it ranged from 1.19 to 1.71 for erect- and from 1.27 to 2.27 for prostrate- grain legume species under rainfed conditions (Siddique *et al.*, 2001). The values found in the present study under the water stress treatments are within the range of the reported values. The ratios reported here for the three species are useful to adjust water supply based on phenological stages in different water supply environments.

#### 4.3.3. Water use efficiency (WUE)

The pre-flowering water use efficiency ( $WUE_b$ ) ranged from 17.9-18.8 kg ha<sup>-1</sup> mm<sup>-1</sup> in the second season and from 10.9-13.4 kg ha<sup>-1</sup> mm<sup>-1</sup> in the third season (Table 4.3). Differences in  $WUE_b$  were not significant among species (Table 4.3). Post-flowering water use efficiency ( $WUE_a$ ) was higher than pre-flowering water use efficiency ( $WUE_b$ ) in all seasons. This is explained by higher water loss through soil surface evaporation than plant transpiration during the early period of the vegetative growth compared to the post-flowering period when the canopy fully covers the ground and reduces soil evaporation. Pre-flowering water use efficiency ( $WUE_a$ ) was also higher than seasonal total above ground dry matter ( $WUE_d$ ) and grain yield ( $WUE_g$ ) water use efficiency in both seasons which could be due to dry matter loss by respiration until harvest during which vegetative growth had already ceased. It is important to note that respiration consumes up to 50% of the photosynthate produced and thereby lowers the seasonal WUE as compared to the WUE calculated on the short-term basis (Ong *et al.*, 1996).

Difference in  $WUE_a$  was significant among species in the second season and among water regimes in the third season (Table 4.3). In the second season, the  $WUE_a$  ranged from 17.1 kg ha<sup>-1</sup> mm<sup>-1</sup> in the MS to 49.9 kg ha<sup>-1</sup> mm<sup>-1</sup> in the LS treatments in beans and in the third season, it ranged from 11.9 kg ha<sup>-1</sup> mm<sup>-1</sup> in chickpea in the MS to 37.8 kg ha<sup>-1</sup> mm<sup>-1</sup> in

beans in the C treatment. The  $WUE_a$  in the third season was significantly ( $P < 0.05$ ) reduced by the MS treatment in all species when compared to the C and LS treatments which had similar values (Table 4.3).

**Table 4.3. Water use efficiency ( $\text{kg ha}^{-1} \text{mm}^{-1}$ ) for pre-flowering ( $WUE_b$ ), post flowering ( $WUE_a$ ), above ground dry matter at harvest ( $WUE_d$ ) and grain yield ( $WUE_g$ ) and transpiration efficiency for grain yield ( $TE_g$ ,  $\text{g mm}^{-1}$ ) of three grain legume species for 2002 and 2002/2003 seasons.**

Water regime ( $W_R$ )	Species ( $S_P$ )	2002					2002/2003				
		$WUE_b$	$WUE_a$	$WUE_d$	$WUE_g$	$TE_g$	$WUE_b$	$WUE_a$	$WUE_d$	$WUE_g$	$TE_g$
C	BN	18.5	29.6	14.2	6.0	0.69	12.8	37.8	14.8	5.7	1.14
	CHP	18.5	29.7	9.9	3.2	0.58	10.9	25.0	12.4	4.7	0.86
	COP	18.5	26.2	12.2	3.3	0.37	13.4	31.2	13.6	5.8	0.77
MS	BN	18.5	17.1	4.8	0.6	0.22	12.3	14.3	11.1	3.9	1.10
	CHP	18.7	34.1	10.0	2.0	0.41	11.6	11.9	9.0	3.2	0.63
	COP	17.9	26.1	6.8	1.6	0.31	12.5	13.7	12.2	5.1	0.71
LS	BN	18.3	49.9	14.5	6.2	0.71	11.9	29.3	14.0	6.0	1.13
	CHP	18.4	36.4	10.5	3.8	0.70	12.2	35.2	14.7	5.5	1.02
	COP	18.8	28.4	13.5	2.6	0.46	11.3	33.1	14.3	5.3	0.76
LSD ( $P < 0.05$ )	$W_R$	n.s.	n.s.	1.7**	1.1**	0.15*	n.s.	9.3**	1.8*	1.1*	n.s.
	$S_P$	n.s.	5.6*	1.3*	0.5**	0.07**	n.s.	n.s.	n.s.	n.s.	0.12
	$W_R \times S_P$	n.s.	9.7**	2.3**	1.9**	0.14**	n.s.	n.s.	n.s.	n.s.	n.s.
CV (%)		3.0	17.7	12.7	16.0	15.9	13.3	28.7	16.6	18.3	12.5

\*, \*\*: Significant at 5 and 1% probability level respectively; °: Soil water was measured to a depth of 600 mm. BN: beans; CHP: chickpea; COP: cowpea.

$WUE_d$  was significantly ( $P < 0.05$ ) affected by the water regime treatments in both seasons (Table 4.3). The values ranged from 4.8-14.5  $\text{kg ha}^{-1} \text{mm}^{-1}$  (between MS and LS treatment in beans) in the second season and from 9.0-14.8  $\text{kg ha}^{-1} \text{mm}^{-1}$  (between MS and C treatments in chickpea) in the third season (Table 4.3). Among the water regimes, the lowest  $WUE_d$  was recorded in the MS treatment while the highest was recorded in the LS treatments in both seasons for all species except in chickpea in the second season. The lowest WUE recorded in the MS treatment is a result of low dry matter production and possibly a high soil surface evaporation resulting from reduction in leaf area in contrast to the LS treatment where the plants mature before a significant loss of foliage. Beans and cowpea have similar  $WUE_d$  across the water regimes in both seasons. Although chickpea had a higher or similar value of  $WUE_d$  to that of beans and cowpea in a few cases, it generally tended to have lower values across the water regimes in both seasons. This shows that beans and cowpea are more efficient than chickpea in producing dry matter under water limited environments. Therefore,  $WUE_d$  can be used as a criterion to select crops for water limited environments.

The  $WUE_g$  differed significantly ( $P < 0.05$ ) among the water regime treatments in both seasons (2<sup>nd</sup> and 3<sup>rd</sup>) and among the species in only in the second season (Table 4.4). The average  $WUE_g$  were 4.1, 1.4 and 4.2 kg ha<sup>-1</sup> mm<sup>-1</sup> in the second season and 5.4, 4.1, and 5.6 kg ha<sup>-1</sup> mm<sup>-1</sup> in the third season for the C, MS and LS treatments, respectively indicating that the MS treatment had the lowest  $WUE_g$ . Among the species, beans had the highest (4.3 kg ha<sup>-1</sup> mm<sup>-1</sup>) and cowpea had the lowest (2.4 kg ha<sup>-1</sup> mm<sup>-1</sup>)  $WUE_g$  in the second season while beans and cowpea had the highest (5.3 kg ha<sup>-1</sup> mm<sup>-1</sup>) and chickpea had the lowest (4.8 kg ha<sup>-1</sup> mm<sup>-1</sup>)  $WUE_g$  in the third season. The  $WUE_d$  and  $WUE_g$  found in the present study are comparable to previous reports in chickpea under drought stress and irrigation conditions (Silim and Saxena, 1993a), lentil (Silim *et al.*, 1993b), and mungbean (Pannu and Singh, 1993) under rainfed and irrigated conditions. In many environments, chickpea is reported to use 100-450 mm of water in a season depending on yield produced with a  $WUE_d$  ranging from 5.2-35.2 kg ha<sup>-1</sup> mm<sup>-1</sup> and a  $WUE_g$  from 1.1-15.7 kg ha<sup>-1</sup> mm<sup>-1</sup> (Sandhu *et al.*, 1978; Singh and Bhushan, 1980; Sivakumar and Singh, 1987; Siddique and Sidgley, 1987; Keatinge and Cooper, 1983; Singh and Virmani, 1990; Silim and Saxena 1993a). The current  $WUE_d$  are also within the range of values reported for beans (8.5-24.8 kg ha<sup>-1</sup> mm<sup>-1</sup>) over different seasons and population densities (Tsubo *et al.*, 2003). The present  $WUE_d$  recorded are generally lower than the values reported for a number of erect- (up to 30 kg ha<sup>-1</sup> mm<sup>-1</sup>) and prostrate- (up to 38 kg ha<sup>-1</sup> mm<sup>-1</sup>) grain legumes in the Mediterranean environment (Siddique *et al.*, 2001) suggesting genotypic differences in WUE. However, the values reported for  $WUE_g$  in the same study, with the exception of fababean and pea, are within the range of values found in the present study. The current values are far below the maximum  $WUE_d$  (30-36 kg ha<sup>-1</sup> mm<sup>-1</sup>) reported for *V. faba* and *V. narbonensis* and  $WUE_g$  (14-16 kg ha<sup>-1</sup> mm<sup>-1</sup>) for *V. faba* and *P. sativum* in the Mediterranean environments (Loss *et al.*, 1997; Siddique *et al.*, 2001). This indicates that the species in the current study have lower maximum WUE than other grain legume species such as faba bean and field pea, suggesting that the current species may have a lower potential for water use than the mentioned cool-season food legumes.

#### 4.3.4. Seasonal transpiration and transpiration efficiency (TE)

The calculated seasonal transpiration ( $T_s$ ) values were significantly different among water regime treatments ( $P < 0.01$ ) in both the second and third seasons and among species in the second season ( $P < 0.05$ ) (Table 4.2). The seasonal transpiration ranged from 94.1 to 364.0 mm in the second season and from 165.1 to 264.5 mm in the third season. Pooled over the

species, the seasonal transpiration values were 302.3, 128.2, and 190.2 mm in the second season and 245.8, 198.2 and 197.8 mm in the third season for the C, MS and LS treatments, respectively. These transpiration values comprised 78, 43 and 67% of the  $ET_s$  in the second season and 58, 52 and 63% in the third season for the C, MS and LS treatments, respectively. Subtraction of  $T_s$  from  $ET_s$  shows that water loss due to soil surface evaporation can be as high as 57% in the mid-season drought prone semi-arid areas and as low as 22% in those semi-arid areas where water supply is favourable. Pilbeam *et al.* (1995) found that 49-83% of the rainfall in the semi-arid area of Kenya was lost as soil surface evaporation, and the seasonal average transpiration was only 23% of the evapotranspiration. Cooper *et al.* (1987) estimated soil surface evaporation in the range of 40-50% of the seasonal crop evapotranspiration, which is within the range of the present values found in a semi-arid environment. The pattern of water use in the form of transpiration among the species was different over the seasons. Beans and cowpea had the highest transpiration in the second season whereas cowpea had the highest in the third season. The transpiration in beans, chickpea and cowpea constitute 69, 54 and 68% of the  $ET_s$  in the second season and 59, 51 and 62% of the  $ET_s$  in the third season, respectively. In most of the cases, soil evaporation was the highest in chickpea across the water regimes (Table 4.2) mainly because of its slow leaf area growth (Chapter 3) and poor ground cover. Therefore, management practices that increase ground cover and reduce the soil surface evaporation are expected to increase the WUE of this crop. Except for a few instances, beans and cowpea had similar transpiration values in both seasons under both well-watered and water stress conditions.

The TE calculated based on grain yield ( $TE_g$ ) was significant ( $P < 0.05$ ) among the water regime treatments in the second season but not in the third (Table 4.3). The highest  $TE_g$  was recorded in the LS while the lowest was recorded in the MS. The values ranged from 0.22-0.71 g mm<sup>-1</sup> in the second season and from 0.63-1.14 g mm<sup>-1</sup> in the third season.  $TE_g$  values for grain legumes are not available in the literature. However, the TE values (based on total dry matter) reported in other studies include 1.89-2.33 g mm<sup>-1</sup> for chickpea (Cooper *et al.*, 1988), 2.21-3.57 g mm<sup>-1</sup> for cowpea (Ashok *et al.*, 1999), 2.2-3.7 g mm<sup>-1</sup> for beans (Pilbeam *et al.*, 1995; Ogindo, 2003), and 1.5-5.2 g mm<sup>-1</sup> for groundnut (Ong *et al.*, 1987; Matthews *et al.*, 1988; Azam-Ali *et al.*, 1989). The LS treatments had slightly higher  $TE_g$  values as compared to the control in 2002 which could be explained by reductions in the mean transpiration rate (Ashok *et al.*, 1999) as a result of partial

stomatal closure while the lower values in the MS stressed treatments could be explained by reductions in transpiration as a result of high soil surface evaporation (Table 4.3).

#### 4.3.5. Relationship between harvest index, water use and water use efficiency

The correlation between HI, water use and WUE parameters in the second and third seasons is shown in Table 4.4. In beans, correlations among the water use and WUE parameters were not strong under well-watered conditions except a significant ( $P < 0.05$ ) positive correlation between  $WUE_d$  and  $WUE_a$ . HI was also not strongly correlated with any of the water use and WUE parameters under the control water regime. Except significant positive correlations between  $WUE_d$  and  $WUE_a$  and HI and  $WUE_g$ , similar conditions were observed in the LS treatments. However,  $WUE_d$ ,  $WUE_g$  and HI were significantly positively correlated with  $ET_b$  and negatively with  $WUE_b$  in the MS treatment (Table 4.4). This suggests the importance of high water use during the vegetative stage for high WUE and HI at harvest in mid-season drought stressed beans. Moreover,  $WUE_g$  was strongly ( $P < 0.01$ ) correlated with  $WUE_d$ , and HI was significantly and positively correlated with both  $WUE_d$  and  $WUE_g$ . On the other hand,  $WUE_a$  and  $WUE_g$  are important for high HI of beans in terminal drought environments. Thus, high reproductive period WUE is an important mechanism that enables the plant to maximize dry matter production under limited water supply during the period of grain growth.

In chickpea, correlations among the water use and WUE parameters and HI were weak except that HI was positively significantly ( $P < 0.05$ ) correlated with  $WUE_g$  in the MS and LS treatments, and  $WUE_g$  was positively correlated with  $WUE_b$  in the C treatment. Weak correlations among water use, WUE and HI across the water regime treatments in chickpea suggest that HI in this crop may not depend on water use and water use efficiency.

On the other hand, for cowpea  $WUE_d$  and HI in the C treatment and  $WUE_g$  and HI in the LS treatment were significantly positively correlated with vegetative stage water use ( $ET_b$ ).  $WUE_g$  and HI were significantly negatively correlated with  $WUE_b$  in both the MS and LS treatments of cowpea (Table 4.4). In addition,  $WUE_g$  was positively correlated with  $WUE_d$  in both the MS and LS treatments. HI was positively correlated ( $P < 0.05$ ) with  $WUE_g$  in the water regimes but the correlation was significant only in LS treatments. HI was significantly negatively correlated with  $WUE_d$  in the C treatment while it had weak

positive correlation in the MS and LS treatments. The results in cowpea indicated that high  $WUE_d$  and HI at harvest are achievable through high water use during the vegetative stage under well-watered and mid-season water stress conditions which could result in high dry matter and seed yield at harvest. Therefore, management practices in mid-season drought environments should focus on increasing the water use of cowpea during the vegetative period in order to increase HI of the crop.

**Table 4.4. Correlation coefficients for water use, water use efficiency and HI in three grain legumes.<sup>+</sup>**

Species	Water regime		$ET_b$	$ET_a$	$WUE_b$	$WUE_a$	$WUE_d$	$WUE_g$
			----- (mm) -----		----- $kg\ ha^{-1}\ mm^{-1}$ -----			
Beans	C	$WUE_d$	-0.52	-0.76	0.70	0.84*		
		$WUE_g$	-0.14	-0.23	0.29	0.42	0.80	
		HI	0.30	0.20	-0.15	0.11	0.15	0.45
	MS	$WUE_d$	0.89*	0.67	-0.84	-0.31		
		$WUE_g$	0.95**	0.74	-0.92**	-0.27	0.97**	
		HI	0.98**	0.82*	-0.99**	-0.34	0.87*	0.96**
	LS	$WUE_d$	-0.69	-0.53	0.77	0.91**		
		$WUE_g$	0.21	-0.03	0.32	0.64	0.65	
		HI	-0.16	0.52	0.26	0.52	0.42	0.89*
Chickpea	C	$WUE_d$	0.09	0.00	-0.05	0.45		
		$WUE_g$	0.04	0.04	0.18	0.35	0.84*	
		HI	0.41	0.44	-0.09	-0.35	0.32	0.68
	MS	$WUE_d$	-0.41	-0.60	0.53	0.20		
		$WUE_g$	0.22	0.08	0.09	0.30	0.22	
		HI	0.37	0.32	-0.16	0.25	-0.44	0.81*
	LS	$WUE_d$	0.17	0.30	-0.50	0.10		
		$WUE_g$	-0.36	-0.15	0.45	0.38	0.68	
		HI	-0.56	-0.31	0.64	0.48	0.18	0.81*
Cowpea	C	$WUE_d$	0.95**	-0.44	0.99***	0.27		
		$WUE_g$	0.16	0.61	-0.04	0.26	-0.09	
		HI	0.85*	0.40	-0.83*	-0.12	-0.86*	0.59
	MS	$WUE_d$	0.41	-0.37	-0.49	-0.51		
		$WUE_g$	0.77	-0.30	-0.84*	-0.77	0.88*	
		HI	0.97*	-0.05	-0.98**	-0.80	0.37	0.77
	LS	$WUE_d$	0.62	0.17	-0.54	-0.34		
		$WUE_g$	0.88*	-0.03	-0.83*	0.19	0.85*	
		HI	0.88*	-0.16	-0.88*	0.65	0.40	0.82*

<sup>+</sup> n = 6 ( three observations and two seasons).

\*, \*\*, \*\*\* = values significant at 5, 1 and 0.1% P levels.

Comparison of species under well-watered condition indicate that high  $WUE_d$  at harvest was strongly positively correlated with high  $WUE_a$  in beans and high  $WUE_b$  in cowpea while it is not dependent on any of the water use parameters in chickpea. High HI was strongly positively associated with high  $WUE_g$  in all species under terminal water stress as well as in chickpea under mid-season stress.

WUE<sub>g</sub> and HI were significantly negatively correlated with WUE<sub>b</sub> in the MS treatment in beans and in the MS and LS treatments in cowpea but significantly positively correlated with ET<sub>b</sub> in the same species and treatments indicating the importance of high vegetative period water use for high HI and grain yield. However, although maximum utilization of water is important when it is available for high dry matter production, it will cause early depletion of soil water and will have a negative effect on yield if there is water shortage during the reproductive period. As a result the advantage of high vegetative water use depends on the availability of water later in the season. Comparison of the water regime treatments over species indicated that HI was negatively correlated with WUE<sub>a</sub> in the MS treatment ( $r = -0.34$  to  $-0.51$ ) in beans and cowpea and positively ( $r = 0.48$  to  $0.65$ ) in the LS treatment in all species while the relationship was weak in the C treatment ( $r = -0.35$  to  $0.11$ ). This shows that water applied after stress in the MS treatment is mainly utilized in the production of vegetative matter rather than contributing to grain yield. This was observed in the field when plants of beans and cowpea started producing new leaves and flowers upon re-watering while previously developed pods dried out faster. When pooled over the species, WUE<sub>g</sub> was strongly correlated with HI in all water regimes and explained 60, 81 and 82% of the variability in HI in the C, MS and LS treatments, respectively suggesting that high grain WUE of a crop is important in increasing HI of grain legumes in different environments with respect to water supply. As indicated by Passioura (1977) for cereal crops, the present results show that HI is strongly correlated with grain yield in all water regimes (Chapter 7) but the association of HI with the components of WUE in grain legumes is environment dependent. For example, selection for high reproductive period water use and WUE could result in high HI in terminal drought environments in beans and cowpea unlike mid-season drought and high rainfall environments where selection for the same may not bring any success.

HI depends largely on the relative proportion of pre- and post-flowering dry matter and the mobilization of pre-flowering assimilates to the grain (Ludlow and Muchow, 1990; Chapter 3), and is considered as a potential source of yield stability in terminal-drought environments (Turner *et al.*, 2001). In crops like chickpea that are usually grown on stored soil water, HI is related to the amount of water available after flowering (Passioura, 1977), and greater water use in the post flowering period was associated with higher HI and WUE<sub>g</sub> in grain legumes (Siddique *et al.*, 2001). Therefore, as shown in the present



work and stated by Ludlow and Muchow (1990), the study of HI in relation to water use and use efficiency is the best avenue for improving grain yield of crops by increasing the amount of water transpired so as to maintain high HI and yield.

#### **4.4. Conclusion**

Water use and water use efficiency are important components in the study of resource utilization by plant species. The present study indicated that water use and its efficiency were greatly influenced by the time (growth stage) and amount of water supply in grain legumes. The mid-season water stress treatment had intermediate seasonal water use but the lowest crop WUE resulting from low leaf area index, high soil surface evaporation, (particularly in chickpea) and reduced sink size. Therefore, crop management practices that decrease soil evaporation are expected to increase the WUE of these crops under mid-season drought environments. On the other hand, water use was much higher for the well-watered treatment compared to the late season stress treatment while the two treatments had similar WUE values at harvest. Therefore, in water limited environments, applying a certain period of water stress towards the end of the growing season is advantageous in increasing water saving while maintaining high WUE. Among species, beans and cowpea had similar WUE values while chickpea had the lowest record during all the seasons. Therefore, grain legume species that efficiently utilize the available water, such as beans and cowpea, are important in drought prone crop growing environments. The information generated in this study will be valuable in modeling the water use and WUE of the species for the semi-arid regions and also in facilitating crop choice for a given environment regarding water supply.

## CHAPTER 5

### Resource Utilization of Three Grain Legume Species in a Semi-Arid Environment. II. Canopy Development, Radiation Interception and Radiation Use Efficiency

#### 5.1. Introduction

Under non-stressed environmental conditions, the amount of dry mass produced by a crop is linearly related to the amount of solar radiation (SR), specifically photosynthetically active radiation (PAR), intercepted by the crop (RI) (Monteith, 1977a; Gallagher and Biscoe, 1978; Russell *et al.*, 1989). The slope of the linear regression between biomass and cumulative radiation intercepted by a crop has been used to determine the radiation use efficiency (RUE) (e.g. Muchow *et al.*, 1993; Muchow and Sinclair, 1994; Ceotto and Castelli, 2002). This relationship is also employed to develop simple crop models. For example, Monteith (1977a) and Russell *et al.* (1989) expressed yield (Y) as a function of RI, RUE and harvest index (HI) as shown in equation 1.6.

Radiation interception is variable throughout the crop growing period (Sivakumar and Virmani, 1984; Watiki *et al.*, 1993) influenced mainly by the green leaf area duration and canopy extinction coefficient (K) (Thomson and Siddique, 1997; Jeuffroy and Ney, 1997). Many studies on grain legumes indicated the variability of K values for a given species resulting from the effect of environmental constraints (like drought) on its canopy through the modification of angle, spatial distribution and optical properties of leaves (Jeuffroy and Ney, 1997). These indicate that radiation interception and use are influenced by both genetic and environmental factors. Comparisons of species with respect to photosynthetic processes indicate that C<sub>4</sub> species have higher RUE than C<sub>3</sub> species, and within C<sub>3</sub> species non-leguminous C<sub>3</sub> species have higher RUE than leguminous species (Goss *et al.*, 1986). Large variation in RUE was also reported among grain legume species mainly due to a variety of environmental conditions (Sinclair and Muchow, 1999). Reductions in RUE due to water deficits have been reported in many studies on grain legumes (e.g. Hughes and Keatinge, 1983; Muchow, 1985a; Green *et al.*, 1985; Singh and Sri Rama, 1989).

RUE is a major component of the radiation-based crop growth models, which integrate several developmental, morphological, physiological, and biochemical processes at a higher level of plant functions (Turner *et al.*, 2001). Therefore, RUE can be used to

evaluate crop performance and yield limitations under different seasonal and climatic conditions (Sinclair and Muchow, 1999). Since the RUE of grain legumes (with low energy content) is lower than that of other non-leguminous C3 species (Sinclair and Muchow, 1999), further research is needed to investigate whether the reported low value is due to the inherent characteristic of these species or the result of environmental effects. Moreover, little information on the radiation interception and use of grain legumes are available for the semi-arid regions in Ethiopia where drought is a major crop yield limiting factor. This study was, therefore, initiated to compare radiation capture and utilization in common bean (*Phaseolus vulgaris* L.), chickpea (*Cicer arietinum* L.) and cowpea (*Vigna anguiculata* L.) grown under different water regimes at a semi-arid region in Ethiopia.

## **5.2. Materials and Methods**

### **5.2.1. Field experiments**

Detail explanations of the experimental site, experimental material, experimental design, cultural practices and irrigation schedule are given in Chapter 3 and will only be explained here in brief. Three field experiments were conducted at Dire Dawa, Ethiopia during the periods from early December 2001 to late March 2002 (first season), from late March to early July 2002 (second season) and from mid October 2002 to early February 2003 (third season). Radiation data was collected in the second and third seasons only. Seeds of common bean (cv. Roba-1), chickpea (cv. ICC-4958) and cowpea (cv. black eye bean) were planted on March 27, 2002 and October 17, 2002 for the second and third seasons, respectively. The experiments had three water regime treatments as shown in Table 3.1. The experimental treatments, replicated three times, were arranged in a randomized split plot design using the stress treatments as main plot and the crop species as sub-plot. The total experimental area was 22.8 m x 40.2 m.

### **5.2.2. Experimental measurements**

Incident and transmitted PAR (0.4 to 0.7  $\mu\text{m}$  wavelength) were measured using the SunScan Canopy Analysis System, BF2 type (Delta-T Devices, U.K.) at 10 day intervals from 17 and 20 days after planting (DAP) in the second and third seasons, respectively until physiological maturity. The instrument has a single quantum sensor and a one-meter long probe with 64 photodiodes equally spaced along its length. While the former measures

incident PAR above the canopy, the latter measures transmitted PAR beneath the canopy placed at right angle to the crop rows on the soil surface. The PAR measurement was taken between 12:00 to 13:30 local time (GMT+3) for a period of about 5 minutes in each plot.

In the second season, daily total incident SR was determined using the Ångström's equation (Ångström, 1924) as:

$$SR = SR_o (a + b n/N) \quad (MJ \text{ m}^{-2} \text{ d}^{-1}) \quad (5.1)$$

where  $SR_o$  is extraterrestrial radiation ( $MJ \text{ m}^{-2} \text{ d}^{-1}$ ),  $N$  is maximum possible sunshine duration (hour),  $n$  is measured sunshine duration (hour) and  $a$  and  $b$  are constants. The data for  $n$  was obtained from the class A weather station at Dire Dawa International Airport (latitude  $9^{\circ}36' \text{ N}$ , longitude  $41^{\circ}51' \text{ E}$ , and altitude 1260m above sea level; 500m away from the experimental area). In the third season, SR was measured by an automatic weather station (CM10, Campbell Scientific, USA) installed adjacent to the experimental field. The measured SR and  $n$  in 2002/2003 were used to determine  $a$  and  $b$  for the experimental site. The values of  $a$  and  $b$  found by a linear regression of  $SR/SR_o$  vs  $n/N$  were 0.212 and 0.479 respectively with  $R^2 = 0.94$ . These figures are very close to the values recommended by Allen *et al.* (1998) for areas where measured SR data is not available. Daily PAR was determined by multiplying the value of SR by 0.5 (Campbell and Norman, 1989; Monteith and Unsworth, 1990). Cumulative intercepted PAR for each plot was calculated by multiplying daily PAR by the value of the fractional interception ( $F$ ) obtained on each measurement date and by the slope of the regression line ( $F$  versus time) for the period between measurement dates, and finally by summing up all the daily values in the season.

Above ground dry matter (ADM) was measured from five plants ( $0.2 \text{ m}^2$  area) per plot at intervals of 10 days starting at 17 and 20 DAP for the second and third seasons, respectively. The plant samples were separated into leaf, stem, pod and seed and dried in an oven for 72 hours at  $60^{\circ}\text{C}$ . After drying, each component was weighed separately and the total above ground dry matter was obtained by adding the weight of each component. Leaf area was measured throughout the growing period using a portable leaf area meter (Model CI-202, CID Inc., USA) from five plants per plot. Leaf area index (LAI) was calculated as the ratio of total leaf area to area of ground. The final harvest took place between Jun 7 and July 4 and between January 13 and February 5 in the second and the third seasons, respectively for the different treatments.

A linear regression of accumulated biomass versus cumulative PAR was used to calculate seasonal RUE. Canopy extinction coefficient ( $K$ ) was determined from the slope of the regression line between the natural logarithm of PAR transmission and leaf area index (LAI) (Monteith, 1965) assuming zero interception.

### 5.3. Results and Discussion

#### 5.3.1. Leaf area index and fractional PAR interception

The two growing seasons were characterized by similar pattern of LAI development (Fig. 5.1). The second season, however, had a higher peak than the third season. In all the species, maximum LAI was achieved between 50 and 60 DAP in the second season and between 60 and 70 DAP in the third season. Once the maximum value was attained, LAI declined in both seasons. However, the rate of LAI decline was not similar across the species; for example, the rate of LAI decline was faster in beans and cowpea than in chickpea in the C treatment. LAI development was similar among the water regimes until commencement of stress. Greater reduction in LAI was observed when the plants were stressed during the flowering period (MS). However, an increase in LAI was observed in beans for the MS treatment after the plants were re-watered and recovered from the stress in both seasons. This adjustment of canopy development is one type of developmental plasticity which is important for the crop to perform well in dry environments. The importance of developmental plasticity towards better adaptation to water deficits was reported for many crops, including beans (Singh and White, 1988), chickpea (Saxena *et al.* 1993a), and groundnut (Harris *et al.*, 1988). Compared to the MS, the rate of LAI decline due to water stress was faster in the LS treatment in all species and seasons mainly due to the shedding of leaves. Muchow *et al.* (1993) reported high rate of leaf shedding and decline of specific leaf nitrogen in soybean, mungbean and cowpea under rainfed condition. Comparison of species indicated that beans had the highest maximum LAI in both seasons followed by cowpea and chickpea in that order.

Seasonal fractional PAR interception ( $F$ ) was similar over the two seasons (Fig. 5.2). The fraction of PAR intercepted in the MS treatment never reached the same maximum value as the C treatment, and the difference was slightly higher in the second than in the third season. However, compared to the MS treatment, the difference in fractional PAR interception between the C and LS treatments was small, indicating that water stress in early reproductive stage is more important in reducing the fraction of PAR intercepted by the respective crops

than in late reproductive stage. Fractional PAR interception was positively correlated with LAI ( $r = 0.78^*$  to  $0.98^{**}$ ) in all species and treatments in both seasons. Therefore, the low

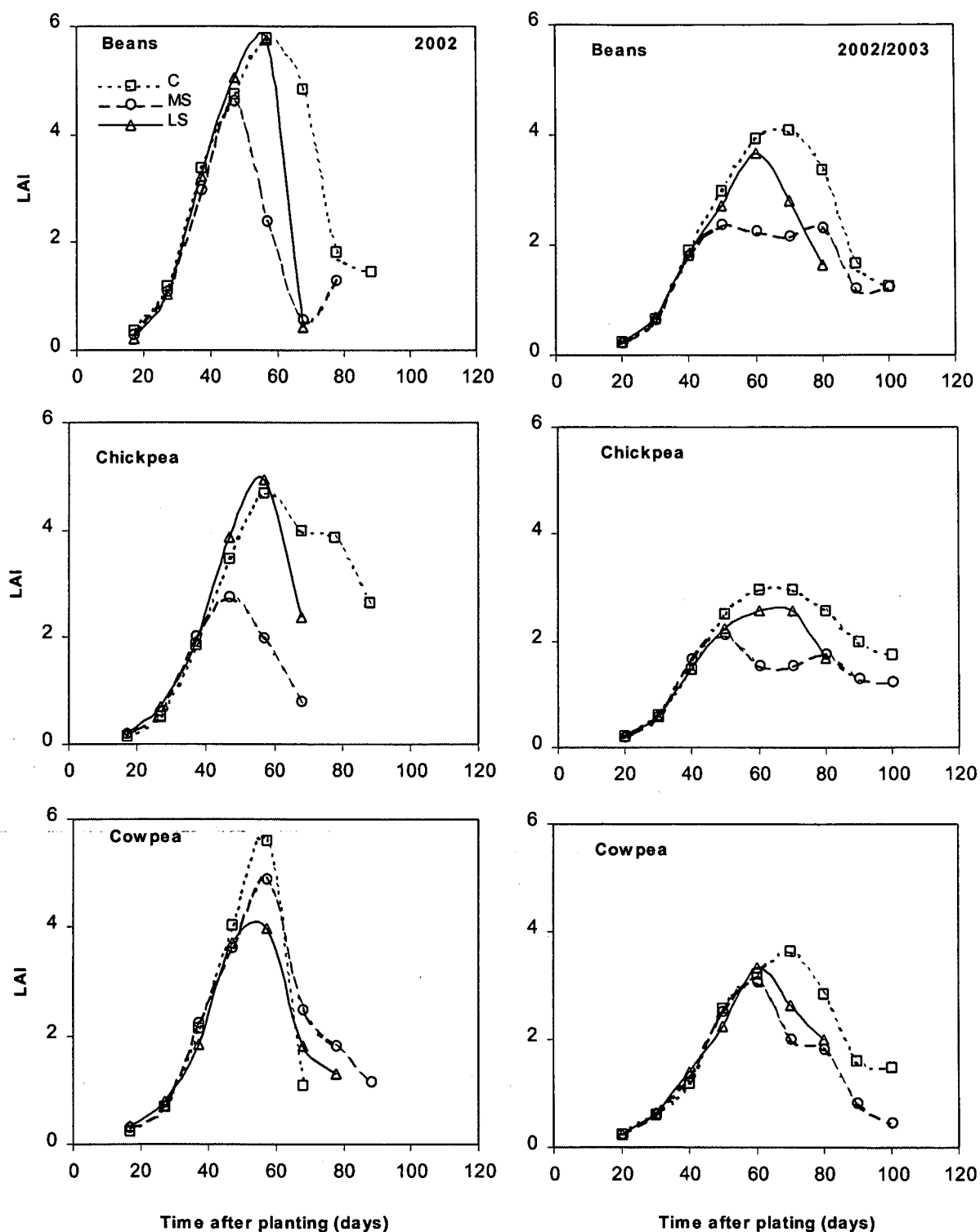


Figure 5.1. Seasonal course of leaf area index (LAI) in beans, chickpea and cowpea under mid-season (MS) and late season (LS) water stresses and well-watered (C) conditions in 2002 (left) and 2002/2003 (right) seasons.

fraction of PAR intercepted in the MS treatment could be attributed to the effect of water stress on leaf area development (Lecoeur *et al.*, 1995; Blum, 1996) and canopy extinction coefficient (Jeuffroy and Ney, 1997). Since dry matter production is linearly related to PAR interception, low post-flowering dry matter production in the MS treatment (Chapter 3) is mainly attributed to low PAR interception.

### 5.3.2. Canopy extinction coefficient

The fitted regression lines between the natural logarithm of transmitted PAR and LAI are shown in Fig. 5.3 (combining the two seasons). The regression lines were forced through the origin assuming that  $I = I_0$  when LAI = 0. The slopes of the regression lines were tested for similarity using the t-test. The K values were generally higher in the non-stressed than in the stressed treatments and in the third than in the second season (data not shown). The K values for beans, chickpea and cowpea in the C treatment were found to be 0.84, 1.02, and 0.86, respectively (Fig. 5.3). As compared to the C and LS treatments, the MS treatment resulted in the lowest values of K (0.45, 0.63 and 0.53 for bean, chickpea and cowpea, respectively). Intermediate values of K between the C and MS treatments were recorded in the LS treatment. In comparing the species under well-watered conditions, chickpea had the highest K value followed by cowpea and beans. K is a function of leaf size and orientation (Saeki, 1960) ranging from 0.3 to 1.3 where K less than 1 refers to non-horizontal or clumped leaf distributions and K greater than 1 refers horizontal or regular leaf distributions (Szeicz, 1974, Jones, 1992). In the present study, therefore, chickpea had more horizontal leaves than beans and cowpea in the C treatment.

There was significant difference in K between C and MS and between MS and LS for beans (Table 5.1). As shown in Table 5.1, difference between C and MS was also significant ( $P < 0.05$ ) in chickpea and cowpea whereas differences between C and LS and between MS and LS were not significant ( $P > 0.05$ ). The lower values of K recorded in the MS treatment could be attributed to the modification of leaf angle and orientation by the water deficit (Jeuffroy and Ney, 1997). The values of K observed in the C treatment are higher than previous reports on beans (0.4 by Gardner *et al.*, 1979 and 0.64 by Tusbo *et al.*, 2001), chickpea (0.4-0.61 by Hughes *et al.*, 1987), pea (0.33-0.49 by Heath and Hebblethwaite, 1985) but within the range of values reported by Thomson and Siddique

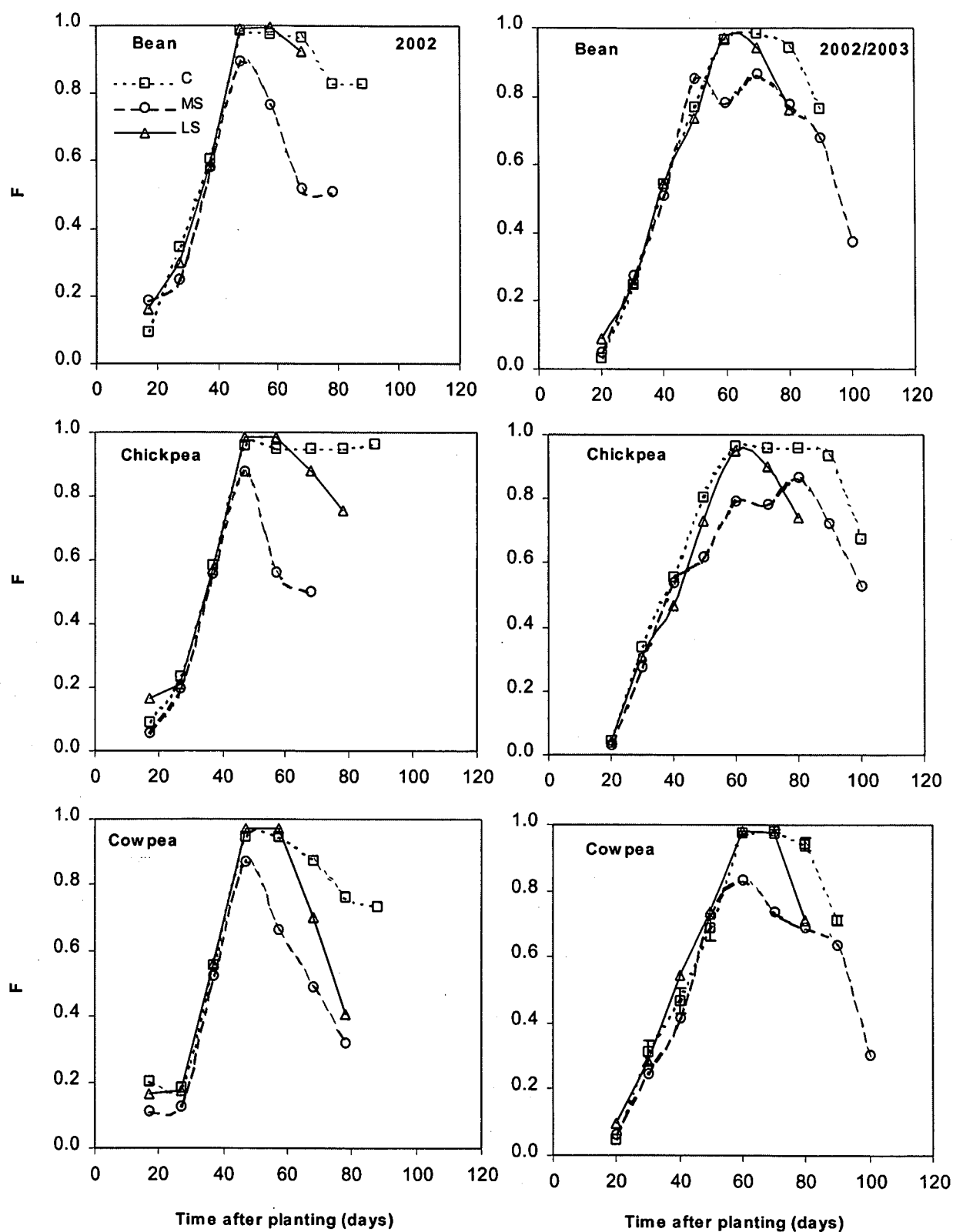
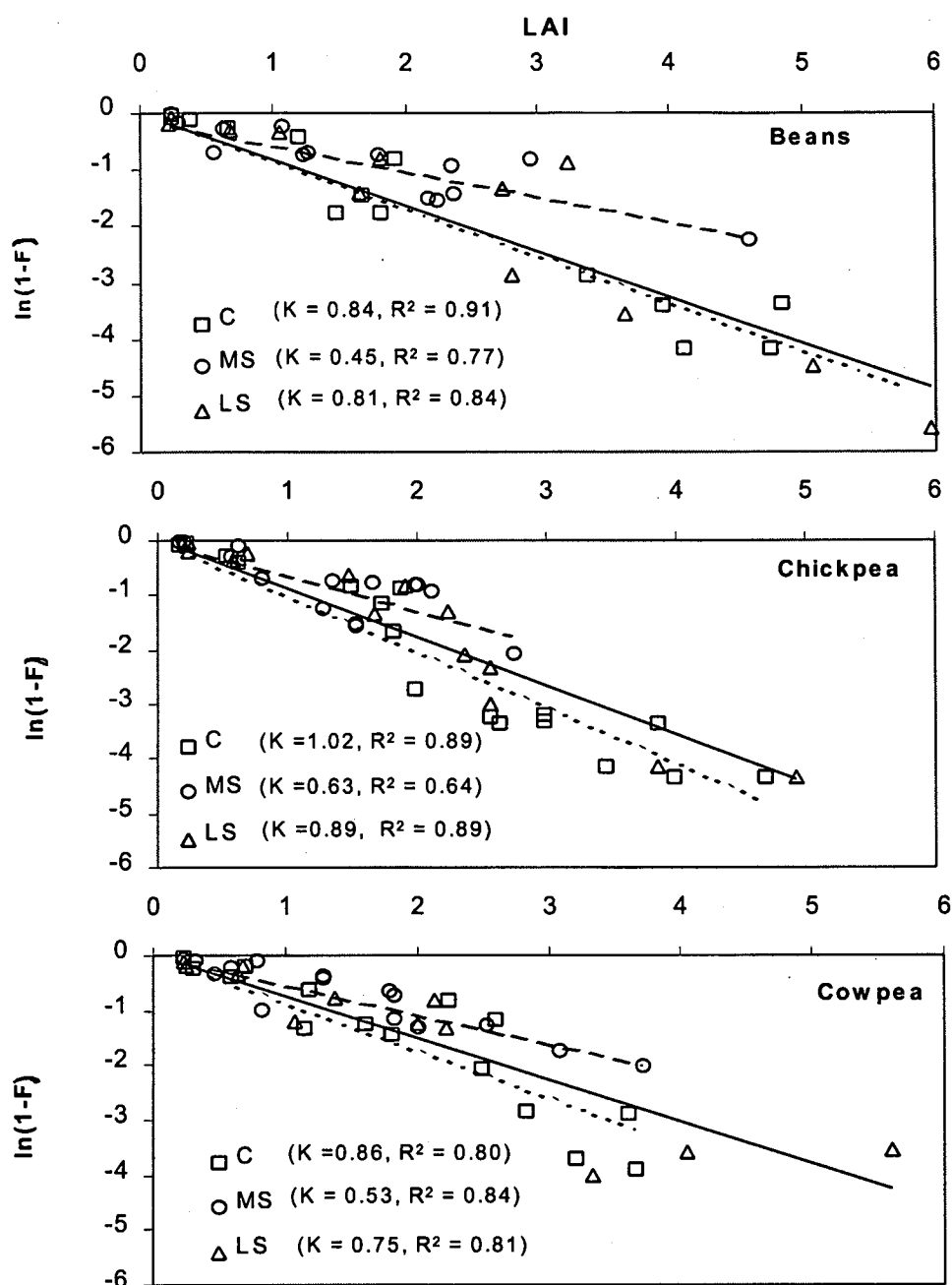


Figure 5.2. Measured fraction of PAR intercepted ( $F$ ) in beans, chickpea and cowpea under mid-season (MS) and late season (LS) water stress and well-watered (C) conditions during 2002 (left and 2002/2003 (right) seasons.





**Figure 5.3. Illustration of canopy extinction coefficient (K) for beans, chickpea and cowpea under mid-season (MS ---) and late season (LS —) water stress and well-watered (C —) conditions for data combined over two seasons (LAI = leaf area index, F = fractional PAR interception).**

(1997) for many grain legumes. The previously reported K value for cowpea was 0.93 (Varlet-Grancher and Bonhomme, 1989 in Jeuffroy and Ney, 1997) which is higher than the value found in this study. As indicated in some reports (Jeuffroy and Ney, 1997; Thomson and Siddique, 1997), K varies depending on environmental differences such as water deficit and season and crop species.

**Table 5.1. Test of homogeneity of regression coefficients for K and RUE pooled over the two seasons.**

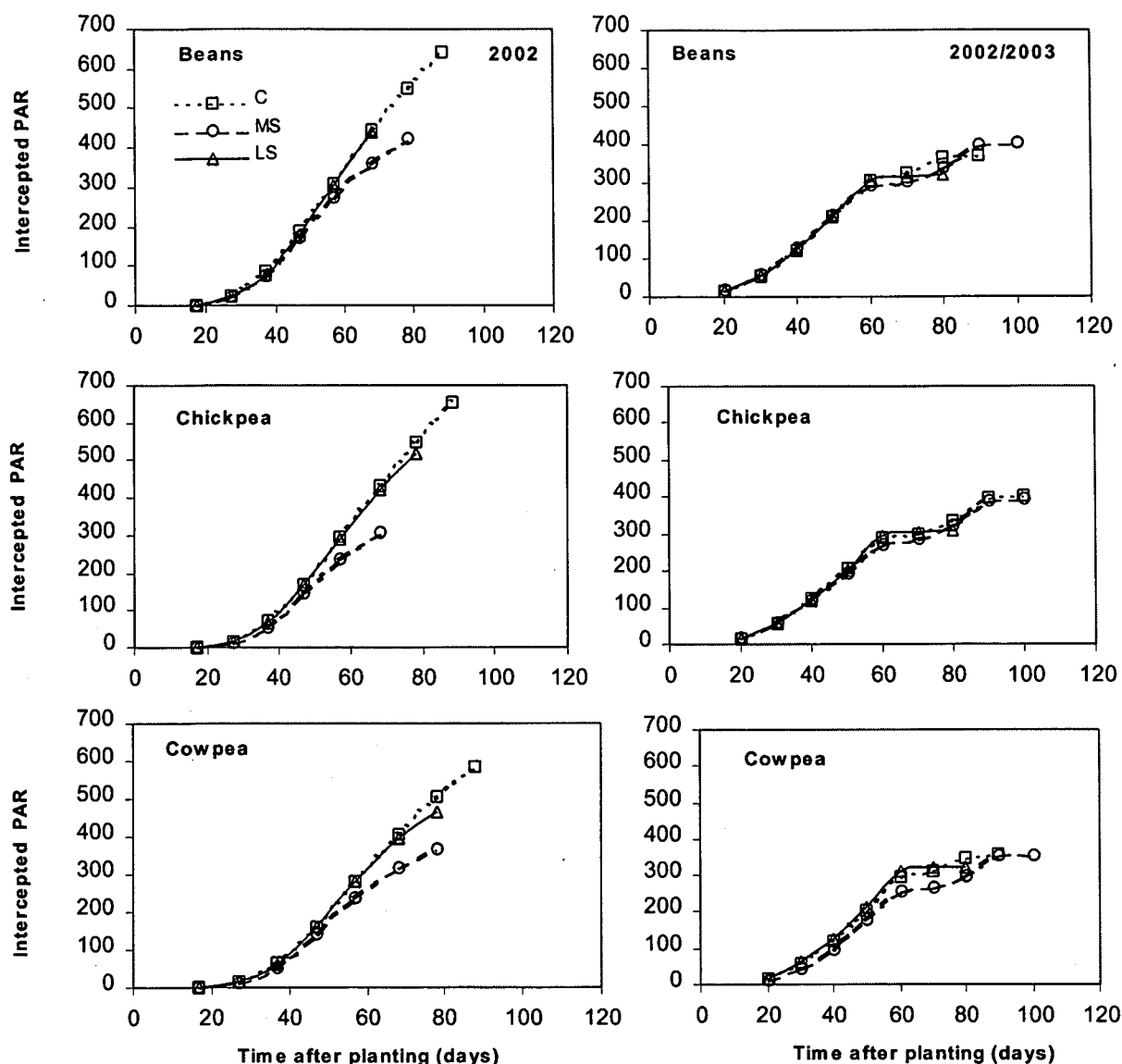
Species	Water regime	K*	RUE (g MJ <sup>-1</sup> )*
Bean	C	a	a
	MS	b	b
	LS	a	ab
Chickpea	C	a	a
	MS	b	b
	LS	ab	ab
Cowpea	C	a	a
	MS	b	a
	LS	ab	a

\* Similar letters within species in a column are not significant ( $P > 0.05$ ). Values are shown in the respective graphs.

Compared to the respective controls, the highest reduction in K (46%) was observed for beans in the MS treatment whereas the reduction in chickpea and cowpea was similar (38%). The lowest value of K in the MS treatment showed better canopy adjustment (such as leaf movement) of the crops in response to water deficit which is an important mechanism by which grain legumes adapt to drought stress (Begg, 1980). Unlike the MS treatment, however, beans had higher K value in the LS treatment when compared with chickpea and cowpea indicating its poor leaf adjustment to water deficit occurring late in the season. Such differences among species in canopy adjustment to the timing of water stress suggest that K could be used as a selection criterion in grain legumes to identify cultivars that are capable of adjusting their canopy in response to water deficit at different stages of growth.

### 5.3.3. Dry matter production and interception of PAR

As shown in Chapter 3, above ground dry matter (ADM) production was higher in 2002/2003 than in 2002 season because of longer growing period in the third season. Under non-limiting water conditions, ADM production was similar for all species in the second season but it was higher for beans and cowpea in the third season. In all the species, ADM increase was fastest during the initial exponential growth phase, as expected, and declined towards the end of the growing season under well-watered conditions. Compared to the C treatment, ADM production was severely affected by the MS treatment in all of the species in both seasons (Chapter 3). Reduction in ADM due to the LS treatment was variable between species and seasons. The reduction in ADM of beans and chickpea due to the LS was higher in the third season than in the second season, in contrast the reduction in cowpea was smaller in the third season than in the second season (Appendix 4B & C).



**Figure 5.4.** Seasonal cumulative intercepted PAR ( $\text{MJ m}^{-2} \text{ day}^{-1}$ ) in beans, chickpea and cowpea under mid-season (MS) and late season (LS) water stress and well-watered (C) conditions in 2002 (left) and 2002/2003 (right) seasons.

Seasonal changes in PAR intercepted by the species are presented in Fig. 5.4. The cumulative intercepted PAR was higher in the second than in the third season. The increase in cumulative PAR in the C treatment after 60 DAP in 2002/2003 was not as fast as in 2002 because of a long period (>20 days) of cloudy weather that reduced the incoming radiation and thereby hindered photosynthesis and canopy growth.

There was no significant difference in the PAR intercepted between the C and LS treatments in all the species and both seasons. Although an increase in cumulative PAR interception was observed after re-watering of the MS treatment in the third season, the cumulative

intercepted PAR was slightly lower than that of the C treatment in all the species and in both seasons. The cumulative intercepted PAR was higher in 2002 than in 2002/2003 season and significantly correlated with F in the third season ( $r = 0.83^*$  to  $0.96^{**}$ ). However, there was poor correlation between incident PAR and the seasonal cumulative PAR intercepted in both seasons. This agrees with the result by Thomson and Siddique (1997) in which differences among crops in PAR interception is not a function of the length of time that crops intercept radiation.

#### 5.3.4. Radiation use efficiency

RUE of the C treatment was higher in the second season than in the third season (Fig. 5.5). In the LS treatment, the RUE values were higher in the second season than in the third season whereas the values for the MS treatment were variable among species and seasons. So, the best fit of the linear regression was obtained by pooling the data of the two seasons (Fig. 5.5). The RUE values for the C treatment were higher than those for the MS and LS treatments. Under non-limiting water conditions, the RUE was 2.44 (1.22), 2.07 (1.04) and 2.16 (1.08) g MJ<sup>-1</sup> PAR (SR, values in brackets) for beans, chickpea and cowpea, respectively (Fig. 5.5). Beans, chickpea and cowpea had the RUE values of 2.00 (1.00), 1.68 (0.84), and 1.80 (0.90) g MJ<sup>-1</sup> PAR (SR) respectively in the LS treatment. The values in the LS treatments were not significantly different ( $P > 0.05$ ) from the values recorded in both the C and LS treatments in beans and chickpea (Table 5.1). As compared to well-watered conditions, water stress during the flowering period resulted in significantly lower ( $P < 0.05$ ) RUE values in beans and chickpea but not in cowpea (Table 5.1). The figures in the MS treatment were 1.50 (0.75), 1.45 (0.73) and 1.59 (0.80) g MJ<sup>-1</sup> PAR (RS) for beans, chickpea and cowpea, respectively (Fig. 5.5). RUE was not significantly affected by any of the treatments in cowpea (Table 5.1). Although the values were not significantly different from each other ( $P > 0.05$ ), beans had the highest RUE, followed by cowpea and chickpea in that order under well-watered conditions.

The maximum RUE values found in this study are slightly higher than the range of values (in g MJ<sup>-1</sup> SR) reported for several grain legumes in different environments, including 0.30-0.93 for chickpea (Hughes *et al.*, 1987; Singh and Sri Rama, 1989; Leach and Beech, 1988), 0.15-0.78 for beans (Tsubo *et al.*, 2003), 0.72 for pea (Martin *et al.*, 1994), 0.92 for mung bean (Muchow and Charles-Edwards, 1982), 0.96 for lentil (McKenzie and Hill, 1991), 0.58 for lupin (Gregory and Eastham, 1996) and 0.41-0.99 for various grain legumes, including

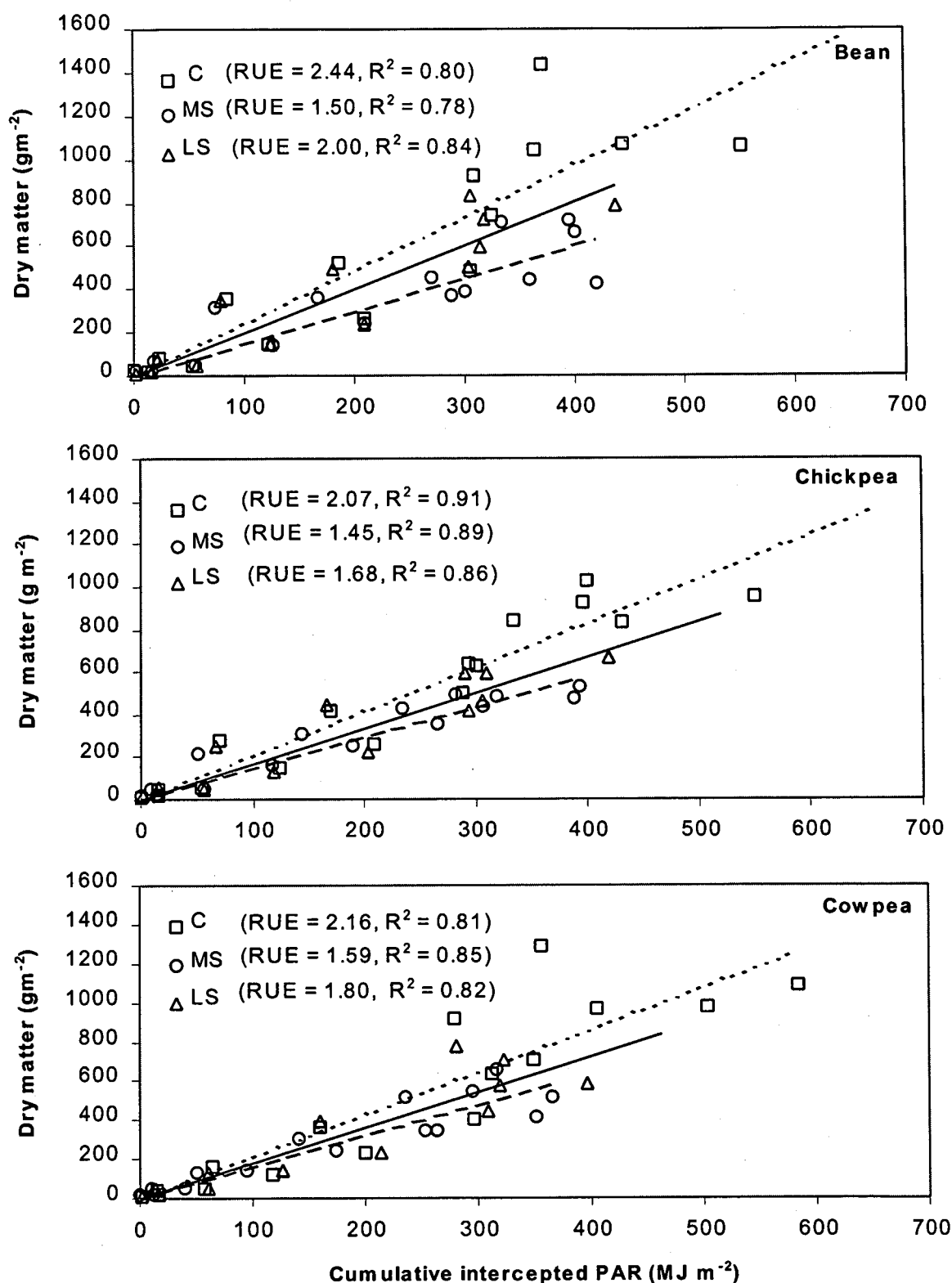


Figure 5.5. Radiation use efficiency (RUE, g MJ<sup>-1</sup>) of beans, chickpea and cowpea under mid-season (MS ---) and late season (LS —) water stress and well-watered (C —) conditions for data combined over two seasons.

chickpea, lentil, faba bean, pea, and some others (Thomson and Siddique, 1997). However, the present maximum values ( $\text{g MJ}^{-1} \text{SR}$ ) are within the range of other reports for groundnut (1.02-1.37, Bell *et al.*, 1987; Marshall and Willey, 1983), cowpea (1.09, Muchow *et al.*, 1993), pigeon pea (1.23, Hughes and Keatinge, 1983), pea (0.96-1.46, Heath and Hebblethwaite, 1985) and faba bean (2.04, Fasheun and Dennet, 1982). Variations in the reported RUE values among experiments could be due to differences in crop variety and other environmental factors.

As summarized in Sinclair and Muchow (1999), the maximum RUE values ( $\text{g MJ}^{-1} \text{SR}$ ) reported for C4 species were 2.00, 1.77 and 1.40 for sugarcane, maize and sorghum respectively and for non-leguminous C3 species were 1.75, 1.56, 1.46, 1.39, and 1.30 for potato, sunflower, wheat, rice and barley respectively. Therefore, the values for cereals and non-legume C3 species are higher than the maximum values reported for grain leguminous species (Sinclair and Muchow, 1999) including those found in present study.

Relative to well-watered conditions, reduction in RUE due to water stress in the flowering period was 39, 30 and 26% in beans, chickpea and cowpea respectively. Reduction in RUE under water stress conditions was also reported for many grain legumes such as soybean, cowpea and other grain legumes (Muchow, 1985a), chickpea (Singh and Sri Rama, 1989), beans (Ogindo, 2003), faba bean (Green *et al.*, 1985), pea (Keatinge *et al.*, 1985; Heath and Hebblethwaite, 1985) and pigeon pea (Hughes and Keatinge, 1983). This could be due to the depressing effects of water deficit on leaf photosynthesis, such as high leaf temperature, leaf senescence, stomatal closure, restricted leaf expansion, and poor leaf area development. The latter two mostly apply to the MS treatment. Therefore, the magnitude of reduction in RUE in grain legumes can be dependent on the growth stages at which the stress is imposed, and its severity.

#### 5.4. Conclusion

The results from the present study indicate that dry matter production is highly associated with the fraction of PAR intercepted, which in turn is highly and positively correlated with green LAI. Therefore, species that intercept a large fraction of the PAR are important in the dry environments. Under non-limiting water supply, the efficiency of radiation conversion into dry matter is comparable in the three species, indicating the conservative nature of RUE in grain legumes under well-watered conditions. The RUE values found in the present study

are within the range of previous reports, confirming that low RUE in grain legumes could be the inherent characteristics of these species. RUE is more sensitive to water stress during early than late stage reproductive period in some species (e.g. beans and chickpea) while it is not significantly affected by any of the stress treatments in others (e.g. cowpea). This species variability could be exploited in a crop breeding programme to develop cultivars that have stable RUE under variable soil water conditions in dry environments. Although a high K value under well-watered conditions is important for high F and RUE, species with high K values during early stage reproductive water stress have low RUE, suggesting the importance of canopy modification in response to water deficits (which helps decrease leaf temperature) in grain legumes to maintain photosynthesis and RUE in dry environments. The information obtained from this study will be valuable in developing radiation-based crop growth models suitable for the dry areas.

## CHAPTER 6

### Comparative Water Relations, Leaf Gas Exchange and Assimilation of Three Grain Legumes Under Water Deficit

#### 6.1. Introduction

Water shortage is a major constraint to crop production as crops are usually exposed to drought periods of varying duration and intensity during their growth (Sadras and Milroy, 1996), particularly in the semi-arid regions of the world (Squire, 1990). Semi-arid climates are characterized by fluctuating rainfall both in amount and distribution, and plants grown under these climates are prone to frequent atmospheric drought, even when the soil water reserves are adequate (Maroco *et al.*, 1997). Grain legumes are grown under rainfed conditions in the semi-arid tropical regions and their yield depends on the amount of water transpired and the seasonal pattern of soil water availability (Adams *et al.*, 1985; Rachie, 1985; Turk *et al.*, 1980b, Cooper *et al.*, 1988). Because of the erratic nature of the rainfall during the season, these crops can experience intermittent or continuous water deficits during their growth.

When plants are exposed to water deficits, they often exhibit physiological responses that can result in adaptation to the environment. The plants that are usually grown under dry environments have evolved their own adaptation strategies which can be categorized as drought escape, dehydration postponement and dehydration tolerance (Levitt, 1980; Turner, 1986; Laffary and Louguet, 1990; Turner, 1991; Turner *et al.*, 2001). "Escaping" drought involves completion of the life cycle after a significant rainfall and before the onset of the drought period. Dehydration postponement involves maintenance of plant water status in the presence of environmental drought (drought avoidance) while dehydration tolerance involves maintenance of plant function in the presence of drought (drought tolerance). Both these include whole plant mechanisms that provide the plant with the ability to respond and survive drought (Turner, 1986; Blum, 1988; Laffary and Louguet, 1990; Turner, 1991). Therefore, different plant responses induced by drought should reflect the different adaptations, or the lack of them.

Plant productivity generally depends on the rate of CO<sub>2</sub> assimilation (Srivasta and Strasser, 1996; Costa Franca *et al.*, 2000), and transpiration, which serves as a major cooling mechanism for plant leaves through the evaporation process (Jalali-Farahani *et al.*, 1993). Stomatal pores act as the exchange pathway for both CO<sub>2</sub> and H<sub>2</sub>O between



the atmosphere and the plant cells and hence control the rate of photosynthesis and water use (Cowan and Troughton, 1971; Farquhar and Sharkey, 1982; Collatz *et al.*, 1991). Stomatal adjustment is one of the prominent examples of plant responses to drought, and stomata can be considered to be integrators of all environmental factors that affect plant growth (Morison, 1998). Stomata regulate water use and the development of water stress, and influence plant growth rates through effects on availability of CO<sub>2</sub> assimilation (e.g. Baldocchi *et al.*, 1985). Thus, stomatal responses to environmental drought have a substantial influence on plant adaptation in dry climates (Bates and Hall, 1982b).

Leaf water status and humidity of the air are reported to have a major influence on stomatal conductance in the field (Turner, 1991). Stomatal conductance usually decreases when plants are subjected to soil water deficits (Bates and Hall, 1982b; Lopez *et al.*, 1988), and differences in stomatal conductance in response to leaf water potential have been reported in many grain legumes (Lawn, 1982; Muchow, 1985b; Flower and Ludlow, 1986). Maintenance of stomatal conductance and photosynthesis during leaf water deficit has been associated with favorable seed yield in soybean genotypes (Solane *et al.*, 1990).

In general, water flow in the soil-plant-atmosphere system is governed by differences in the water potential of the three systems and the resistances in the water flow pathway. The soil water potential usually determines the upper limit of leaf water potential while the lower limit is set by the combined action of atmospheric variables, soil water potential and the resistances to flow (Choudhury, 1985). Therefore, proper understanding and modelling of plant processes and reactions to water deficit requires the determination of the quantitative relationships between soil-plant water relations, growth, gas exchange and assimilation rate (Ritchie, 1981; Sadras and Milroy, 1996). Thus, actual plant responses to soil water deficit in the field can be obtained by a simultaneous study of soil and plant water status, stomatal resistance and its effect on gas exchange and assimilation. Several studies have attempted to understand the different response of grain legumes to water deficits under controlled and some field conditions (Sinclair and Ludlow, 1986; Muchow, 1985b; Lawn 1982; Angus *et al.*, 1983; Turk *et al.*, 1980a,b; Parson and Howe, 1984; Markhart, 1985; Kupperts *et al.*, 1988; Vasquez-Tello *et al.*, 1990; Cruz de Carvalho *et al.*, 1998; Leport *et al.*, 1998; 1999). Next to pigeonpea, many studies indicate cowpea as a drought tolerant crop among grain legumes (Sinclair and Ludlow, 1986; Vasquez-Tello *et al.*, 1990; Cruz de Carvalho *et al.*, 1998) while beans is

considered to be susceptible (Vasquez-Tello *et al.*, 1990; Cruz de Carvalho *et al.*, 1998). Chickpea is also considered as a drought tolerant crop among the cool-season food legumes (Singh, 1993; Leport *et al.*, 1999). However, the underlying physiological responses of these three species have not been investigated in the field under the same seasonal, environmental and experimental conditions. Knowledge of a particular response by each species under the same conditions is important for evaluation and development of crop simulation models, and to develop guidelines for crop choice for a specific environment in areas like Ethiopia where the species are grown in diverse environments with poor yield.

Therefore, the objective of this investigation was to determine and compare the relationship between soil water, leaf water potential, stomatal resistance, rate of photosynthesis and transpiration in common bean (*Phaseolus vulgaris* L.), chickpea (*Cicer arietinum* L.) and cowpea (*Vigna anguiculata* L. Walp) under water stressed and non-stressed conditions during the reproductive stages in the field under a semi-arid environment.

## **6.2. Materials and Methods**

### **6.2.1. Field experiments**

Descriptions of experimental site, agronomic information, irrigation schedule, experimental layout and treatments and weather conditions during the experimental periods are given in Chapter 3. Except leaf water potential, all physiological data were collected in the 2002 and 2002/2003 seasons only.

### **6.2.2. Measurements**

#### **6.2.2.1. Soil water**

The soil water content to a depth of 300 mm in 2001/02 and 600 mm in 2002 and 2002/03 was monitored every day using Time Domain Reflectometry, TDR (Soil Moisture Equipment Corp., CA, USA) starting from planting. The available soil water during the measurement period was above 60% in the control plots while it reached up to the lowest 23% in the stressed plots.

### 6.2.2.2. Leaf water potential

Midday (12:00-14:00 local time) leaf water potential of the stressed and non-stressed plots for the three seasons was measured on upper fully exposed leaves of five plants per plot using a pressure chamber (PMS Instrument Company, Oregon, U.S.A) every other day throughout each stress period. The leaves were covered with a white polythene bag before excision and then water potential measurement of each leaf was completed within the next 2 minutes to avoid evaporative water loss that affects the readings.

### 6.2.2.3. Stomatal resistance

The stomatal resistance of the stressed and non-stressed plots was measured in parallel with the water potential measurement using diffusion porometer (Model AP4, Delta-T Devices Ltd. U.K) in 2002 and 2002/03 on similar leaves to those used for the water potential measurement. The measurement was made from three leaves per plant and five plants per plot giving a total of 15 measurements per plot. The abaxial surface of the upper fully expanded leaves was considered for this purpose. The measurement was made between 12:00-14:00 local time (GMT +3) every other day during each stress period. The porometer was calibrated regularly against a calibration plate depending on changes in relative humidity and temperature of the environment during the measurements dates.

### 6.2.2.4. Rate of photosynthesis and transpiration

Leaf gas exchanges and leaf temperatures were measured using an Infrared Gas Analyser, IRGA, Type LCA-4 (ADC Bio Scientific Ltd., U.K.) between 12:00-13:00 local time every other day during each stress treatment. The IRGA was recalibrated every week against a standard gas (compressed gas taken from unpolluted area with CO<sub>2</sub> concentration of 360 ppm) to obtain accurate readings of CO<sub>2</sub> within the acceptable range. The IRGA calculates the rate of photosynthesis ( $\mu\text{mol m}^{-2}\text{s}^{-1}$ ) from the measured parameters using the following equation:

$$A = u_s * \Delta c \quad (6.1)$$

where  $\Delta c$  is difference in CO<sub>2</sub> concentration through chamber ( $\mu\text{mol mol}^{-1}$ ) and  $u_s$  is mass flow of air per m<sup>2</sup> of leaf area ( $\text{mol m}^{-2} \text{s}^{-1}$ ).

Transpiration rate ( $\text{mmol m}^{-2} \text{s}^{-1}$ ) was also calculated as

$$E = u_s * \Delta w \quad (6.2)$$

E is leaf transpiration rate;  $\Delta w$  is the difference in water vapour concentration ( $\text{mmol mol}^{-1}$ ) within and out of the chamber.

#### 6.2.2.5. Diurnal measurements

Diurnal measurements of leaf water potential, stomatal resistance, and gas exchange were made in the third season on 10 December 2002 for chickpea and 16 December 2002 for beans and cowpea on stressed and non-stressed plots of each species. Leaf water potential was measured from 6:00 to 18:00 local time while the other measurements were made from 6:00 to 16:00 because of the low level of daylight at 18:00 during the measurement periods. The measurements were taken from the upper two fully expanded leaves of five randomly selected plants per plot.

#### 6.2.3. Data analysis

Mean and standard error calculations and t-tests were made using Number Cruncher Statistical System, NCSS 97 (Hintze, 1997). Correlation and regression analyses were performed using MINITAB for Windows, release 12.21 (Minitab Inc., 1998). Some linear regressions were also fitted using Microsoft Excel (Microsoft Corporation). The increase or decrease of parameters with time was determined by linear regression. Threshold (cutoff) values for a given variable were calculated as intersection point of two linear regression lines obtained from data points clustered based on similarity of trend.

### 6.3. Results and Discussion

#### 6.3.1. Leaf water potential ( $\psi_L$ )

The midday  $\psi_L$  under well-watered conditions remained above -1.50 MPa in beans, -1.58 MPa in chickpea and -1.25 MPa in cowpea during all the seasons (Tables 6.1, 6.2 & 6.3). The values observed under well-watered conditions in the present study are lower than the value (-0.6 MPa) reported for six unstressed cool-season grain legumes including chickpea in a Mediterranean-type environment (Leport *et al.*, 1998). The midday  $\psi_L$  recorded at the end of the stress treatments never fell below -1.70 and -1.60 MPa in beans and cowpea, respectively, and the range of variations in  $\psi_L$  between the control and stressed plants were small in these two species. This agrees with previous observations made by Bates and Hall (1982a), Turk *et al.*, (1980b), Nwalozie and Annerose (1996) and Diallo *et al.* (2001) for cowpea. The lowest midday  $\psi_L$ , which ranged from -3.98 to -3.02

MPa between the three seasons, was recorded for chickpea (Tables 6.1, 6.2 & 6.3). Midday  $\psi_L$  values of less than -3.0 MPa were also reported for water stressed chickpea in a Mediterranean-type environment (Leport *et al.*, 1998; 1999). Relative to the controls, the average decline in  $\psi_L$  was 3.4, 7.7, and 4.8% per day in the MS treatments and 1.6, 10.1, and 2.8% per day in the LS treatments in beans, chickpea and cowpea, respectively. Therefore, the relative rate of leaf water potential decline due to water deficit is faster in chickpea than in beans and cowpea. The fastest decline in chickpea could be attributed to its slower and lower stomatal adjustment relative to the decline in  $\psi_L$  as explained below.

**Table 6.1. Leaf water potential (MPa) of three grain legume species under well-watered (C) and water stressed conditions during flowering (MS) and pod filling (LS) periods in the 2001/2002 season.**

Species and water regime treatments													
DAW*	BN		CHP		COP		DAW	BN		CHP		COP	
	C <sup>a</sup>	MS	C	MS	C	MS		C	LS	C	LS	C	LS
8	-1.28 (0.05)	-1.57 (0.02)	-1.17 (0.07)	-1.92 (0.04)	-1.09 (0.01)	-1.10 (0.02)	3					-1.19 (0.04)	-1.10 (0.02)
10	-1.34 (0.03)	-1.67 (0.02)	-1.51 (0.07)	-2.45 (0.07)	-1.10 (0.02)	-1.15 (0.04)	6	-1.23 (0.03)	-1.54 (0.01)	-1.49 (0.01)	-2.11 (0.05)	-1.17 (0.02)	-1.30 (0.04)
14	-1.38 (0.02)	-1.68 (0.02)	-1.55 (0.03)	-2.93 (0.02)	-1.19 (0.04)	-1.27 (0.02)	8	-1.36 (0.04)	-1.57 (0.05)	-1.24 (0.08)	-3.62 (0.10)	-1.19 (0.04)	-1.34 (0.01)
16	-1.30 (0.02)	-1.69 (0.06)	-1.58 (0.05)	-3.72 (0.18)	-1.19 (0.47)	-1.27 (0.04)	10	-1.39 (0.03)	-1.68 (0.05)	-1.42 (0.05)	-3.70 (0.16)	-1.15 (0.03)	-1.37 (0.02)
19+	-1.36 (0.04)	-1.25 (0.00)	-1.24 (0.08)	-1.55 (0.10)	-1.21 (0.19)	-1.28 (0.12)	12	-1.28 (0.06)	-1.64 (0.04)	-1.29 (1.02)	-3.89 (0.11)	-1.24 (0.02)	-1.37 (0.02)
22+	-1.39 (0.03)	-1.28 (0.07)	-1.42 (0.05)	-1.55 (0.00)			15	-1.29 (0.05)	-1.60 (0.04)	-1.29 (0.09)	-3.98 (0.12)	-1.24 (0.01)	-1.38 (0.02)

\* DAW= days after withholding water, + = measurement after re-watering

<sup>b</sup> Numbers in parenthesis refer to standard error of means.

**Table 6.2. Leaf water potential (MPa) of three grain legume species under well-watered (C) and water stressed conditions during flowering (MS) and pod filling (LS) periods in the 2002 season.**

DAW	Species and water regime treatments											
	BN			CHP			BN	CHP	COP	BN	CHP	COP
	C <sup>b</sup>	MS	C	MS	C	MS						
4	-1.34 (0.04)	-1.44 (0.04)	-1.52 (0.10)	-2.34 (0.04)	-1.25 (0.07)	-1.48 (0.03)	-1.28 (0.03)	-1.47 (0.04)	-1.53 (0.02)	-1.73 (0.02)	-1.15 (0.06)	-1.32 (0.03)
6	-1.26 (0.02)	-1.45 (0.04)	-1.53 (0.04)	-2.44 (0.08)	-1.19 (0.05)	-1.38 (0.04)	-1.18 (0.04)	-1.40 (0.03)	-1.27 (0.04)	-2.35 (0.09)	-1.10 (0.03)	-1.43 (0.04)
8	-1.20 (0.05)	-1.48 (0.02)	-1.55 (0.02)	-2.74 (0.07)	-1.20 (0.02)	-1.57 (0.04)	-1.23 (0.04)	-1.57 (0.04)	-1.35 (0.03)	-2.50 (0.15)	-1.07 (0.06)	-1.53 (0.02)
10	-1.15 (0.05)	-1.57 (0.04)	-1.52 (0.03)	-3.08 (0.12)	-1.05 (0.03)	-1.57 (0.04)	-1.33 (0.09)	-1.63 (0.02)	-1.55 (0.03)	-2.70 (0.03)	-1.02 (0.04)	-1.55 (0.03)
12	-1.07 (0.02)	-1.58 (0.03)	-1.53 (0.06)	-3.37 (0.10)	-1.02 (0.03)	-1.57 (0.02)	-1.33 (0.02)	-1.70 (0.03)	-1.61 (0.07)	-2.90 (0.03)	-1.13 (0.02)	-1.60 (0.03)

<sup>b</sup> Numbers in parenthesis refer to standard error of means.

**Table 6.3. Leaf water potential (MPa) of three grain legume species under well-watered (C) and water stressed conditions during flowering (MS) and pod filling (LS) periods in the 2002/2003 season.**

DAW	Species and water regime treatments											
	BN		CHP		COP		BN		CHP		COP	
	C <sup>a</sup>	MS	C	MS	C	MS	C	LS	C	LS	C	LS
2							-1.07 (0.03)	-1.12 (0.03)	-1.23 (0.02)	-1.23 (0.02)	-0.96 (0.02)	-1.00 (0.03)
4	-1.25 (0.02)	-1.23 (0.01)	-1.30 (0.02)	-1.37 (0.01)	-0.91 (0.02)	-0.95 (0.02)	-1.20 (0.03)	-1.18 (0.04)	-1.00 (0.03)	-1.20 (0.02)	-1.18 (0.04)	-1.18 (0.02)
6	-1.29 (0.02)	-1.30 (0.02)	-1.30 (0.02)	-1.76 (0.01)	-0.61 (0.02)	-1.10 (0.03)	-0.88 (0.07)	-1.12 (0.02)	-0.63 (0.07)	-1.28 (0.07)	-0.84 (0.04)	-0.92 (0.02)
8	-1.16 (0.02)	-1.38 (0.01)	-1.37 (0.01)	-2.11 (0.02)	-0.97 (0.02)	-1.20 (0.03)	-1.02 (0.02)	-1.13 (0.03)	-0.52 (0.04)	-1.48 (0.04)	-0.70 (0.05)	-0.85 (0.03)
10	-1.10 (0.01)	-1.43 (0.01)	-1.53 (0.03)	-2.37 (0.05)	-0.96 (0.02)	-1.35 (0.02)	-0.78 (0.02)	-1.05 (0.03)	-0.53 (0.02)	-1.28 (0.02)	-0.57 (0.04)	-1.02 (0.02)
12	-1.05 (0.02)	-1.49 (0.02)	-1.10 (0.02)	-2.45 (0.02)	-1.18 (0.04)	-1.50 (0.02)	-0.76 (0.02)	-1.07 (0.03)	-0.82 (0.04)	-1.17 (0.02)	-0.73 (0.04)	-0.87 (0.02)
14	-1.00 (0.02)	-1.59 (0.02)	-1.23 (0.03)	-2.57 (0.03)	-0.84 (0.04)	-1.46 (0.07)	-0.99 (0.07)	-1.21 (0.02)	-0.81 (0.06)	-1.55 (0.07)	-0.83 (0.03)	-1.05 (0.02)
16	-1.10 (0.03)	-1.62 (0.03)	-1.29 (0.04)	-3.02 (0.02)	-0.57 (0.04)	-1.53 (0.02)						
18	-1.07 (0.03)	-1.66 (0.02)										

<sup>a</sup> Numbers in parenthesis refer to standard error of means.

### 6.3.2. Stomatal resistance ( $r_s$ )

The  $r_s$  in the control plots ranged from 0.4 to 6.0 s cm<sup>-1</sup> in 2002 and 1.2 to 3.6 s cm<sup>-1</sup> in 2002/2003 during the measurement period (Tables 6.4 & 6.5). The maximum  $r_s$  at the end of the MS treatment was 12.5, 11.0, and 9.2 in 2002 and 16.5, 15.9, and 37.9 s cm<sup>-1</sup> in 2002/2003 in beans, chickpea and cowpea, respectively (Tables 6.4 & 6.5). The maximum  $r_s$  recorded in the LS treatment was 11.8, 10.4 and 9.3 in 2002 and 2.3, 2.6 and 3.0 s cm<sup>-1</sup> in the three species in the same order. Although both temperature and VPD were higher in 2002 than 2002/2003, the latter season had higher  $r_s$  values than the former in the MS treatment. This could be due to the effect of high temperature (in 2002) on the physiological mechanisms that control stomatal adjustment during water stress. On the other hand, the lower  $r_s$  values in the LS treatments in 2002/03 were due to low intensity of the stress because of cloudy weather (lower VPD, which ranged from 0.68 to 2.2 kPa compared to 2.4 to 4.2 kPa in 2002 for the same treatment period and lower temperature).

Although there was a significant difference in both midday  $\psi_L$  and  $r_s$  among the species in 2002/2003, there was no significant difference in the maximum  $r_s$  recorded at the end of

**Table 6.4. Stomatal resistance ( $s\text{ cm}^{-1}$ ) of three grain legume species under well-watered (C) and water stressed (S) conditions during flowering (MS) and pod filling (LS) periods in the 2002 season.**

DAW	Species and water regime treatments											
	BN		CHP		COP		BN		CHP		COP	
	C <sup>a</sup>	MS	C	MS	C	MS	C	LS	C	LS	C	LS
4	2.78 (0.05)	5.65 (0.25)	1.56 (0.09)	5.22 (0.36)	1.73 (0.11)	5.45 (0.40)	3.44 (0.15)	4.63 (0.30)	2.10 (0.09)	3.43 (0.18)	1.43 (0.08)	3.99 (0.24)
6	2.52 (0.13)	7.05 (0.37)	1.52 (0.22)	7.18 (0.86)	1.64 (0.013)	5.53 (0.37)	4.59 (0.35)	6.51 (0.40)	1.98 (0.13)	4.10 (0.36)	1.24 (0.09)	4.18 (0.44)
8	1.86 (0.20)	7.55 (0.39)	1.80 (0.12)	8.25 (0.61)	1.88 (0.09)	8.35 (1.00)	6.27 (0.37)	8.49 (0.34)	2.41 (0.13)	5.02 (0.29)	2.22 (0.16)	6.27 (0.47)
10	1.94 (0.09)	9.58 (0.64)	1.68 (0.09)	10.98 (1.35)	1.57 (0.08)	8.40 (1.06)	3.24 (0.27)	9.24 (0.88)	2.08 (0.24)	5.51 (0.89)	1.77 (0.15)	7.11 (0.52)
12	2.90 (0.14)	12.54 (0.69)	2.00 (0.15)	11.02 (1.41)	1.73 (0.04)	9.22 (1.13)	3.57 (0.28)	12.8 (0.77)	1.82 (0.10)	6.35 (0.74)	2.84 (0.20)	9.29 (0.88)

<sup>a</sup> Numbers in parenthesis refer to standard error of means.

**Table 6.5. Stomatal resistance ( $s\text{ cm}^{-1}$ ) of three grain legume species under well-watered (C) and water stressed (S) conditions during flowering (MS) and pod filling (LS) periods in the 2002/2003 season.**

DAW	Species and water regime treatments											
	BN		CHP		COP		BN		CHP		COP	
	C <sup>a</sup>	MS	C	MS	C	MS	C	LS	C	LS	C	LS
2							1.74 (0.21)	2.25 (0.17)	1.56 (0.10)	1.41 (0.08)	1.01 (0.11)	1.45 (0.09)
4	2.43 (0.18)	1.96 (0.13)	0.87 (0.23)	1.17 (0.10)	1.65 (0.18)	3.77 (0.34)	1.52 (0.38)	1.77 (0.31)	0.54 (0.13)	1.33 (0.22)	1.47 (0.29)	1.09 (0.36)
6	3.80 (0.40)	3.48 (0.48)	1.60 (0.13)	4.96 (0.60)	1.61 (0.18)	8.61 (0.92)	0.61 (0.04)	0.89 (0.12)	0.32 (0.02)	0.40 (0.02)	1.10 (0.24)	2.38 (0.54)
8	2.09 (0.22)	6.71 (0.53)	3.27 (0.19)	5.11 (0.56)	3.49 (0.52)	11.92 (2.01)	0.45 (0.06)	1.40 (0.21)	0.58 (0.04)	2.60 (0.45)	0.98 (0.16)	3.03 (0.34)
10	0.56 (0.03)	5.26 (0.50)	6.05 (0.06)	9.68 (1.69)	1.01 (0.11)	32.32 (8.13)	0.45 (0.02)	0.64 (0.06)	0.68 (0.05)	1.15 (0.06)	0.71 (0.05)	0.95 (0.05)
12	2.29 (0.25)	9.36 (0.23)	1.95 (0.06)	10.95 (1.63)	1.90 (0.29)	37.94 (12.77)	0.51 (0.07)	1.65 (0.10)	0.72 (0.09)	1.60 (0.20)	0.93 (0.12)	1.89 (0.31)
14	1.21 (0.04)	9.63 (1.85)	1.17 (0.07)	13.8 (2.92)	1.10 (0.24)	20.98 (4.00)	1.73 (0.38)	5.05 (0.79)	0.59 (0.09)	2.92 (1.06)	1.48 (0.13)	2.96 (0.26)
16	1.45 (0.12)	13.75 (1.86)	2.62 (0.31)	25.94 (6.31)	0.98 (0.16)	5.07 (0.35)						
18	2.40 (0.21)	16.54 (2.66)										

<sup>a</sup> Numbers in parenthesis refer to standard error of means.

MS treatment in 2002 despite significant differences in  $\psi_L$  among the species. Differences in  $r_s$  among species were not significant in the LS treatment in both seasons. Nevertheless, significantly higher  $r_s$  values in the stressed plants than in controls indicate the role of stomatal adjustment to the drought adaptation of grain legumes as reported in

other studies (Bates and Hall, 1982b; Baldocchi *et al.*, 1985; Trejo and Davies, 1991; Barradas *et al.*, 1994; Cruz de Carvalho *et al.*, 1998; Costa Franca *et al.*, 2000).

The trigger for stomatal closure (adjustment) under periods of water stress is reported to be associated with root-to-shoot communication via Abscissic acid (ABA) translocation in many crops (Davies *et al.*, 1990; Davies and Zhang, 1991; Ribaut and Pilet, 1991; Blum and Johnson, 1993) and decreases in hydraulic conductance of the soil-leaf continuum (Sperry, 2000). Relative to the respective control measurements, the reductions in A at the end of the LS treatment ranged from 61-81% in beans, 36-81% in chickpea and 48-66% in cowpea between the two seasons, and the average reduction rate during the whole stress period ranged from 3.5-4.3, 3.9-4.0 and 3.2-3.4 % per day, respectively. This shows that reduction in the rate of net photosynthesis is slightly higher and faster in the mid-season than in the late-season stressed grain legumes.

Fast closure of stomata (even before detection of leaf water deficit) has been measured in beans in response to soil water deficit (Trejo and Davies, 1991; Barradas *et al.*, 1994). Under severe water stress, complete stomata closure at lower  $\psi_L$  was reported in beans when compared to cowpea (Cruz de Carvalho *et al.*, 1998). However, cowpea has a better stomatal adjustment than beans by maintaining partial stomatal opening as stress increases and simultaneously avoiding drought by early regulation of stomatal closure (Cruz de Carvalho *et al.*, 1998).

### 6.3.3. Rate of photosynthesis (A) and transpiration (E)

The maximum photosynthesis rate recorded under well-watered conditions was 20.5, 23.6 and 23.9 in 2002 and 19.7, 20.2 and 21.1  $\mu\text{mol m}^{-2} \text{s}^{-1}$  in 2002/2003 in beans, chickpea and cowpea, respectively (Tables 6.6 & 6.7). The average values for the same treatment were 15.9, 20.6 and 17.0 in 2002 and 16.7, 16.3 and 16.3 in 2002/2003 in beans, chickpea and cowpea, respectively. There was no significant difference in A between the species under favourable water supply conditions. The average values found here are lower than the values reported for chickpea in a Mediterranean-type environment (Leport *et al.*, 1998) but higher than the values reported for beans and cowpea under non-stress conditions in a controlled experiment (Cruz de Carvalho *et al.*, 1998).



**Table 6.6. Rate of photosynthesis ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) of three grain legume species under well-watered (C) and water stressed conditions during flowering (MS) and pod filling (LS) periods in the 2002 season.**

DAW	Species and water regime treatments											
	BN		CHP		COP		BN		CHP		COP	
	C <sup>a</sup>	MS	C	MS	C	MS	C	LS	C	LS	C	LS
4	13.57 (2.25)	5.48 (0.79)	18.23 (3.01)	8.12 (0.32)	10.90 (2.78)	5.80 (1.10)	20.50 (0.61)	10.44 (1.02)	23.55 (0.59)	16.49 (1.68)	23.94 (0.87)	13.11 (0.59)
6	12.91 (1.37)	3.46 (0.60)	16.60 (0.70)	3.12 (0.46)	11.76 (1.35)	5.60 (1.15)	16.38 (0.91)	7.01 (0.52)	17.94 (1.29)	10.54 (1.04)	19.06 (1.03)	10.68 (1.29)
8	14.37 (1.73)	4.22 (0.35)	20.79 (2.56)	2.66 (0.91)	20.69 (0.70)	6.20 (1.15)	16.51 (0.73)	4.62 (0.46)	22.60 (1.47)	8.78 (1.12)	16.58 (0.93)	7.36 (1.36)
10	16.68 (2.28)	2.99 (0.53)	20.73 (2.50)	2.44 (0.75)	15.50 (1.86)	4.70 (1.66)	15.61 (0.59)	2.97 (0.25)	23.27 (1.02)	8.27 (1.45)	18.26 (1.20)	7.29 (0.77)
12	17.81 (0.79)	2.50 (0.59)	22.88 (2.70)	2.27 (0.81)	17.37 (2.85)	5.15 (0.85)	14.19 (0.94)	2.74 (0.86)	18.93 (1.67)	3.53 (1.06)	16.85 (0.57)	5.70 (1.42)

**Table 6.7. Rate of photosynthesis ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) of three grain legume species under well-watered (C) and water stressed conditions during flowering (MS) and pod filling (LS) periods in the 2002/2003 season.**

DAW	Species and water regime treatments											
	BN		CHP		COP		BN		CHP		COP	
	C <sup>a</sup>	MS	C	MS	C	MS	C	LS	C	LS	C	LS
2							16.46 (2.42)	15.56 (0.57)	20.20 (0.44)	18.80 (0.73)	14.80 (1.20)	14.70 (1.19)
4	15.50 (1.78)	17.00 (0.71)	13.29 (2.33)	16.90 (1.58)	14.27 (1.02)	14.70 (1.47)	16.60 (0.87)	13.30 (0.57)	18.80 (1.57)	17.70 (1.94)	16.50 (1.71)	18.80 (0.88)
6	12.80 (1.19)	11.40 (0.96)	15.49 (1.74)	8.40 (1.23)	16.40 (0.57)	10.62 (0.37)	17.00 (0.65)	10.10 (0.28)	10.20 (1.20)	11.40 (1.07)	11.95 (0.47)	10.40 (1.20)
8	16.50 (0.69)	7.40 (0.46)	18.70 (0.89)	5.82 (0.42)	14.91 (1.44)	7.83 (0.29)	16.31 (0.15)	9.14 (0.58)	4.05 (0.44)	4.16 (0.36)	6.17 (0.30)	4.22 (0.51)
10	18.10 (0.54)	7.80 (0.37)	16.22 (0.57)	3.70 (0.46)	14.82 (0.57)	4.64 (0.28)	16.60 (0.57)	9.50 (0.55)	17.00 (2.51)	7.54 (0.50)	18.80 (0.99)	14.20 (2.04)
12	16.41 (0.81)	3.90 (0.50)	14.59 (1.31)	3.10 (0.28)	13.50 (1.71)	2.20 (0.35)	19.70 (0.60)	13.35 (1.14)	18.40 (0.95)	11.70 (2.08)	21.10 (1.44)	15.87 (0.96)
14	18.03 (1.01)	5.49 (0.61)	16.19 (1.67)	2.33 (0.36)	16.95 (0.47)	2.22 (0.43)	14.97 (1.06)	5.78 (0.54)	19.68 (1.06)	12.52 (1.67)	18.61 (1.19)	9.66 (0.86)
16	18.90 (1.44)	2.25 (0.47)	12.47 (0.81)	2.66 (0.61)	17.17 (0.30)	2.80 (0.41)						
18	16.46 (2.42)	1.75 (0.30)										

<sup>a</sup> Numbers in parenthesis refer to standard error of means.

The A values recorded at the end of the MS treatment were 2.50, 2.27, and 5.15  $\mu\text{mol m}^{-2} \text{s}^{-1}$  in 2002 and 1.75, 2.66 and 2.80  $\mu\text{mol m}^{-2} \text{s}^{-1}$  in 2002/2003 in beans, chickpea and cowpea, respectively indicating a reduction of photosynthesis by 86-89% in beans, 79-90% in chickpea and 70-84% in cowpea during the two seasons when compared to the

respective control measurements. As shown by similar A values, species difference during the severe stage of water stress was not significant. The average relative rate of decline in A during the MS treatment was 4.6, 5.5, and 4.0% per day in beans, chickpea and cowpea, respectively. The minimum values of A recorded at the end of the LS treatment were 2.74, 3.53, and 5.70 in 2002 and 5.78, 12.52 and 9.66  $\mu\text{mol m}^{-2} \text{s}^{-1}$  in 2002/2003 for beans, chickpea and cowpea, respectively (Tables 6.6 & 6.7).

Relative to the respective control measurements, the reductions in A at the end of the LS treatment ranged from 61-81% in beans, 36-81% in chickpea and 48-66% in cowpea between the two seasons, and the average reduction rate during the whole stress period ranged from 3.5-4.3, 3.9-4.0 and 3.2-3.4 % per day, respectively. This shows that reduction in the rate of net photosynthesis is slightly higher and faster in the mid-season than in the late-season stressed grain legumes. Among the species, reduction in A was much faster in chickpea than beans, and in beans than in cowpea in all the seasons and treatments. Relative to the control, however, reductions in A were higher in beans and chickpea than in cowpea under both seasons and stress treatments. As indicated by Cruz de Carvalho *et al.* (1998), the lower decrease rate of A in cowpea, compared to beans and chickpea, could be either due to its ability to maintain partial stomatal opening under stress or due to less sensitivity of its photosynthetic activity to the stress. Reductions in A due to water stress have been reported for a number of grain legumes including chickpea, beans and cowpea (Leport *et al.*, 1998; Cruz de Carvalho *et al.*, 1998). The major reason for the reduction of A in beans and cowpea under severe water stress has been reported to be stomatal closure (Cruz de Carvalho *et al.*, 1998; Costa Franca *et al.*, 2000) and reduced biochemical capacity such as reduced rubisco activity and increases in internal  $\text{CO}_2$  concentration (Sage and Reid, 1994; Bordribb, 1996; Vu *et al.*, 1998). The high values of A in the LS treatment in 2002/2003 were due to low intensity of the water stress.

The reduction of E as a result of the MS stress in the two seasons ranged from 64-87% in beans, 87-88% in chickpea and 72-73% in cowpea at the end of the stress period. The average relative reduction rate of E during the MS stress was 2.6, 6.4 and 1.8% per day in beans, chickpea and cowpea, respectively. The minimum E values in the LS treatment ranged from 1.7-3.4, 4.0-4.4 and 3.2-3.4  $\text{mmol m}^{-2} \text{s}^{-1}$  between the two seasons in beans, chickpea and cowpea, respectively (Tables 6.8 & 6.9). Relative to the respective control measurements at the end of the stress, the LS treatment reduced E by 50-65% in beans,

22-49% in chickpea and 29-51% in cowpea in the two seasons. The relative decline rate of E during the LS stress was 4.7-4.9, 3.0-5.5 and 2.8-3.7% per day. While the rate of decline in E was higher in chickpea in the MS stress, it was higher in beans in the LS stress.

**Table 6.8. Rate of transpiration ( $\text{mmol m}^{-2} \text{s}^{-1}$ ) of three grain legume species under well-watered (C) and water stressed conditions during flowering (MS) and pod filling (LS) periods in the 2002 season.**

DAW	Species and water regime treatments											
	BN		CHP		COP		BN		CHP		COP	
	C <sup>a</sup>	MS	C	MS	C	MS	C	LS	C	LS	C	LS
4	8.13 (1.32)	3.48 (0.41)	8.66 (1.32)	6.58 (0.25)	5.80 (1.53)	3.94 (0.69)	10.83 (0.50)	7.27 (0.46)	11.87 (0.38)	9.73 (0.99)	9.95 (1.03)	7.76 (0.69)
6	6.40 (0.54)	3.40 (0.46)	7.90 (0.82)	3.58 (0.67)	6.47 (0.49)	3.58 (0.40)	9.37 (0.54)	5.00 (0.29)	11.63 (0.45)	7.59 (0.48)	9.47 (0.50)	7.09 (0.63)
8	7.35 (0.89)	2.73 (0.18)	7.56 (0.39)	2.84 (0.71)	9.10 (0.59)	3.28 (0.52)	8.79 (0.31)	3.49 (0.24)	10.34 (0.59)	6.82 (0.55)	8.57 (0.40)	4.93 (0.65)
10	8.42 (0.92)	2.98 (0.38)	11.20 (1.36)	2.44 (0.64)	7.21 (0.87)	2.72 (0.72)	8.75 (0.39)	3.23 (0.19)	11.92 (0.78)	5.98 (0.51)	8.40 (0.32)	4.95 (0.33)
12	6.83 (0.51)	2.54 (0.37)	12.41 (1.40)	1.65 (0.28)	8.66 (0.72)	2.32 (0.49)	9.58 (0.57)	3.39 (0.65)	8.69 (0.55)	4.44 (0.22)	6.47 (0.31)	3.19 (0.51)

<sup>a</sup> Numbers in parenthesis refer to standard error of means.

**Table 6.9. Rate of transpiration ( $\text{mmol m}^{-2} \text{s}^{-1}$ ) of three grain legume species under well-watered (C) and water stressed conditions during flowering (MS) and pod filling (LS) periods in the 2002/2003 season.**

DAW	Species and water regime treatments											
	BN		CHP		COP		BN		CHP		COP	
	C <sup>a</sup>	MS	C	MS	C	MS	C	LS	C	LS	C	LS
2							5.19 (0.70)	5.22 (0.56)	7.73 (1.21)	5.28 (0.40)	4.91 (0.54)	4.75 (0.61)
4	6.68 (0.70)	6.74 (0.56)	5.96 (0.64)	6.30 (0.66)	3.89 (0.48)	4.80 (0.44)	5.60 (0.41)	4.90 (0.35)	7.00 (0.33)	5.60 (0.56)	3.80 (0.76)	4.10 (0.51)
6	5.60 (0.53)	4.30 (0.71)	5.60 (0.43)	3.20 (0.39)	4.83 (0.20)	3.26 (0.07)	6.61 (0.12)	3.27 (0.18)	7.05 (0.19)	3.92 (0.14)	4.02 (0.17)	3.70 (0.21)
8	6.80 (0.66)	2.90 (0.33)	3.86 (0.29)	2.38 (0.49)	4.43 (0.32)	3.35 (0.21)	2.50 (0.06)	1.54 (0.05)	7.40 (0.04)	1.77 (0.07)	5.81 (0.08)	3.66 (0.08)
10	9.25 (0.46)	3.30 (0.23)	2.91 (0.32)	1.54 (0.29)	5.81 (0.54)	1.90 (0.12)	3.63 (0.10)	1.67 (0.16)	8.40 (0.27)	2.34 (0.19)	5.10 (0.12)	3.38 (0.17)
12	5.93 (0.60)	1.66 (0.19)	6.20 (0.39)	2.50 (0.31)	4.00 (0.76)	1.50 (0.12)	5.67 (0.30)	2.57 (0.21)	7.41 (0.53)	2.74 (0.47)	4.73 (0.09)	3.33 (0.18)
14	8.56 (0.21)	1.74 (0.14)	7.60 (0.79)	1.20 (0.21)	6.30 (0.17)	1.28 (0.18)	3.45 (0.43)	1.73 (0.22)	5.09 (0.35)	3.99 (0.49)	4.81 (0.35)	3.40 (0.13)
16	7.54 (0.45)	0.98 (0.19)	4.81 (0.23)	0.57 (0.14)	5.60 (0.08)	1.58 (0.07)						
18	5.19 (0.70)	0.69 (0.10)										

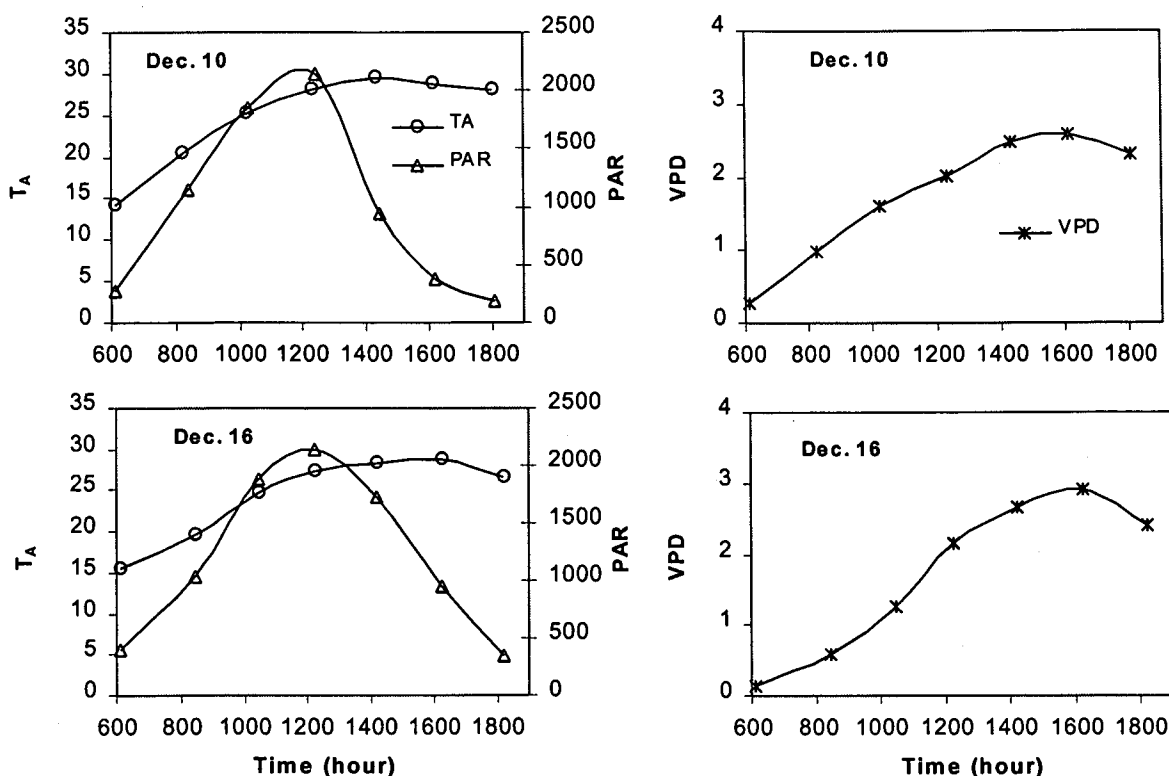
<sup>a</sup> Numbers in parenthesis refer to standard error of means.

Rate of E decline was lower in cowpea than in beans and chickpea in both the MS and LS stresses. High E values in cowpea, despite high  $r_s$ , suggest that the crop may have the ability to maintain partial stomatal opening under water stress. Similar results were also reported under controlled conditions (Cruz de Carvalho *et al.*, 1998). Transpiration serves as a major mechanism for cooling plant leaves through the evaporation process. As soil water becomes limiting, however, the evaporation cooling is reduced leading to an increase in leaf or canopy temperature (Jalali-Farahani *et al.*, 1993) and a decrease in CO<sub>2</sub> assimilation. Thus, a crop like cowpea that maintains its E under water deficit also maintains better CO<sub>2</sub> assimilation.

#### 6.3.4. Diurnal measurements

The hourly changes in  $\psi_L$ ,  $r_s$ , A and E measured on December 10, 2002 (chickpea) and December 16, 2002 (beans and cowpea). The two measurement dates have similar photosynthetically active radiation (PAR), air temperature and VPD (Fig. 6.1). The maximum PAR, air temperature and VPD recorded were 2145  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , 29.6 °C and 2.58 kPa on 10 December 2002 and 2145  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , 28.6 °C and 2.90 kPa on 16 December 2002, respectively.

The minimum  $\psi_L$  in chickpea was observed around 14:00 local time in both the stressed and control plants while in beans it was observed between 12:00-14:00 in the control plants and around 14:00 in the stressed bean plants (Fig. 6.2). In cowpea, the minimum was observed between 12:00-14:00 and at 16:00 for the control and stressed plants, respectively (Fig. 6.2). The hourly  $\psi_L$  of cowpea plants declined from early morning until 16:00 and only started to recover after 16:00 in both the stressed and well-watered plants unlike the case in beans and chickpea where the  $\psi_L$  started to recover just after 14:00. Late afternoon recovery of  $\psi_L$  was faster in the stressed than in the well-watered plants in beans and cowpea while it was faster in the well-watered plants in chickpea. The hourly rate of  $\psi_L$  decline in the stressed plants was faster between 6:00-8:00 in beans and chickpea while the change between 8:00-14:00 was very small. Difference in  $\psi_L$  between well-watered and stressed plants was higher in chickpea but less in cowpea and beans (Fig. 6.2). The decline of diurnal  $\psi_L$  with time until late afternoon in both well-watered and stressed plants could be mainly due to the lag in water absorption vis-à-vis transpiration as a result of rising radiation load and increasing VPD (Ehrler *et al.*, 1978).

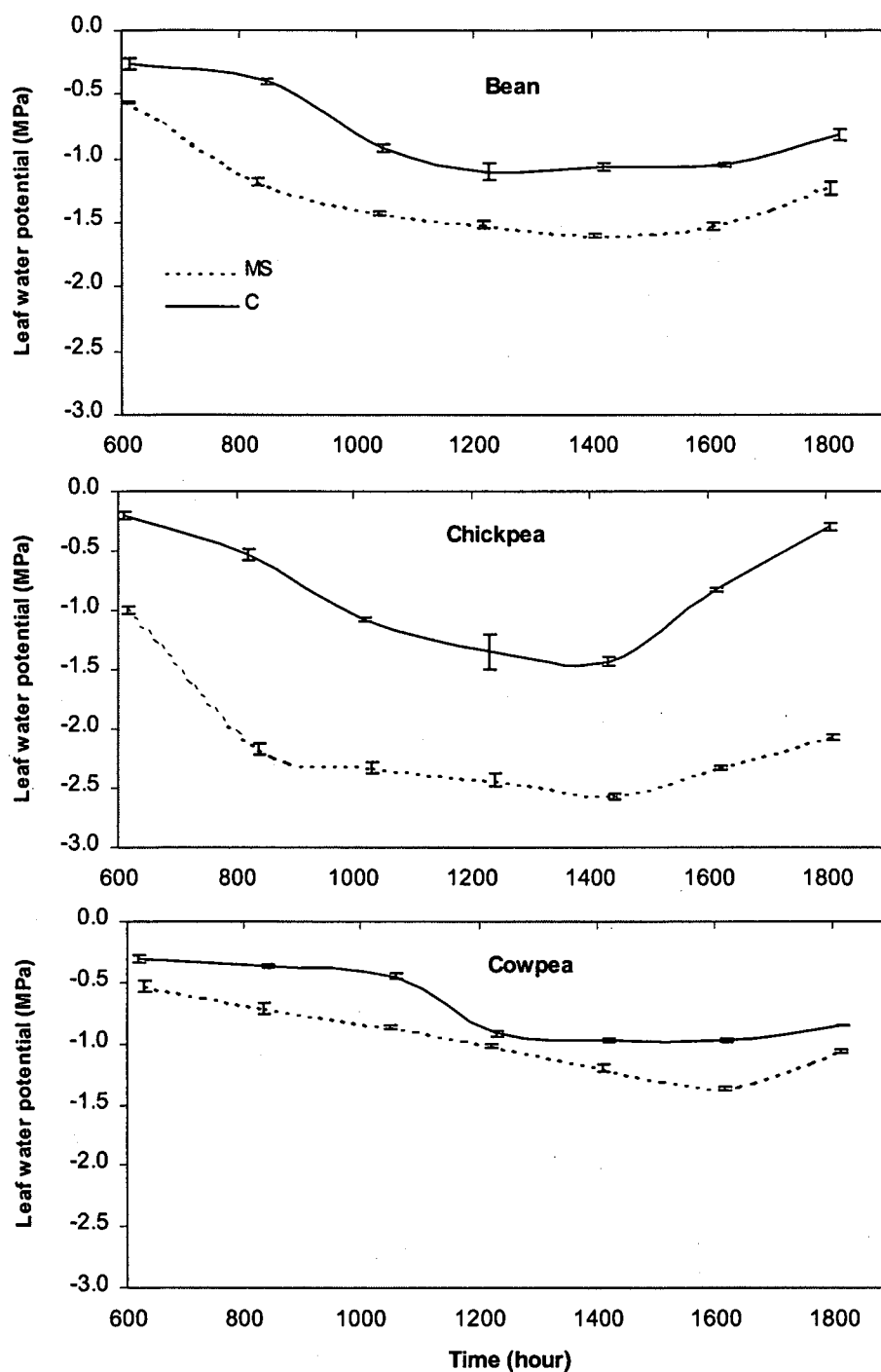


**Figure 6.1.** Diurnal variation of photosynthetically active radiation (PAR,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), air temperature ( $T_A$ , °C) and weather station vapour pressure deficit (VPD, kPa) on 10 (top) and 16 (bottom) December 2002.

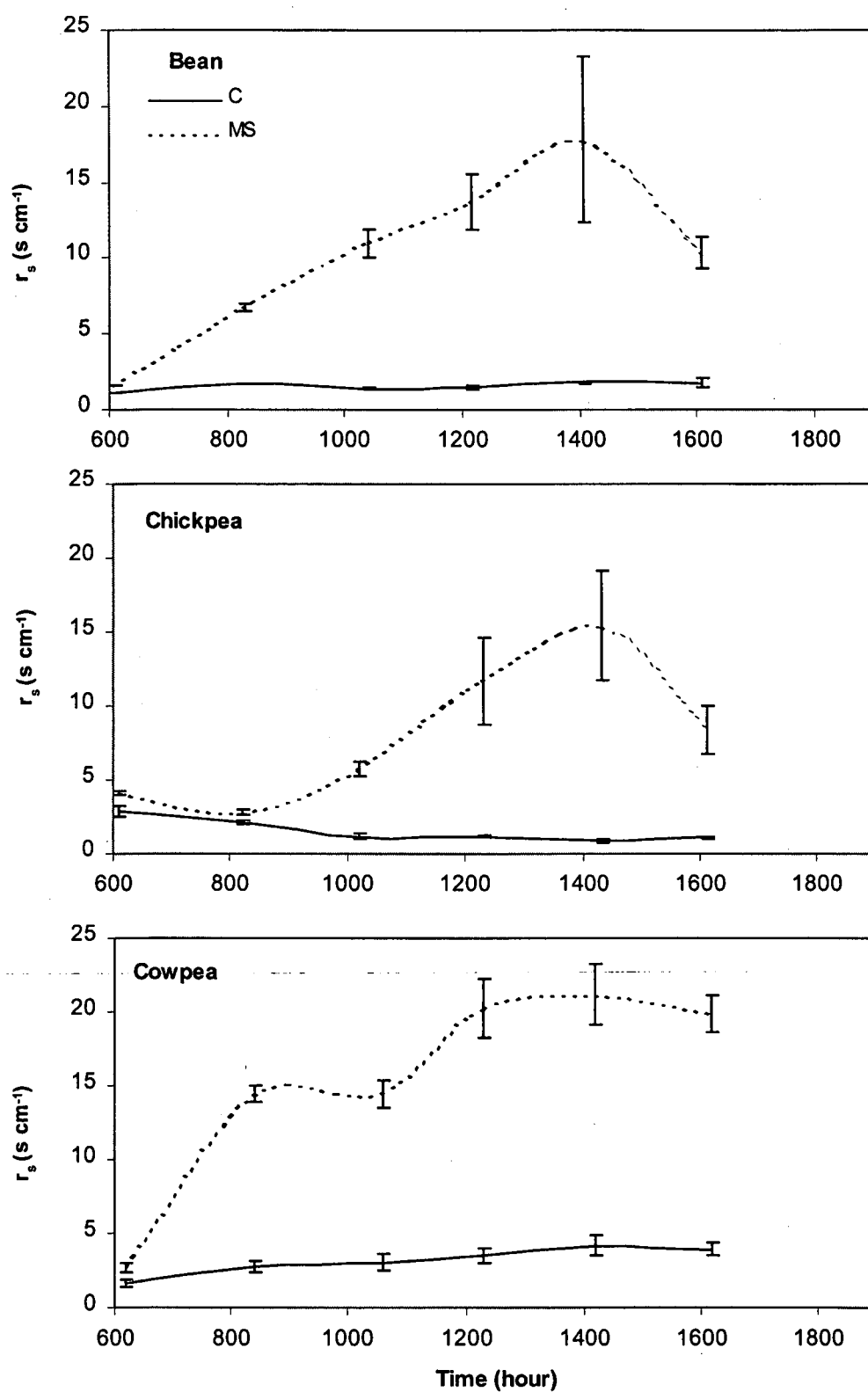
The diurnal change of  $\psi_L$  in the three species was highly associated with the diurnal changes of VPD ( $r = -0.81^*$  to  $-0.98^{**}$ ) and air temperature ( $r = -0.89^*$  to  $-0.98^{**}$ ) both of which are responsible for increased water loss from the plant (Squire, 1990).

The diurnal change in  $r_s$  was very high in the stressed plants while it was very small in the well-watered plants in all species (Fig. 6.3), that is, the stomata remained open in the well-watered plants but closed in the stressed plants. This indicated that the decline in  $\psi_L$  in the control plants did not cause a major increase in  $r_s$  in all the species suggesting the existence of a threshold  $\psi_L$  value beyond which the  $r_s$  increases. On the other hand, the decline in  $\psi_L$  in the stressed beans and cowpea was significantly correlated with an increase in  $r_s$  ( $r = -0.87^*$  to  $-0.91^*$ ) (Table 6.10). While differences in  $r_s$  were observed by 8:00 in beans and cowpea, there was no any difference between the control and stressed plants in chickpea despite the fact that there was big difference in  $\psi_L$  between the water regimes at the same time. Therefore, the weak correlation of hourly values of  $\psi_L$  and  $r_s$  in chickpea ( $r = -0.32$  to  $-0.59$ ) in both the control and stress plants suggested that

low leaf water potential was not the trigger of stomatal closure in chickpea. Therefore, the differential response of the species is mainly attributed to the relative nature of water stress in that a water potential which induces stomatal closure in one species may have little effect on another (Sperry, 2000).



**Figure 6.2.** Diurnal variation of leaf water potential in beans, chickpea and cowpea under mid-season water stress (MS) for 14 days and well-watered (C) conditions at a semi-arid environment. Vertical bars indicate standard errors.



**Figure 6.3.** Diurnal variation of stomatal resistance in beans, chickpea and cowpea under mid-season water stress (MS) for 14 days and well-watered (C) conditions in a semi-arid environment. Vertical bars indicate standard errors.

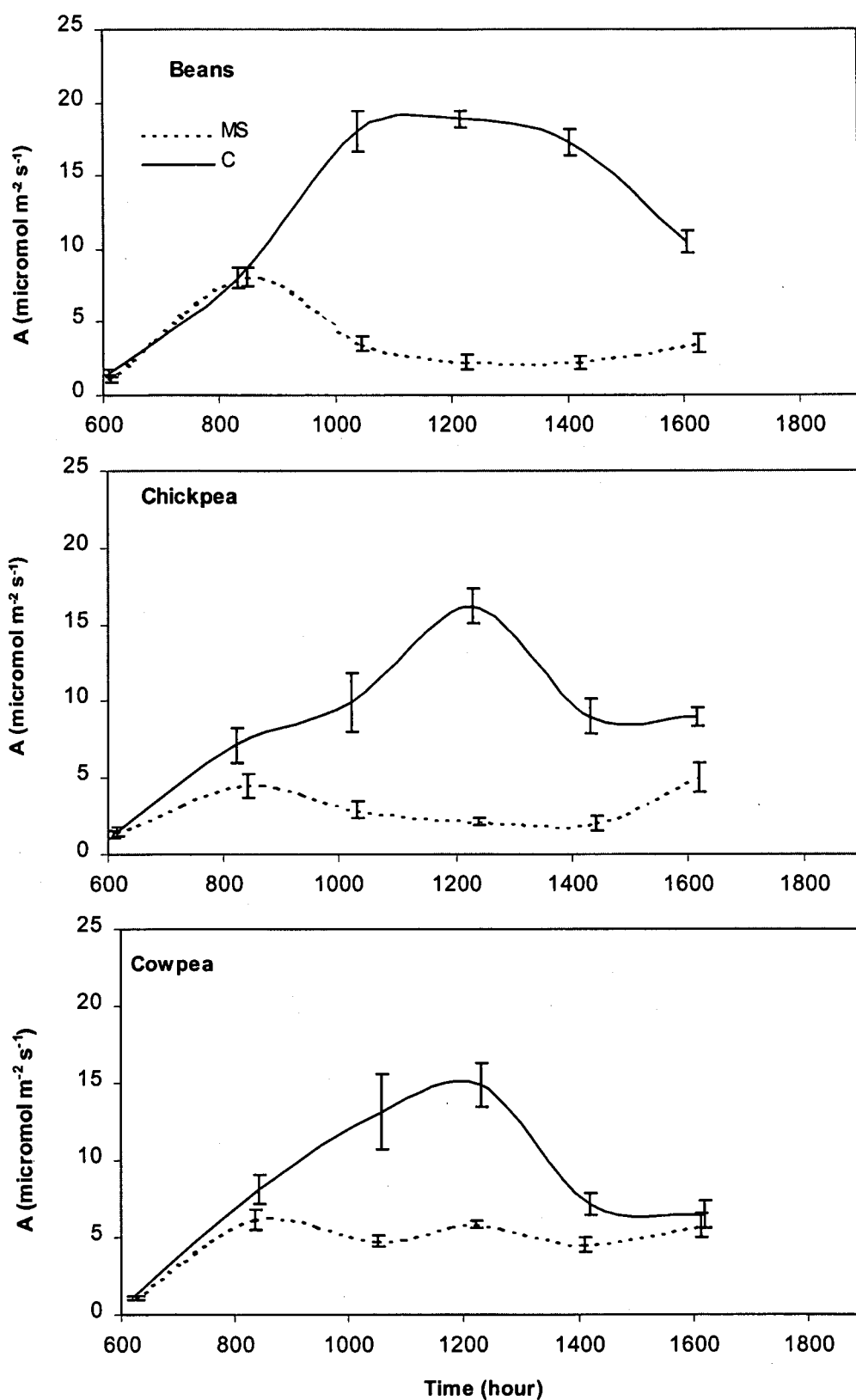


Figure 6.4. Diurnal variation of the rate of photosynthesis in beans, chickpea and cowpea under mid-season water stress (MS) for 14 days and well-watered (C) conditions at a semi-arid environment. Vertical bars indicate standard errors.



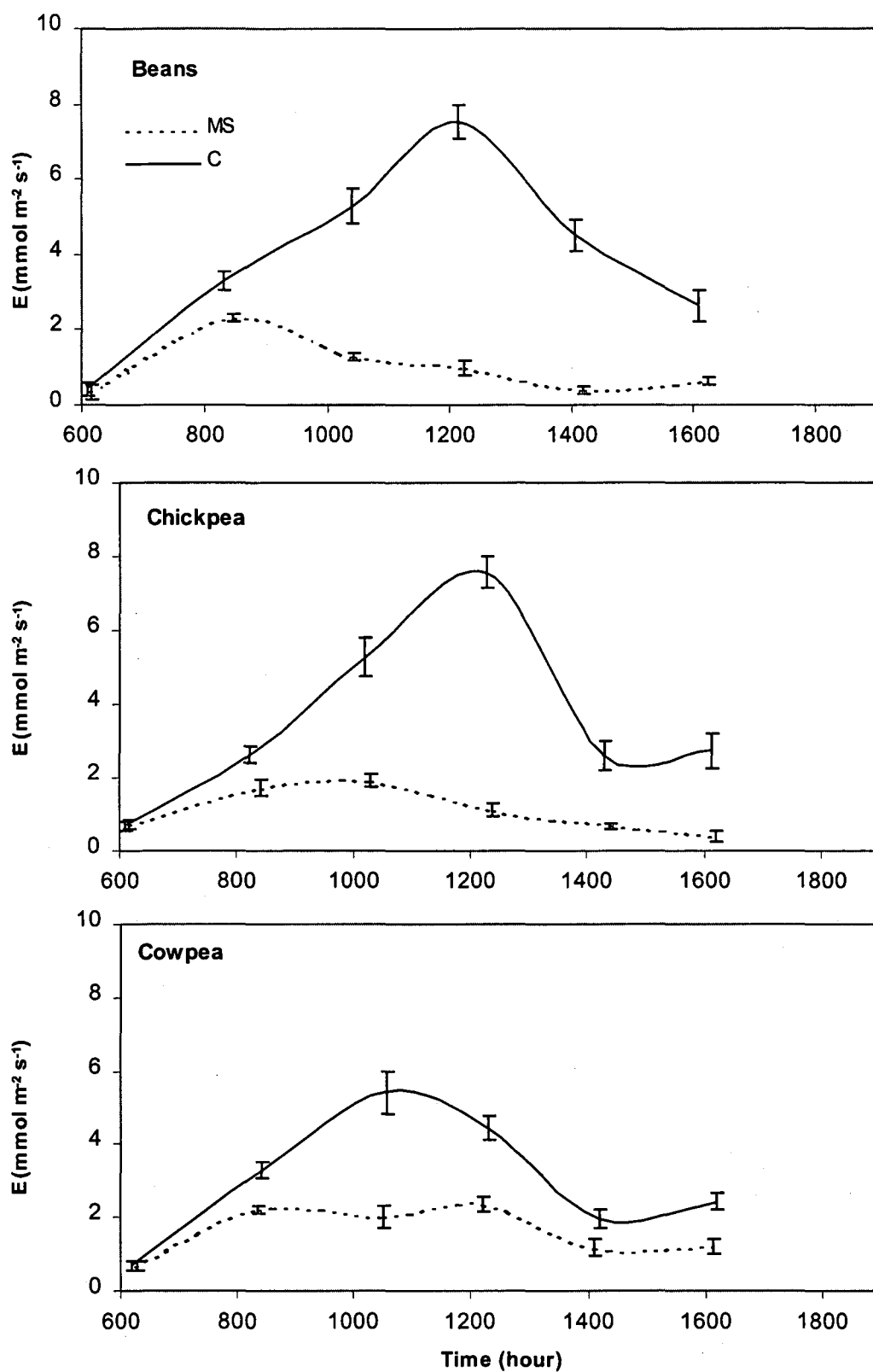


Figure 6.5. Diurnal variation of the rate of transpiration in beans, chickpea and cowpea under mid-season water stress (MS) for 14 days and well-watered (C) conditions in a semi-arid environment. Vertical bars indicate standard errors.

The diurnal change of  $r_s$  was positively correlated with VPD ( $r = 0.79$  to  $0.94^*$ ) and air temperature ( $r = 0.61$  to  $0.96^{**}$ ) (Table 6.10). Bates and Hall (1982b) also found strong correlation of stomatal conductance with VPD in cowpeas. Stomatal response to the leaf-to-air VPD was found to be strongly associated with the survival strategies adopted by dryland  $C_4$  grasses and  $C_3$  species (Maroco *et al.*, 1997). Increases in air temperature results in greater water vapour gradients between leaf and air which promotes stomatal closure (Sage and Reid, 1994). Stomata response to both air temperature and vapour pressure gradient between leaf and air under non-stress conditions is variable in  $C_3$  plants.

**Table 6.10. Correlation coefficients among diurnal measurements of leaf water potential ( $\psi$ , MPa), stomatal conductance ( $r_s$ ,  $s\ cm^{-1}$ ), rate of photosynthesis ( $A$ ,  $\mu mol\ m^{-2}\ s^{-1}$ ), rate of transpiration ( $E$ ,  $mmol\ m^{-2}\ s^{-1}$ ), air temperature ( $T_A$ ,  $^{\circ}C$ ), vapor pressure deficit (VPD, kPa) and photosynthetically active radiation (PAR,  $\mu mol\ m^{-2}\ s^{-1}$ ).<sup>a</sup>**

Species	Water regime		$\psi$	$r_s$	$A$	VPD <sup>b</sup>	$T_A$	PAR
Bean	C	$r_s$	-0.46					
		$A$	-0.86*	0.37				
		VPD	-0.92**	0.63	0.63			
		$T_A$	-0.98**	0.61	0.80*	0.96**		
		PAR	-0.76	0.25	0.98**	0.49	0.69	
		$E$	-0.71	0.25	0.92*	0.45	0.64	0.97**
	MS	$r_s$	-0.91*					
		$A$	-0.12	-0.84*				
		VPD	-0.86*	0.82*	-0.23			
		$T_A$	-0.95**	0.89*	-0.15	0.96**		
		PAR	-0.76	0.81*	-0.11	0.54	0.70	
		$E$	-0.06	-0.17	0.93*	-0.39	-0.24	-0.10
Chickpea	C	$r_s$	-0.32					
		$A$	-0.83	-0.77				
		VPD	-0.81*	0.94**	0.67			
		$T_A$	-0.89*	0.98**	0.79	0.98**		
		PAR	-0.65	0.53	0.88*	0.31	0.48	
		$E$	-0.69	0.75	0.93*	0.40	0.55	0.99**
	MS	$r_s$	-0.59					
		$A$	-0.34	-0.69				
		VPD	-0.80*	0.79	0.28			
		$T_A$	-0.88*	0.77	0.23	0.98**		
		PAR	-0.55	0.20	-0.17	0.19	0.38	
		$E$	-0.34	-0.52	0.68	0.00	-0.09	0.40
Cowpea	C	$r_s$	-0.88*					
		$A$	-0.31	0.47				
		VPD	-0.97**	0.94**	0.33			
		$T_A$	-0.91*	0.96**	0.55	0.96**		
		PAR	-0.46	0.56	0.92*	0.46	0.65	
		$E$	-0.44	0.28	0.94**	0.13	0.38	0.78
	MS	$r_s$	-0.87*					
		$A$	-0.57	-0.43				
		VPD	-0.98**	0.88*	0.53			
		$T_A$	-0.94**	0.93**	0.64	0.96**		
		PAR	-0.51	0.72	0.47	0.57	0.74	
		$E$	-0.001	0.44	0.75	0.02	0.23	0.43

<sup>a</sup>  $n = 6$ ; \*, \*\* Correlation coefficients significant at 5 and 1% P level, respectively. <sup>b</sup> The VPD is a mean of half hourly measurements between 10:00 to 13:30 local time.

For example, stomatal conductance increases with temperature at constant VPD between leaf and air in many species, while in some species such as sweet pepper and caster bean, stomata open with increasing temperature under high and low VPDs, respectively (Sage and Reid, 1994 and references there in). There was also a positive correlation between  $r_s$  and PAR, particularly under stress conditions. A similar condition was reported in wheat where diurnal differences in stomatal conductance between stressed and unstressed plots were related to differences in net radiation (Choudhury, 1985).

There was no significant difference in the hourly changes of A between the control and stressed plants before 8:00 in the morning in any of the species (Fig. 6.4). Rate of photosynthesis attained its maximum between 10:00-14:00 in beans and at midday in chickpea and cowpea in the well-watered plants while it attained its lowest in the stressed plants at the same time (Fig. 6.4). Therefore, the maximum difference in A between the C and MS treatments was observed at midday in all the species. A was slightly higher in the morning and late afternoon than the midday values in the stressed plants, particularly in chickpea. In beans, the stressed plants had similar A values to that of the C early in the morning (8:00) indicating the adaptation strategy of the plant to maintain its photosynthesis under water limited conditions. The pattern in the diurnal change of E was similar to that of A in chickpea and cowpea, except that recovery in the late afternoon was slow (Fig. 6.5). Beans showed a drastic decline in E after midday in contrast to the observation in A where reduction was slow between 12:00-14:00.

Diurnal change of A and E in the control plots was strongly correlated with the change of air temperature and PAR and moderately with  $\psi_L$  and VPD (Table 6.10). However, both A & E were not correlated with any of these parameters in the stressed plants because photosynthesis in the stress plants responded favourably to these weather variables until 10:00 in the morning but declined afterwards when the weather elements increase to the highest. These results indicate the different response of the stressed plants to diurnal change of weather conditions from that of well-watered plants. A was positively correlated with  $r_s$  in the controls whereas the correlation was negative in the stressed plants indicating that there was a threshold  $r_s$  beyond which A declined.

One of the effects of water stress is an increase in leaf temperature ( $T_L$ ) of the stressed plants as a result of stomatal closure and reduced transpiration. Most of the diurnal

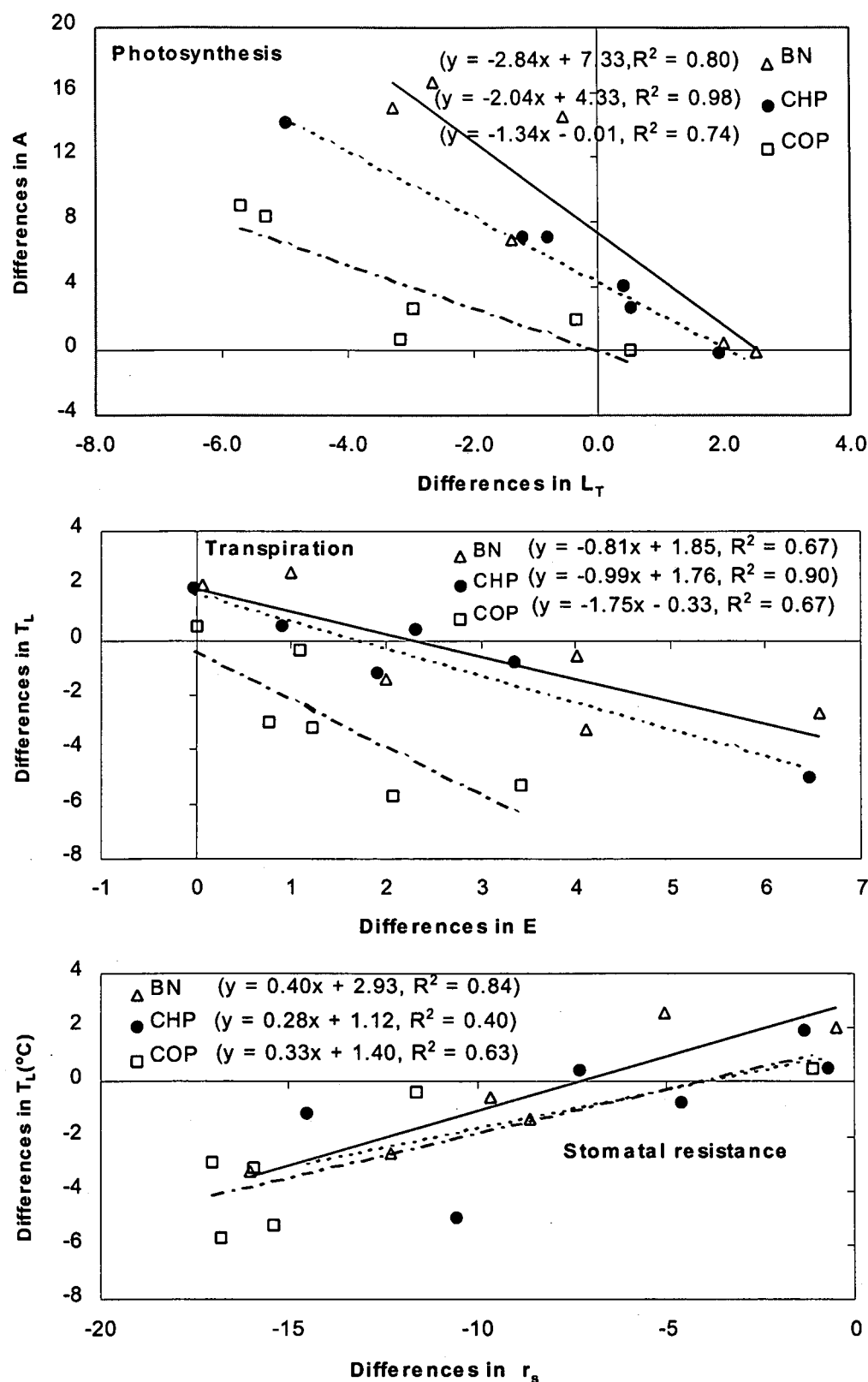
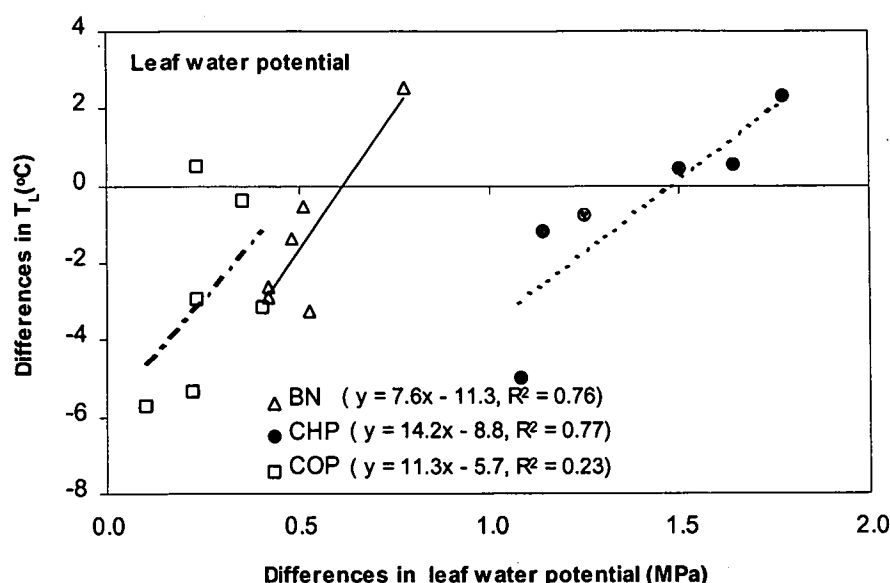


Figure 6.6. Relation of diurnal differences in leaf temperature ( $T_L$ , °C) to diurnal differences in rate of photosynthesis ( $A$ , μmol m<sup>-2</sup> s<sup>-1</sup>), transpiration ( $E$ , mmol m<sup>-2</sup> s<sup>-1</sup>) and stomatal resistance ( $r_s$ , s cm<sup>-1</sup>) between well-watered and mid-season water stressed plants of beans (BN, —), chickpea (CHP, ----) and cowpea (COP, ----) at a semi-arid environment.

variation in  $T_L$  difference between the control and stressed plants was explained by differences in  $r_s$  (84, 40 and 46%) and  $E$  (67, 90 and 67%) for beans, chickpea and cowpea, respectively (Fig. 6.6). Therefore,  $T_L$  in the stressed plants integrates the other effects of water stress, and it explains most of the differences in photosynthesis. Differences in diurnal  $T_L$  between the C and MS treatments explained 80, 98, and 74% of the diurnal variation of the difference in  $A$  between the two treatments in beans, chickpea and cowpea, respectively (Fig. 6.6). The graphs indicate that when leaf temperatures of the well-watered and stressed plants are equal, there is no difference in  $A$  between the stress and control treatments. Therefore, the major diurnal difference in the rate of photosynthesis between well-watered and stressed plants is a drastic increase in  $T_L$  in the stressed plants which results in disruption of enzymatic activities which are responsible for  $CO_2$  assimilation.

It has been indicated that thermal extremes directly damage biochemical systems through protein denaturation, loss of membrane integrity, photoinhibition and ion imbalance (Sage and Reid, 1994). An increase in air temperature also results in greater water vapour gradients between leaf and air and promotes stomatal closure and  $T_L$  increase which in turn limit photosynthesis (Sage and Reid, 1994, and references there in). Leaf temperatures are determined by the energy exchange processes involving radiation, convection, and transpiration (Sivakumar, 1986). When soil water becomes limiting, stomatal closure occurs resulting in reduced transpiration, increased heat load on the canopy and a consequent rise in leaf temperatures which can reach up to 10 °C above air temperature in some  $C_4$  species (Pearcy *et al.*, 1971). High temperature, which occurs during periods of water stress, can affect  $CO_2$  assimilation and reduce water use efficiency (Baldocchi *et al.*, 1981b; Baldocchi *et al.*, 1985). Species may have different responses and mechanisms to regulate their leaf temperature. For example, differences in  $\psi_L$  explained 77 and 76% of the variability in  $T_L$  difference between the stressed and unstressed plants in beans and chickpea, respectively while there was no significant correlation in cowpea (Fig. 6.7). Comparison of the species indicated that cowpea had a better mechanism of maintaining its photosynthesis under high leaf temperature as compared to beans and chickpea.



**Figure 6.7.** Relation of diurnal differences in leaf temperature ( $T_L$ ) to diurnal differences in leaf water potential between well-watered and mid-season water stressed plants of beans (BN), chickpea (CHP) and cowpea (COP) for two measurement dates (10 and 16 December 2002) at a semi-arid environment.

### 6.3.5. Relationship between ASW, $\psi_L$ , $r_s$ , A and E

The response of plants to the environmental conditions is complex and interrelated. Therefore, it is necessary to understand the interrelationships of, at least, the major environmental and physiological variables to explain and model the response of plants to environmental constraints such as water deficit. Here an attempt is made to investigate the relation of soil and leaf water status, stomatal resistance, photosynthesis and transpiration in beans, chickpea and cowpea. To do so, data were combined for the well-watered (C) and stressed (MS and LS) treatments to investigate the relationships during the whole reproductive period of the three species.

There was a strong linear relationship ( $R^2 > 0.70$  except in chickpea in 2002/2003) between  $\psi_L$  and ASW (%) in all seasons and species (Fig. 6.8). On average,  $\psi_L$  declined by 0.01 MPa per a percent decline in ASW in beans and cowpea and by 0.03 MPa per a percent decline ASW in chickpea during both seasons. The consistent relationship between  $\psi_L$  and ASW across seasons suggests that  $\psi_L$  can be easily determined from a measurement of soil water in grain legumes. Since water flows from a higher energy to a lower energy level, water movement in the soil-plant-atmosphere continuum (SPAC) is a function of soil water status, plant water status, atmospheric vapour pressure deficit and

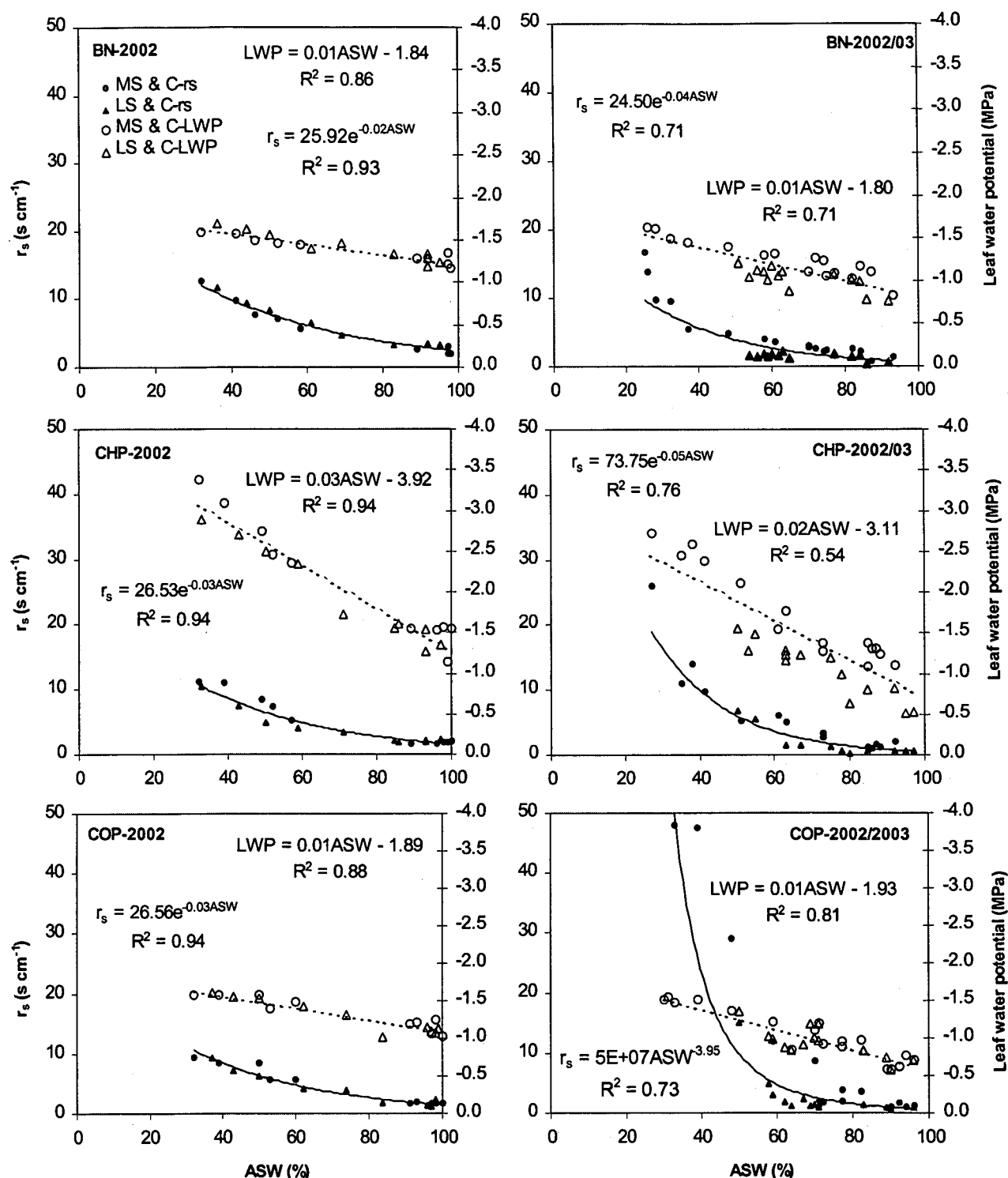


Figure 6.8. The relationship between available soil water (ASW), stomatal resistance ( $r_s$ ) and leaf water potential (LWP) in three grain legumes under water stress (MS & LS) and well-watered (C) conditions in 2002 (left) and 2002/2003 (right) seasons. (BN= beans, CHP = chickpea, COP = cowpea).

the resistance encountered at each level. Therefore, the above mentioned values could be useful in relating soil water to plant water status so that an efficient system of irrigation scheduling could be devised for these crops.

On the other hand, the relation between ASW and  $r_s$  was not linear and was more appropriately explained by an exponential function (Fig. 6.8). With a decline in ASW, the  $r_s$  increased exponentially at rate of 0.02-0.04, 0.03-0.05 and 0.03 s cm<sup>-1</sup> per ASW (%) in beans, chickpea and cowpea, respectively in the two seasons. The increase in  $r_s$  with the decline in ASW (%) was higher and faster in cowpea in 2002/2003 and the relationship was best explained by a power function (Fig. 6.8). The relationship of  $r_s$  to ASW indicated that stomata closure was triggered at higher soil water in 2002 than in 2002/2003. The exponential relationship between  $r_s$  and ASW was broken down into two linear regressions to find the threshold value above which  $r_s$  increased drastically with a decrease in ASW. Linear regressions of the data points and finding the intersection point of the regression lines indicated that stomatal closure was initiated when ASW reached 62.3, 62.4 and 86.2% in the high temperature season (2002) and 55.0, 45.5 and 65.4% in the more mild temperate season (2002/2003) in beans, chickpea and cowpea, respectively. The closure of stomata at higher ASW in 2002 could be due to the high temperature prevailing during that season as compared to 2002/2003.

Linear regressions of the data shown in Fig. 6.9 between the control and stressed plants indicated that a trigger of stomatal closure occurred at an average threshold  $\psi_L$  value of -1.48, -2.08 and -1.11 MPa in beans, chickpea and cowpea, respectively. This shows a more rapid closure of stomata at higher  $\psi_L$  in cowpea than beans and chickpea which also agrees with other reports on the same crop (Shackel and Hall, 1983; Diallo *et al.*, 2001). However, the value obtained for beans is higher than the values reported (-0.6 to -0.9 MPa) for complete stomatal closure of this crop in another study (Costa Franca *et al.*, 2000). The lower  $\psi_L$  thresholds obtained here compared to the previous reports could be a result of cultivar and/or environmental differences between the studies. On the contrary, Cruz de Carvalho *et al.* (1998) observed a complete stomatal closure in beans at higher plant water status than a drought tolerant cowpea cultivar under severe water stress conditions. In addition, the relation of  $r_s$  with ASW indicates that stomatal closure in cowpea occurs at higher soil water status than in beans and chickpea (Fig. 6.8). This better stomatal adjustment behaviour of cowpea in response to water deficit makes it one



of the droughts avoiding  $C_3$  species (Squire, 1990; Cruz de Carvalho *et al.* (1998). As mentioned earlier, the lower  $\psi_L$  for the initiation of stomatal closure in chickpea is mainly associated with the low stomatal adjustment behaviour of the species. In general, stomatal closure in chickpea was observed at lower ASW and  $\psi_L$  than beans and cowpea in both seasons suggesting that the contribution of stomatal closure to drought avoidance of the crop is limited compared to the other two species.

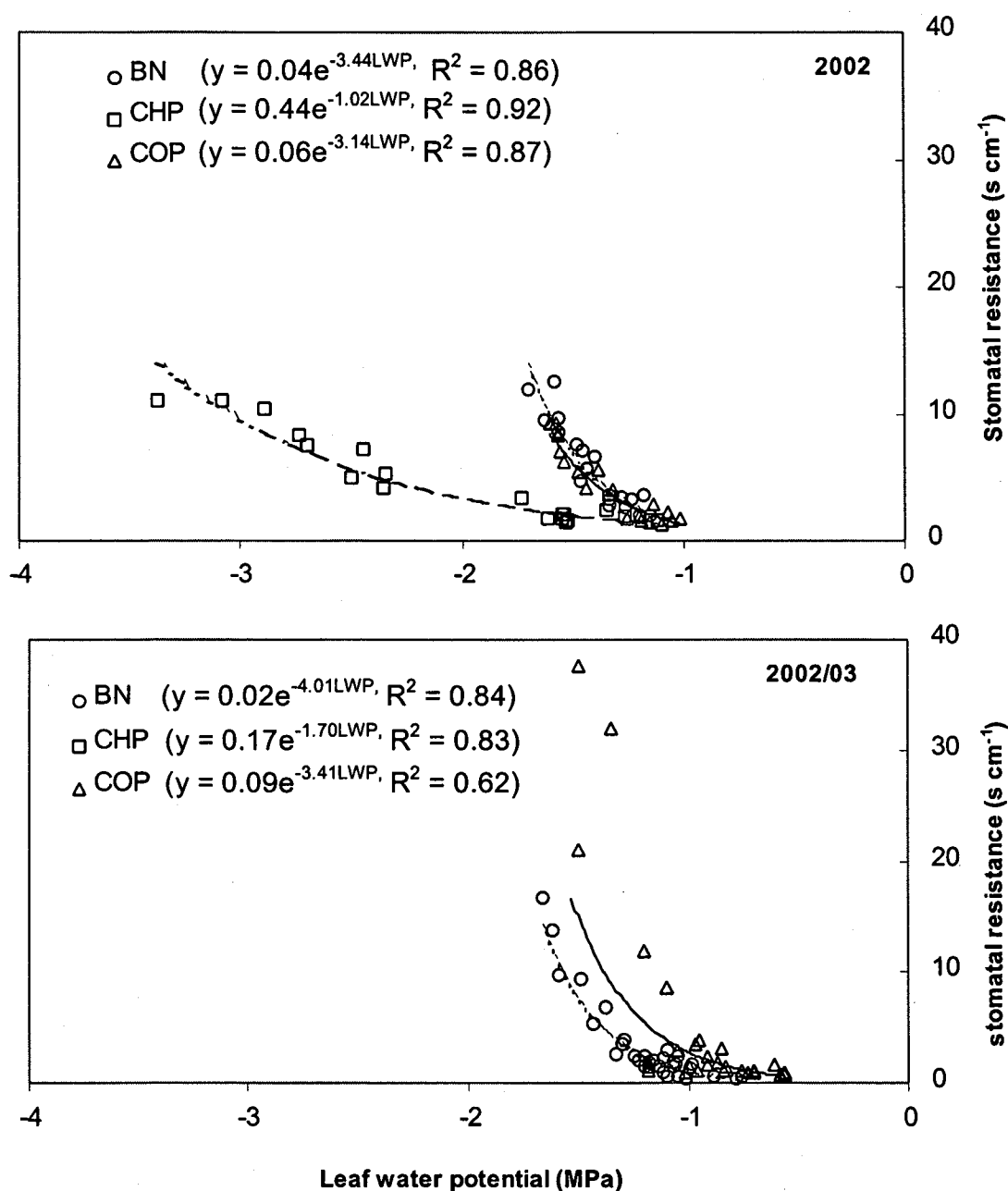


Figure 6.9. The relationship between leaf water potential and stomatal resistance during the reproductive period of three grain legumes under water stress (MS & LS) and well-watered (C) conditions in 2002 (top) and 2002/2003 (bottom) seasons. BN= beans, CHP = chickpea, COP = cowpea.

A and E were linearly related to ASW for beans and chickpea in both seasons whereas the relation was best explained by a power function in cowpea (Fig. 6.10). There was no significant difference between the two seasons in the response of A and E to ASW in any species. Therefore the average decline in A per a percent decline in ASW was 0.24 and 0.29  $\mu\text{mol m}^{-2} \text{s}^{-1}$  and that of E was 0.10 and 0.12  $\text{mmol m}^{-2} \text{s}^{-1}$  in beans and chickpea respectively. The relationship between photosynthesis and transpiration with available soil water in cowpea indicate that the crop has a capacity to photosynthesise and transpire at a higher rate under favourable water supply and also maintain a slower rate of decline in A and E under low soil water conditions. As shown in Fig. 6.10, rate of photosynthesis had decreased by 5 fold when the ASW reached 47.9, 43.3 and 39.0% in the high temperature season (2002) and 30.8, 43.1 and 36.2% in the mild temperature season (2002/2003). The photosynthesis rate of beans was affected at higher ASW in the high temperature season compared to its performance in the mild temperature season. This may suggest that high temperatures under conditions of water stress could affect the productive capacity of the plant when it is coupled with water deficit.

The present results indicated that the rate of photosynthesis was more sensitive to the decline of soil water than the rate of transpiration in all species. This could be explained by the sensitivity of photosynthesis to increased leaf temperatures even before the stomata close completely. It is suggested that limitations to  $\text{CO}_2$  assimilation in beans was caused by metabolic restrictions that can be differentiated between those occurring in the range of 20 to 30 °C and 30 to 35 °C (Pastenes and Horton, 1996).

Both A and E were exponentially related to  $\psi_L$  in all species and seasons (Fig. 6.11). Rate of photosynthesis declined exponentially with  $\psi_L$  at a rate of 4.00, 1.18 and 2.31  $\mu\text{mol m}^{-2} \text{s}^{-1}$  in 2002 and 3.36, 0.82 and 1.88  $\mu\text{mol m}^{-2} \text{s}^{-1}$  in 2002/2003 in beans, chickpea and cowpea, respectively. Similarly, E declined exponentially with  $\psi_L$  at a rate of 2.60, 0.80, 1.94  $\text{mmol m}^{-2} \text{s}^{-1}$  in 2002 and 3.30, 0.82, 1.07  $\text{mmol m}^{-2} \text{s}^{-1}$  in 2002/2003 in the three species order as above (Fig. 6.11). The data shows that the decline in A and E with  $\psi_L$  was higher in beans while it was lowest in chickpea. Although chickpea had the fastest declining  $\psi_L$ , it showed the lowest rate of exponential decline in A and E. This implies that either  $\psi_L$  may not be a good indicator of plant water status in chickpea or the crop may have other mechanisms to maintain its A and E at a lower plant water status. Most

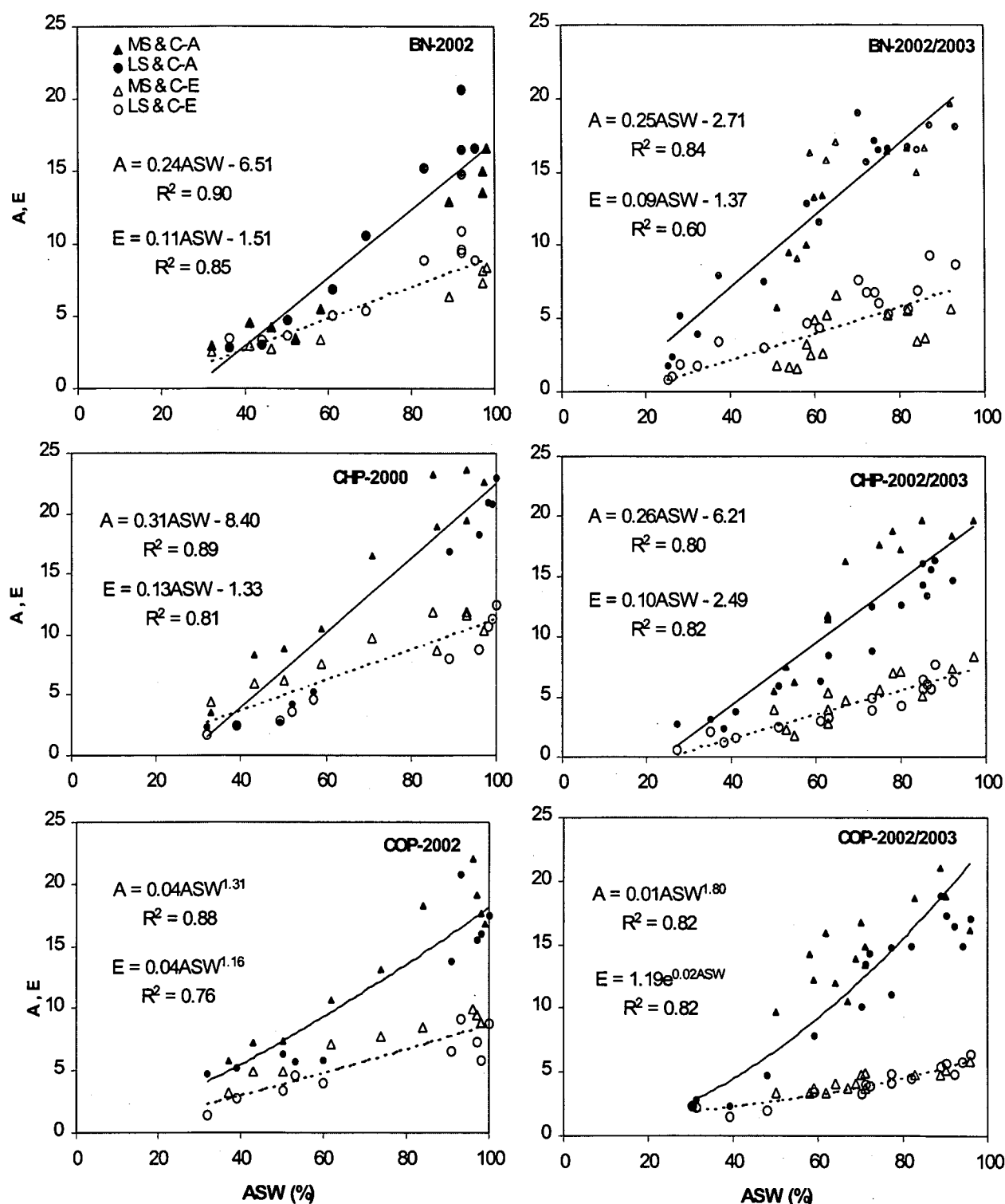


Figure 6.10. The relationship between available soil water (ASW), rate of photosynthesis (A,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) and transpiration (E,  $\text{mmol m}^{-2} \text{s}^{-1}$ ) in three grain legumes under water stress (MS & LS) and well-watered (C) conditions in 2002 (left) and 2002/2003 (right) seasons. BN= beans, CHP = chickpea, COP = cowpea.

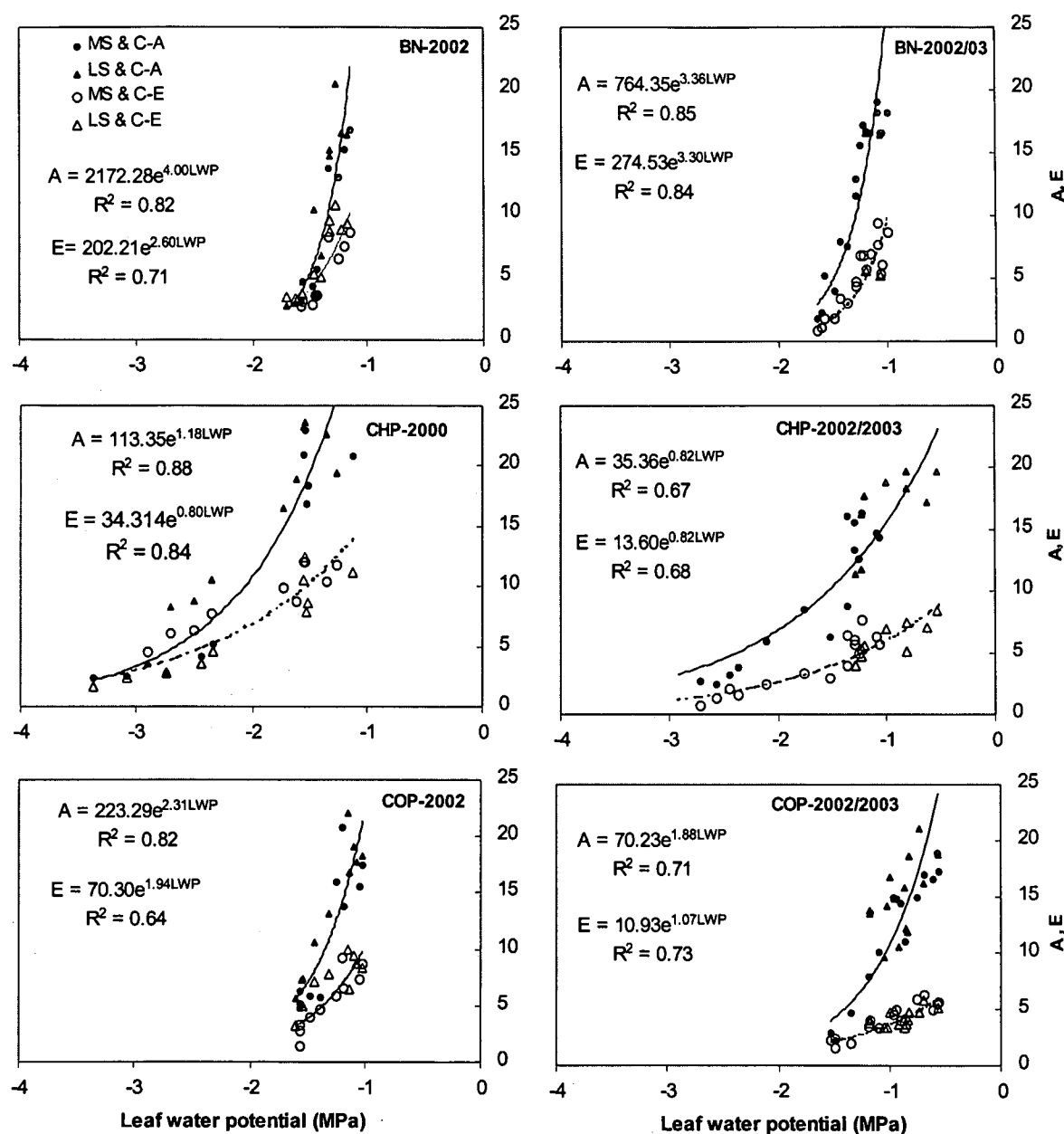


Figure 6.11. The relationship between leaf water potential (LWP), rate of photosynthesis (A,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) and transpiration (E,  $\text{mmol m}^{-2} \text{s}^{-1}$ ) in three grain legumes under water stress (MS & LS) and well-watered (C) conditions in 2002 (left) and 2002/2003 (right) seasons. BN= beans, CHP = chickpea, COP = cowpea.

probably, the maintenance of A and E under low  $\psi_L$  in chickpea could be related to the ability of the crop to adjust osmotically in response to decreasing  $\psi_L$  (Morgan *et al.*, 1991; Leport *et al.*, 1998) compared to cowpea in which osmotic adjustment is absent (Diallo *et al.*, 2001). The first decline in A was observed at an average  $\psi_L$  of -1.2, -1.5, and -1.1 MPa and it was affected by as much as five fold when  $\psi_L$  reached -1.5, -2.7 and -1.5 MPa in beans, chickpea and cowpea, respectively.

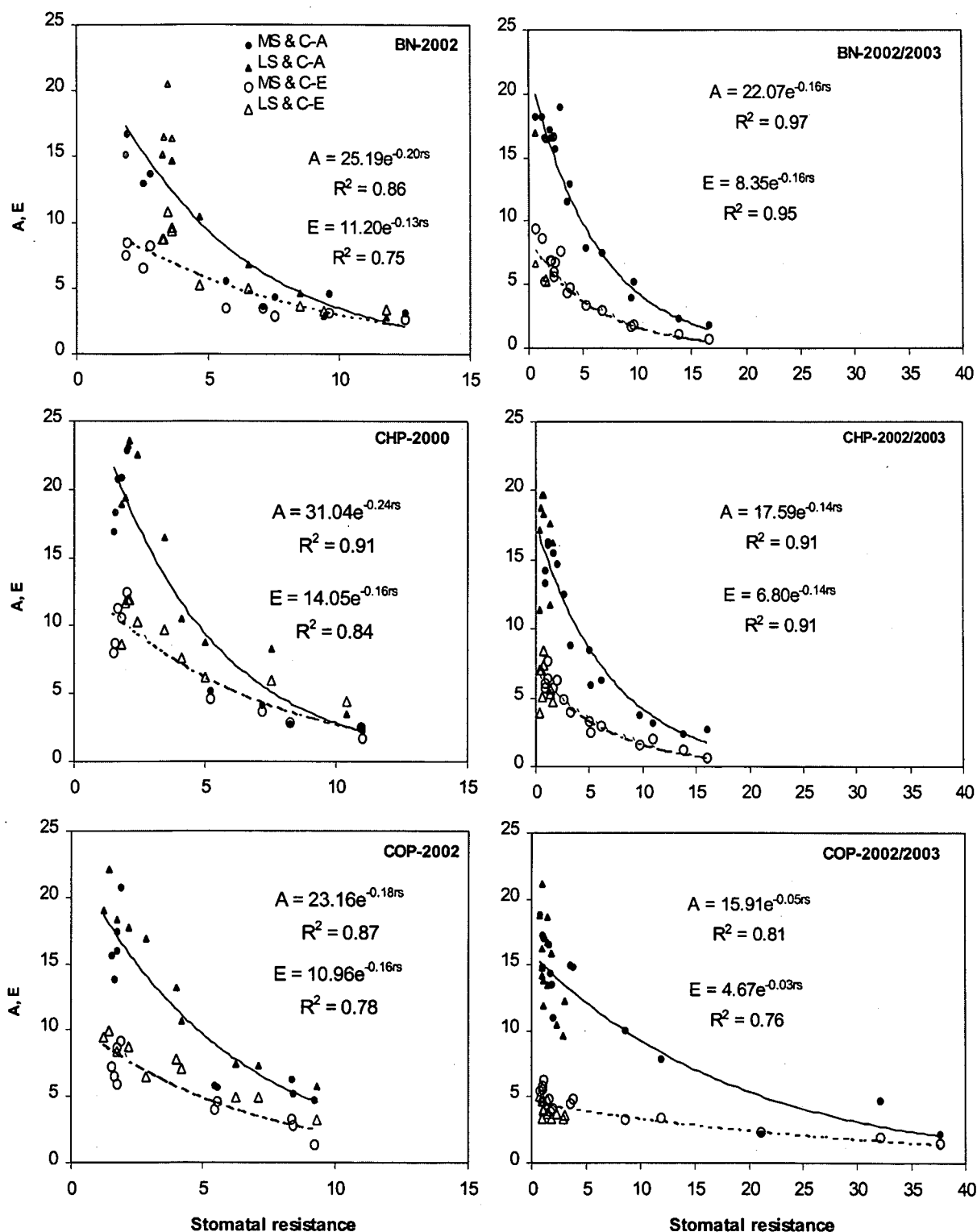


Figure 6.12. The relationship between stomatal resistance ( $r_s$ , s cm<sup>-1</sup>), rate of photosynthesis ( $A$ ,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) and transpiration ( $E$ , mmol m<sup>-2</sup> s<sup>-1</sup>) in three grain legumes under water stress (MS & LS) and well-watered (C) conditions in 2002 (left) and 2002/2003 (right) seasons. BN= beans, CHP = chickpea, COP = cowpea.

The present values are lower than the threshold  $\psi_L$  at which a marked decline in the rate of photosynthesis and stomatal conductance was observed in six cool-season food legumes in a Mediterranean-type environment (Leport *et al.*, 1998) as well as in narrow leafed lupin (Turner and Henson, 1989). Marked decrease in A is reported to be associated with  $\psi_L$  at which ABA concentration increased in the leaves causing stomata to close (Turner and Henson, 1989).

A and E were also exponentially related to  $r_s$  in all the species in both seasons (Fig. 6.12). Similar relationships were reported in soybean (Baldocchi *et al.*, 1985). The rate of decline in A and E with an increase in  $r_s$  was higher in 2002/2003 than in 2002. The exponential rate of decline in A and E with an increase in  $r_s$  was similar in beans and chickpea while it was lower in cowpea (Fig. 6.12).

The rate of decline in A with an increase in  $r_s$  was higher than that of E suggesting that A is more sensitive to stomatal closure than E does. This could be as a result of cuticular gas exchange under conditions of stomatal closure which more favours the passage of water vapour than  $\text{CO}_2$  as observed in grape (Boyer *et al.*, 1997). Linear regressions of the data in Fig. 6.12 indicated that both A and E were detrimentally affected when the  $r_s$  increased on average above 8.0, 8.1 and 6.1  $\text{s cm}^{-1}$  in beans, chickpea and cowpea, respectively. This and other similar studies (Cruz de Carvalho *et al.*, 1998; Costa Franca *et al.*, 2000) indicate that early stomatal closure is the main reason for the decline of  $\text{CO}_2$  assimilation under water stress.

#### 6.3.6. Relationship of ASW, A, E, $r_s$ , $\psi_L$ and $T_L$ to VPD

The correlation coefficients between VPD (measured within canopy and at different heights above crop canopy) and the other parameters are presented in Table 6.11. It was found that ASW was negatively correlated with VPD measured within canopy and half a meter above canopy but not with the VPDs measured above this height (Table 6.11). Although not correlated to VPD directly, ASW is reported to influence the sensitivity of stomata to air humidity (Calvet, 2000). The correlations of  $\psi_L$  and  $r_s$  with the VPD measured at the different heights in the canopy were significantly negative and positive, respectively in all three species in both seasons (Table 6.11). A similar relation between VPD and stomatal behaviour (conductance or resistance) has been reported in a number of crops and environments (Schulez and Hall, 1982; Grantz and Meinzer, 1990; Aphalo

and Jarvis, 1991; Maroco *et al.*, 1997). The response of stomata to changes in air VPD can be related to the changes in the rate of transpiration (Mott and Pankhrust, 1991; Schulze, 1994). Therefore, the degree of stomatal response to leaf-to-air VPD depends on a number of factors including water stress (Tewolde *et al.*, 1993; Schulze, 1994), air humidity (Kawamitsu *et al.*, 1993; Hinckley and Braatne, 1994), radiation (Grantz *et al.*, 1987; Hinckley and Braatne, 1994), plant phenological stage (Jones, 1992), concentration of CO<sub>2</sub> and plant growth substances (Hinckley and Braatne, 1994).

**Table 6.11. Correlation of VPD measured at different heights of crop canopy with available soil water (ASW, %), leaf water potential ( $\psi_L$ , MPa), stomatal resistance ( $r_s$ , s cm<sup>-1</sup>), rate of photosynthesis (A,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), rate of transpiration (E, mmol m<sup>-2</sup> s<sup>-1</sup>) and leaf temperature ( $T_L$ , °C) in the three grain legumes grown under water stress and non-stress conditions for two seasons.<sup>+</sup>**

Parameter	2002				2002/2003		
	Within canopy	0.5m (AC) <sup>b</sup>	1m (AC)	VPD 2m (WS)	0.5m (AC)	1m (AC)	2m (WS)
<b>Bean</b>							
ASW	-0.60**	-0.58**	-0.32	-0.37	-0.14	-0.14	-0.14
$\psi_L$	-0.62**	-0.61**	-0.46*	-0.55*	-0.52**	-0.52**	-0.60***
$r_s$	0.67**	0.64**	0.55*	0.65**	0.44*	0.39*	0.41*
A	-0.48*	-0.52*	-0.43	-0.50*	0.15	0.17	0.18
E	-0.42	-0.52*	-0.45*	-0.48*	0.37*	0.41*	0.48**
$T_L$	0.64**	0.58**	0.45*	0.57*	0.73***	0.70***	0.74***
<b>Chickpea</b>							
ASW	-0.72**	-0.64**	-0.36	-0.39	-0.28	-0.26	-0.21
$\psi_L$	-0.62**	-0.55*	-0.47*	-0.53*	-0.66***	-0.63***	-0.60***
$r_s$	0.52*	0.41	0.44*	0.46*	0.50**	0.48**	0.39*
A	-0.51*	-0.42	-0.41	-0.43	-0.08	-0.08	-0.09
E	-0.36	-0.35	-0.37	-0.35	0.11	0.17	0.25
$T_L$	0.50*	0.28	0.25	0.32	0.76***	0.71***	0.68***
<b>Cowpea</b>							
ASW	-0.47*	-0.38	-0.35	-0.41	-0.09	-0.05	-0.01
$\psi_L$	-0.32	-0.29	-0.37	-0.43	-0.36*	-0.31	-0.33
$r_s$	0.39	0.26	0.43	0.49*	0.36*	0.28	0.27
A	-0.35	-0.51*	-0.60**	-0.64**	0.16	0.25	0.16
E	-0.25	-0.38	-0.56*	-0.56*	0.41*	0.44*	0.39*
$T_L$	0.44*	0.62**	0.66**	0.69**	0.78***	0.80***	0.74***

<sup>+</sup>n = 20 and 30 in 2002 and 2002/2003 respectively; \*, \*\*, \*\*\* value significant at 5, 1 and 0.1% P level, respectively. <sup>b</sup>AC= above crop canopy, WS = weather station. <sup>c</sup>The VPD used here is a mean of hourly measurements between 10:00 and 2:00 local time.

A was significantly negatively correlated with VPD ( $r = -0.60^*$ ) under well-watered conditions for beans and cowpea while there was no correlation for chickpea (Fig. 6.13). This suggests that the stomata of beans and cowpea are sensitive to changes in VPD of the air even under high soil water status. Under water stress conditions, however, A was significantly correlated with VPD ( $r = -0.58^*$ ) in cowpea while there is no correlation in beans and chickpea (Fig. 6.13). This could be due to the overriding role of water stress in controlling the stomatal response of beans (stomata remain close irrespective of changes

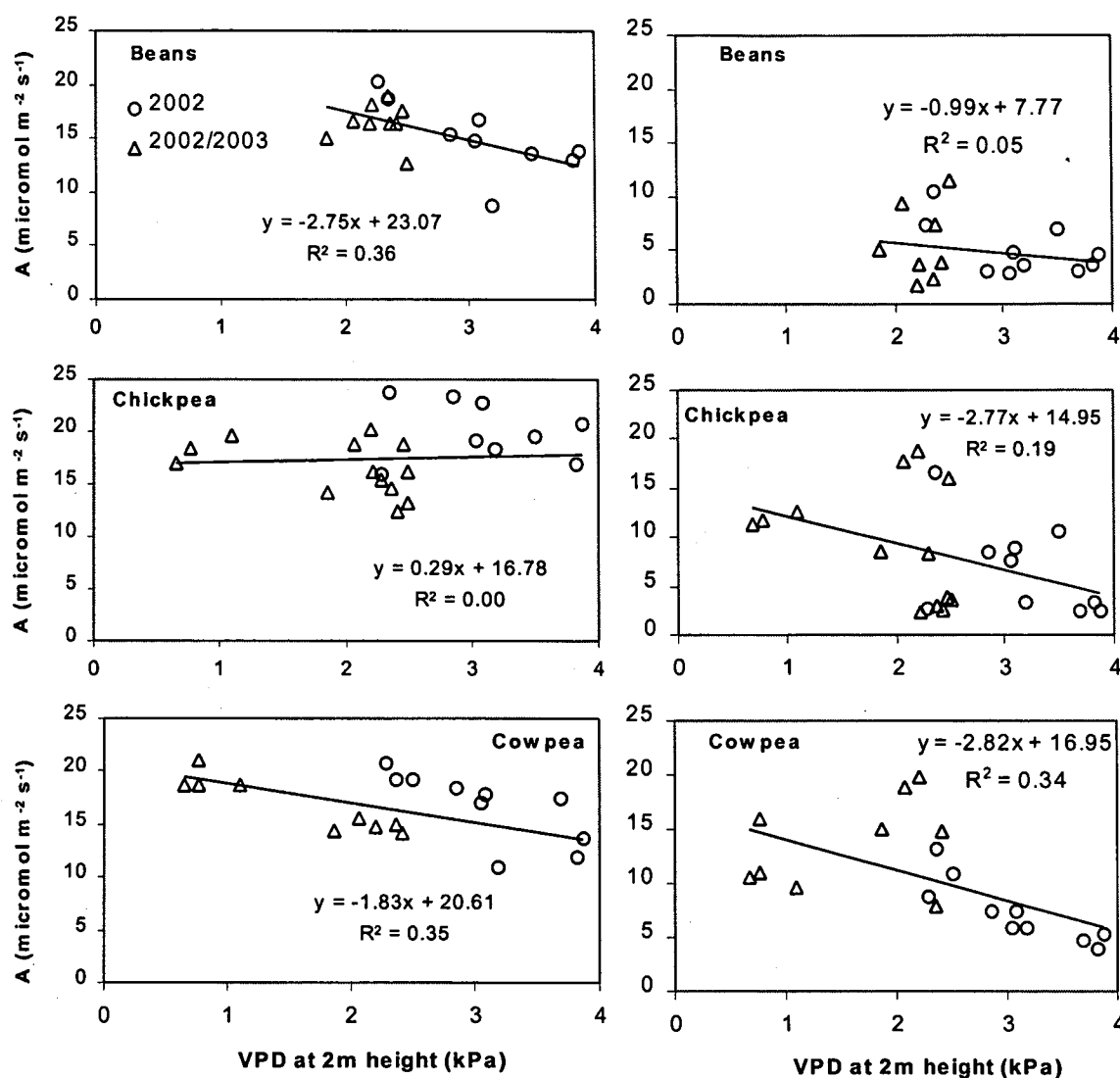


Figure 6.13. The relationship between rate of photosynthesis ( $A$ ) and vapour pressure deficit of the air (VPD) measured at 2 m height for the well-watered (left) and stressed (right) plants of beans, chickpea and cowpea in 2002 and 2002/2003 seasons. Data presented is for non-cloudy day measurements and for both the mid-season and late season stress periods combined over the two seasons. The VPD is a mean of hourly measurements between 10:00 and 2:00 local time.

in VPD) unlike cowpea where the stomata still remained responsive to changes in VPD and soil water deficit.

Lack of any correlation between  $A$  and VPD under both well-watered and stressed conditions in chickpea suggest that the stomata of this crop are not responsive to changes in VPD. Generally, increased VPD is associated with a decrease in  $A$  though the relationship depends on other factors like leaf temperature, leaf conductance and water



stress (Sage and Reid, 1994).  $T_L$  was significantly positively correlated with the VPDs in all crops and seasons (Table 6.11). Increases in leaf temperature are primarily responsible for increases in VPD of the air in the vicinity of the canopy (Sage and Reid, 1994). Since the VPD at weather station (2 m) is correlated with most of the parameters, it could be used as representative of canopy VPD in crop-weather relation studies.

### 6.3.7. Post stress recovery

The extent to which photosynthetic capacity is maintained during periods of water stress and the ability for rapid recovery after re-watering is important in crop adaptation in dry environments. Thus, an understanding of the recovery of photosynthesis and other physiological processes from water stress may aid in identifying drought resistance mechanisms in crop plants. Measurements of A, E and stomatal conductance ( $g_s$ ) made at the end of mid-season stress and three days after re-watering are presented in Table 6.12 as percent of the control at each measurement time. Recovery was calculated as the difference between the two measurements. While the recovery of transpiration was very high in chickpea, the recovery of photosynthesis was higher in beans and cowpea (Table 6.12). On the other hand, the recovery of  $g_s$  was higher in beans and chickpea compared to cowpea. Higher recovery of A while the recovery of  $g_s$  is lower in cowpea indicates the existence of reversible non-stomatal factors that could reduce photosynthesis during periods of water deficit in this crop. One of such factors is leaf temperature (Table 6.12).

**Table 6.12. Recovery of physiological processes upon re-watering after MS stress in 2002/2003.<sup>+</sup>**

Parameter	Measurement	Bean	Chickpea	Cowpea
E (%)	Before re-watering	87	91	83
	After re-watering	43	24	41
	Recovery (%)	44	67	42
$g_s$ (%)	Before re-watering	95	96	97
	After re-watering	50	53	67
	Recovery (%)	45	43	30
A (%)	Before re-watering	90	74	86
	After re-watering	44	40	41
	Recovery (%)	46	34	45
$T_L$ (difference, °C)	Before	-1.8	-7.2	-4.3
	After	2.6	-4.9	0.7

<sup>+</sup>, The values indicated are percent of reductions (or difference for temperature between C and MS) relative to the control just before re-watering and three days after re-watering. Percent of recovery is the difference between the relative percentage values before and after re-watering.

The leaves of the stressed plants were hotter than the controls by -1.8, -7.2 and -4.3 °C in beans, chickpea and cowpea, respectively during the stress but became cooler than the controls by 2.6 °C in beans and by 0.7 °C in cowpea after three days of re-watering (Table 6.12). However, the previously stressed leaves of chickpea remained hotter than their control counter parts by 4.9 °C after re-watering. Comparison of the temperature differences between stressed and control plants before and after re-watering showed that the decline of leaf temperature up on re-watering was higher in cowpea (5 °C) than in beans (4 °C) and in beans than in chickpea (2.3 °C). Therefore, fast recovery of photosynthesis from stress in cowpea is mainly due to fast declining leaf temperatures while the recovery in beans is due to both lowering of temperatures in the stressed leaves and rapid recovery of stomatal conductance. Chickpea, which had slower reduction of leaf temperature upon re-watering, showed the lowest recovery of its photosynthesis, while the recovery of its stomatal conductance resulted in the fast recovery of transpiration. Since chickpea had the lowest leaf water potential during the stress, the lowest recovery of A could also be explained by possible damage in the photosynthesis apparatus caused by the drought. In others studies, slower and partial recovery of photosynthesis following rehydration was observed in beans (Cruz de Carvalho *et al.*, 1998). In comparing beans and cowpea, Cruz de Carvalho *et al.* (1998) found higher recovery of photosynthesis in cowpea than in beans. The low recovery in beans was suggested to be due to the damage of the photosynthetic apparatus. However, since the recovery of photosynthesis of cowpea and beans is similar, one may assume that there has no damage to photosynthetic apparatus of beans in the present study. In pigeonpea, a complete recovery of photosynthesis has been observed after seven days of re-watering (Lopez *et al.*, 1988).

#### **6.3.8. Estimation of photosynthesis and transpiration from other measured parameters**

Studies which involve field measurement of photosynthesis, transpiration and plant and soil water status are big challenges in many developing countries due to lack of equipment. Therefore, simple equations that can relate these variables with other parameters, which are cheaper to measure, could help scientific and educational activities in these countries. In this study, a stepwise regression was employed to estimate A and E from weather and other physiological parameters in the reproductive stage of the three grain legume species.

**Table 6.13.** Estimation of midday rate of photosynthesis ( $A$ ,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), transpiration ( $E$ ,  $\text{mmol m}^{-2} \text{s}^{-1}$ ), leaf water potential ( $\psi_L$ , MPa) and available soil water (ASW, %) from weather, soil and plant parameters in three grain legumes using stepwise regression for 2002 season.

Season 2002	$R^2$ ( $n = 20$ )
<b>Beans</b>	
$A = -11.5 + 0.0824\text{ASW} + 1.72E + 0.105T_L + 0.367\text{VPD}(1\text{m})$	0.95
$A = -6.50 + 0.223\text{ASW} + 0.15\text{VPD}(2\text{m})$	0.80
$E = -2.59 + 0.104\text{ASW} + 0.45\text{VPD}(\text{canopy})$	0.75
$E = -0.68 + 0.092\text{ASW} + 0.015\text{VPD}(2\text{m})$	0.73
$\psi_L = -1.42 - 0.035r_s + 0.019E + 0.084\text{VPD}(2\text{m}) - 0.06\text{VPD}(\text{canopy})$	0.92
$\psi_L = -1.80 + 0.0061\text{ASW} - 0.0072\text{VPD}(2\text{m})$	0.86
$\text{ASW} = 79.0 - 5.70r_s + 2.83E + 2.19\text{VPD}(2\text{m})$	0.92
$\text{ASW} = 105 - 7.60r_s + 2.66\text{VPD}(2\text{m})$	0.89
<b>Chickpea</b>	
$A = 4.13 + 0.120\text{ASW} + 1.28E - 0.232T_L$	0.94
$A = -12.8 + 0.299\text{ASW} + 1.50\text{VPD}(2\text{m})$	0.80
$E = 28.6 - 0.077\text{ASW} + 7.45\text{LWP} - 1.15\text{VPD}(1\text{m}) + 1.20\text{VPD}(\text{canopy})$	0.75
$E = -3.00 + 0.113\text{ASW} + 0.701\text{VPD}(2\text{m})$	0.56
$\psi_L = -3.56 + 0.0199\text{ASW} - 0.045r_s + 0.028E + 0.04\text{VPD}(0.5\text{m})$	0.97
$\psi_L P = -4.26 + 0.028\text{ASW} + 0.0781\text{VPD}(2\text{m})$	0.95
$\text{ASW} = 148.0 + 32.3\psi_L - 4.23\text{VPD}(0.5\text{m})$	0.96
$\text{ASW} = 152 + 33.2\psi_L - 4.16\text{VPD}(2\text{m})$	0.95
<b>Cowpea</b>	
$A = 0.68 + 3.39\text{VPD}(\text{canopy}) - 4.21\text{VPD}(0.5\text{m}) + 0.132\text{ASW}(\%) + 0.871E$	0.97
$A = 5.76 + 0.170\text{ASW} - 1.97\text{VPD}(2\text{m})$	0.77
$E = 11.8 - 0.748r_s - 0.897\text{VPD}(1\text{m}) + 2.15\text{VPD}(\text{canopy}) - 1.84\text{VPD}(0.5\text{m})$	0.86
$E = 2.26 + 0.074\text{ASW} - 0.543\text{VPD}(2\text{m})$	0.67
$\psi_L = -2.04 + 0.009\text{ASW} + 0.041\text{VPD}(\text{canopy})$	0.91
$\psi_L = -2.04 + 0.0086\text{ASW} + 0.036\text{VPD}(2\text{m})$	0.89
$\text{ASW} = 191.0 + 29.8\text{LWP} - 5.35r_s - 1.43T_L$	0.96
$\text{ASW} = 307 - 5.69T_L - 3.74\text{VPD}(2\text{m})$	0.53

Regression equations from the best variables identified with the stepwise regression and from easily available variables such as ASW and VPD are shown in Tables 6.13, 6.14 & 6.15 for each season and for data pooled over the two seasons. The regression equations were highly significant ( $P < 0.01$ ) for all species. The coefficient of determination ( $R^2$ ) was higher for each individual season compared to the pooled data (Table 6.13 to 6.15). However, the  $R^2$  for the pooled data of  $A$  was also higher ( $\geq 0.80$ ) indicating that  $A$  could be determined from the parameters with reasonable accuracy. On the other hand, the  $r^2$  for  $E$  (for each season and pooled data) was low, particularly in cowpea, suggesting that the success of estimating  $E$  from the parameters indicated in Table 6.13 to 6.15 was low. Estimation of  $A$  and  $E$  from ASW and VPD (at weather station) gave a better result in beans ( $R^2 \geq 0.79$ ) compared to chickpea ( $R^2 \geq 0.42$ ) and cowpea ( $R^2 \geq 0.16$ ).

**Table 6.14. Estimation of midday rate of photosynthesis ( $A$ ,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), transpiration ( $E$ ,  $\text{mmol m}^{-2} \text{s}^{-1}$ ), leaf water potential ( $\psi_L$ , MPa) and available soil water (ASW, %) from weather, soil and plant parameters in three grain legumes using stepwise regression for 2002/2003 season.**

Season 2002/2003	$R^2$ (n=30)
<b>Beans</b>	
$A = -5.85 - 2.26\text{VPD}(2\text{m}) + 0.091\text{ASW} + 1.83E + 0.248 T_L$	0.94
$A = -8.82 + 2.44\text{VPD}(2\text{m}) + 0.251\text{ASW}$	0.81
$E = -4.20 + 2.14\text{VPD}(2\text{m}) + 0.072\text{ASW} - 0.119r_s$	0.81
$E = -5.40 + 1.94\text{VPD}(2\text{m}) + 0.090\text{ASW}$	0.79
$\psi_L = -1.26 - 0.129\text{VPD}(2\text{m}) + 0.006\text{ASW} - 0.0017r_s$	0.89
$\psi_L = -1.43 - 0.156\text{VPD}(2\text{m}) + 0.0082\text{ASW}$	0.87
$\text{ASW} = 120 + 1.99\text{VPD}(2\text{m}) + 62.7\psi_L + 3.72E$	0.85
<b>Chickpea</b>	
$A = -10.9 - 2.73\text{VPD}(2\text{m}) + 6.48\psi_L + 2.12E + 0.774 T_L$	0.88
$A = -3.19 + 0.33\text{VPD}(2\text{m}) + 0.202\text{ASW}$	0.43
$E = 2.09 + 1.77\text{VPD}(2\text{m}) + 0.016\text{ASW} + 1.28\text{LWP} - 0.146r_s$	0.64
$E = -2.78 + 1.05\text{VPD}(2\text{m}) + 0.071\text{ASW}$	0.52
$\psi_L = -0.715 - 0.284\text{VPD}(2\text{m}) + 0.012\text{ASW} - 0.0298r_s - 0.03T_L$	0.90
$\psi_L = -2.21 - 0.360\text{VPD}(2\text{m}) + 0.021\text{ASW}$	0.83
$\text{ASW} = 97.6 + 11.0\text{VPD}(2\text{m}) + 34.60\psi_L$	0.74
<b>Cowpea</b>	
$A = -15.9 - 2.32\text{VPD}(2\text{m}) + 0.0875\text{ASW} + 1.22E + 0.666T_L - 0.273r_s$	0.80
$A = -2.73 + 1.38 \text{VPD}(2\text{m}) + 0.182\text{ASW}$	0.36
$E = 3.05 + 4.31\text{VPD}(1\text{m}) - 2.79\text{VPD}(0.5\text{m}) + 0.02r_s - 0.061T_L$	0.22
$E = 2.94 + 0.972\text{VPD}(2\text{m}) - 0.0083\text{ASW}$	0.16
$\psi_L = -1.65 - 0.0113\text{VPD}(2\text{m}) + 0.012\text{ASW} - 0.0020r_s$	0.87
$\psi_L = -1.46 - 0.138\text{VPD}(2\text{m}) + 0.0101\text{ASW}$	0.68
$\text{ASW} = 123.00 + 7.89\text{VPD}(2\text{m}) + 65.6\psi_L$	0.85

Regression equations for determining  $\psi_L$  and ASW from the other parameters are also given in Table 6.13 to 6.15. A better estimate of leaf water potential can be obtained from ASW and VPD in the three crops ( $r^2 = 0.68-0.87$ ). A reasonable estimate of ASW (%) can also be found from VPD and  $\psi_L$  in chickpea and cowpea ( $r^2 = 0.74-0.85$ ) and including  $E$  on these variables in beans ( $r^2 = 0.85$ ).

These equations are useful for determining plant and soil water status from other parameters for the purpose of irrigation scheduling or adjusting other management practices in these species for environments similar to the experimental site. The equations are also important to understand the relationship of the different weather and physiological parameters so as to model the growth and development of the species under water deficit environments.

**Table 6.15.** Estimation of midday rate of photosynthesis ( $A$ ,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ), transpiration ( $E$ ,  $\text{mmol m}^{-2} \text{s}^{-1}$ ), leaf water potential ( $\psi_L$ , MPa) and available soil water (ASW, %) from weather, soil and plant parameters in three grain legumes using stepwise regression for data combined over two seasons.

2002 and 2002/2003 seasons data combined	$R^2$ (n=50)
<b>Beans</b>	
$A = 13.5 - 1.37\text{VPD}(2\text{m}) + 11.9\psi_L + 1.65E + 0.217T_L$	0.88
$A = -2.52 + 0.217\text{ASW} - 0.419\text{VPD}(2\text{m})$	0.67
$E = -4.56 + 0.098\text{ASW} + 1.16\text{VPD}(2\text{m})$	0.73
$\psi_L = -1.07 - 0.090\text{VPD}(2\text{m}) + 0.0022\text{ASW} - 0.031r_s$	0.85
$\psi_L = -132 - 0.144\text{VPD}(2\text{m}) + 0.0059\text{ASW}$	0.78
$\text{ASW} = 87.1 + 29.3\text{LWP} - 1.45r_s + 4.85E$	0.83
<b>Chickpea</b>	
$A = 0.02 + 6.27\psi_L + 1.49E + 0.397T_L$	0.86
$A = -6.96 + 0.248\text{ASW} + 0.719\text{VPD}(2\text{m})$	0.61
$E = -0.385 + 1.65\text{VPD}(2\text{m}) + 0.084\text{ASW} - 0.133r_s$	0.61
$E = -5.49 + 1.54 \text{ VPD}(2\text{m}) + 0.103\text{ASW}$	0.59
$\psi_L = -0.724 - 0.289\text{VPD}(2\text{m}) + 0.014\text{ASW} - 0.027r_s$	0.88
$\psi_L = -2.20 - 0.376\text{VPD}(2\text{m}) + 0.020\text{ASW}$	0.84
$\text{ASW} = 85.7 + 12.8\text{VPD}(1\text{m}) - 8.70\text{VPD}(0.5\text{m}) + 21.0\psi_L + 1.97E - 0.69r_s$	0.80
$\text{ASW} = 100 + 11.0 \text{ VPD}(2\text{m}) + 33.9\psi_L$	0.71
<b>Cowpea</b>	
$A = -0.50 - 0.88\text{VPD}(2\text{m}) - 1.67\text{VPD}(1\text{m}) + 8.28\psi_L - 0.216r_s + 1.42E + 0.604T_L$	0.79
$A = -1.46 - 0.062\text{VPD}(2\text{m}) + 0.191\text{ASW}$	0.49
$E = -8.90 + 0.103\text{ASW} - 5.44\psi_L + 0.029r_s$	0.43
$E = -0.60 + 0.049\text{ASW} + 0.813\text{VPD}(2\text{m})$	0.29
$\psi_L = -1.43 - 0.124\text{VPD}(2\text{m}) + 0.0103\text{ASW} - 0.0321E$	0.81
$\psi_L = -1.41 - 0.15\text{VPD}(2\text{m}) + 0.0088\text{ASW}$	0.76
$\text{ASW} = 110.0 + 5.51\text{VPD}(2\text{m}) + 58.6\psi_L - 0.355r_s + 3.43E$	0.77
$\text{ASW} = 128.0 + 9.38\text{VPD}(2\text{m}) + 69.2\psi_L$	0.61

#### 6.4. Summary and Conclusion

Differences in leaf water potential between well-watered and stressed plants of beans and cowpea were very small despite large variations in soil water, stomatal resistance, photosynthesis and transpiration. However, a higher decline in leaf water potential with declining soil water was observed in chickpea, and the decline was greater in the late-season stress than the mid-season stress. The magnitude and rate of photosynthetic reduction was higher and faster in the mid-season than in the late-season stress in all species, and among the species the rate of photosynthesis declined faster in chickpea than in beans and cowpea. Cowpea had the lowest reduction in its rate of photosynthesis under severe water stress compared to the other two species.

The diurnal course of leaf water potential was different for the control and stressed plants of the three species indicating the differential response of the species to the changing weather conditions. Moreover, the diurnal physiological response of the stress plants to

the changing weather conditions (temperature, radiation and VPD) was different from that of the controls. Such differential responses are partly because of the overriding effect of water stress on other responses (e.g. A and VPD relationship in beans), and partly because of plants' adaptation mechanism to survive and maintain productivity under stress environment while maximizing productivity under favourable environment. Increase in leaf temperature was found to be the major factor for the decline of net photosynthesis in the stressed plants through its effect on stomatal adjustment, transpiration and possibly enzymatic activities. Although most of the physiological parameters considered were highly correlated with mean daytime VPDs measured closer to the canopy, significant correlations were also obtained with the mean daytime VPD measured at the weather station. Because of the ease of measurement and its availability, the use of standard VPD can give good representation of canopy VPD in crop-weather relation studies.

Cowpea closes its stomata at higher leaf and soil water potential followed by beans whereas the stomata of chickpea remain open under lower leaf and soil water status. This fast stomatal response makes cowpea a more drought-avoiding crop than beans and chickpea. On the other hand, the rate of photosynthesis and transpiration decline with leaf water potential was lower in chickpea than in beans and cowpea, suggesting that chickpea may have other mechanisms (possibly osmotic adjustment) to maintain productivity despite its fast declining plant water status. Therefore, two contrasting scenarios were observed. Chickpea had the lowest and fastest declining leaf water potential while cowpea had the highest leaf water potential and fastest closing stomata. Both species, however, maintained similar rate of leaf photosynthesis under severe water stress conditions. This indicates the different adaptation mechanism of the species though the goal (maintaining leaf photosynthesis) remains the same. Nevertheless, post-stress recovery of photosynthesis was lower in chickpea compared to the other two species. The three species have one thing in common that their rate of photosynthesis can be estimated from a few weather and physiological parameters and soil water content with reasonable accuracy.

Chickpea, as a cool-season food legume, is considered to be more drought susceptible than the warm-season food legumes such as beans and cowpea. In the current study, however, chickpea showed considerable performance which is almost similar to the

warm-season grain legumes in terms of maintaining its photosynthesis under severe water stress and high temperature. Therefore, this species has a promising potential to be grown in dry environments with higher temperature and evaporative demand compared to the environments where it is currently grown in Ethiopia.

## CHAPTER 7

### Comparison of Yield and Yield Components Response of Three Grain Legumes Species to Variable Water Supply During the Reproductive Stages

#### 7.1. Introduction

Drought is a major limiting factor to yield and increased productivity of tropical crops. Grain legumes are commonly grown under rainfed conditions in the semi-arid tropics and are subjected to drought as a result of water shortage at one or more of their growth stages (e.g. Turk *et al.*, 1980a; Kumar *et al.*, 1996; Kumar and Abbo, 2001). Drought at various stages in the crop cycle is the major reducer of yield in many grain legumes (e.g. Kumar and Abbo, 2001; Jeuffroy and Ney, 1997) and cereals (e.g. Saini and Westgate, 2000). Plant growth and development can be affected by water deficit at any time during the crop life cycle. However, the extent and nature of damage, the capacity of recovery and the impact on crop yield depends on the developmental stage at which the stress occurs and the type of crop species or cultivars involved (French and Turner, 1991; Kirda and Kanber, 1999; Simane *et al.*, 1993; De Costa *et al.*, 1999; Saini and Westgate, 2000). Compared to the vegetative period, drought at some time during the reproductive phase is responsible for more reduction in grain yield of many crops (Sinoit and Kramer, 1977; Calvache and Reichardt, 1999; Kumar and Abbo, 2001; Jamieson *et al.*, 1995; NeSmith and Ritchie, 1992; Saini and Westgate, 2000). The sensitivity of yield reduction as a result of drought also varies among stages within the reproductive period in grain legumes. For example, bean yield was reported to be more susceptible to water stress at flowering than pod-filling stage (Calvache and Reichardt, 1999) while cowpea grain yield was found to be more susceptible to pod-filling than flowering period water deficit (Turk *et al.*, 1980a). Therefore, characterization of developmental stages and the determination of sensitive periods in a given environment are important to avoid or minimize the effect of water stress on grain legumes (Jeuffroy and Ney, 1997).

The number of pods initiated and their rate of growth, the number of seeds per pod and their mass are important determinants of harvest index in grain legumes (Lawn and Ahn, 1985; Siddique and Sedgley, 1986; Jiang and Egli, 1995). Moreover, yield is a function of sink size and its subsequent filling by the source, both of which are affected by water stress depending on its timing and severity with respect to plant growth stages (Blum, 1996). The ability to mobilize pre- and post- anthesis assimilates during the pod filling



period (especially during water deficit) is also an important mechanism in stabilizing yield of grain legumes (Goldsworthy, 1984; Evans, 1993; Turner *et al.*, 2001).

Although, there have been a number of studies that compared the effect of drought during various stages of reproductive development on crop yield in different environments, it is almost impossible to compare crops at an equivalent tissue water status (Saini and Westgate, 2000) because of environmental, experimental and seasonal differences. Therefore, the objectives of this study were (1) to compare the response of yield and yield components of three grain legume species, viz., beans, chickpea and cowpea, to different water regimes, (2) to determine the physiological cause of yield variation, and (3) to identify the most drought-sensitive reproductive stage for each species under the same environmental, seasonal and experimental conditions.

## **7.2. Materials and Methods**

### **7.2.1. Field experiments**

Detail explanations on experimental site, material, design, cultural practices, and irrigation schedule are given in Chapter 3.

### **7.2.2. Measurements**

#### **7.2.2.1. Number of flowers and pods after water stress**

The numbers of flowers and pods (NP) per plant were counted from five randomly selected plants in the central rows of each plot for the stress treatment and its corresponding control. For the LS treatment, counts were made at maturity. The numbers of primary and secondary branches were also counted from the five randomly selected plants in 2002/2003.

#### **7.2.2.2. Yield and yield components**

At final harvest time, all plants from an area of  $6.4 \text{ m}^2$  in the central four rows were harvested by hand. Five plants were selected randomly from the harvested area and the number of pods (NP) and number of seeds (NS) per pod were counted for each plant, and then the NP and NS  $\text{m}^{-2}$  calculated. Above ground total biomass was determined after drying the harvested plants in the open air for 10 days. After hand threshing, seeds were separated from the straw, weighed and adjusted to 12.5% moisture after determining the

moisture content using a Grain Moisture Tester. The equation used for adjusting the yield to the specified moisture content was as follows:

$$Y_{adj} = \left( \left( \frac{12.5 - mc}{100} \right) * Y \right) + Y \quad (7.1)$$

where  $Y_{adj}$  is moisture adjusted yield,  $Y$  is unadjusted yield and  $mc$  is measured moisture content (%). Hundred seed mass (SW) was determined by weighing 100 dried seeds of each plot using a digital sensitive balance. Harvest index (HI) was calculated as the ratio of grain yield to total above ground biomass.

#### 7.2.2.3. Partition coefficient

Mean crop growth rate ( $C_r$ ,  $\text{g m}^{-2} \text{ } ^\circ\text{Cd}^{-1}$ ) was calculated as the linear rate of increase in above ground biomass over the total growth period expressed in thermal time and pod growth rate ( $C_p$ ,  $\text{g m}^{-2} \text{ } ^\circ\text{Cd}^{-1}$ ) was calculated as the linear rate of increase in pod dry matter for the thermal time between 50% flowering and maturity of each species for each treatment. The partitioning coefficient ( $p$ ) was calculated as explained in Duncan *et al.* (1978), Greenburg *et al.*, (1992) and Williams and Saxena (1991) as

$$p = \frac{C_p}{C_r} \quad (7.2)$$

using the above two growth rates.

#### 7.2.2.4. Statistical Analysis

Analyses of Variance (ANOVA) and mean separation (Least Significant Difference, LSD) were conducted using the NCSS statistical program (Hintze, 1997). Correlation and regression analyses were also performed whenever necessary.

### 7.3. Results and Discussion

#### 7.3.1. Water use and evaporative demand

In order to help the discussions in this chapter, a short summary of the magnitude of water stress in each treatment is presented in Table 7.1 as the seasonal crop evaporative deficit ( $1 - ET/ET_0$ ) which relates the crop water demand ( $ET$ ) to the evaporative demand ( $ET_0$ ) of the site. The seasonal crop evaporative deficit was less than 0.15 in the controls in all species, but ranged between 0.17-0.27 in beans, 0.18-0.39 in chickpea and 0.16-0.33 in cowpea in the MS, and between 0.14-0.37 in beans and 0.15-0.34 in chickpea and 0.14-

0.35 in cowpea in the LS treatment in the three seasons (Table 7.1). This shows that the plants in the LS treatment were generally more stressed in 2002/2002 and 2002 seasons than in 2002/2003 season in all species. As mentioned previously, the low stress intensity in the LS treatment in 2002/2003 was due to cloudy weather conditions during the stress period that reduced the evaporative demand.

**Table 7.1. Crop evaporative deficit ( $1-(ET/ET_0)$ ) of beans, chickpea and cowpea plants under mid-season (MS) and late season (LS) water stress and well-watered (C) conditions at a semi arid environment.**

Season	Species	$1-(ET/ET_0)$		
		C	MS	LS
2001/2002	Beans	0.10	0.17	0.22
	Chickpea	0.01	0.25	0.27
	Cowpea	0.03	0.33	0.33
2002	Beans	0.12	0.27	0.37
	Chickpea	0.15	0.39	0.34
	Cowpea	0.09	0.24	0.35
2002/2003	Beans	0.07	0.22	0.14
	Chickpea	0.05	0.18	0.15
	Cowpea	0.06	0.16	0.14

### 7.3.2. Effect of water stress on yield and yield components

Biomass and yield were higher in 2002/2003 than in 2001/2002 and 2002 seasons. Analysis of variance showed significant differences among water regimes for all parameters in all seasons except for HI in 2002 and final biomass and SW in 2002/2003 (Table 7.2). Significant differences were also observed among species for all variables except HI in 2001/2002 and 2002 and yield in 2001/2002. The water regime x species interaction was also significant for NP  $m^{-2}$ , NS  $m^{-2}$  and SW in 2001/2002 and 2002 seasons (Table 7.2). Pooled over species, yield reductions were 77, 68 and 37% in the MS treatment and 65, 30 and 23% in the LS treatment for the first, second and third seasons, respectively indicating that water stress, irrespective of its timing, resulted in reduced grain yield in all seasons.

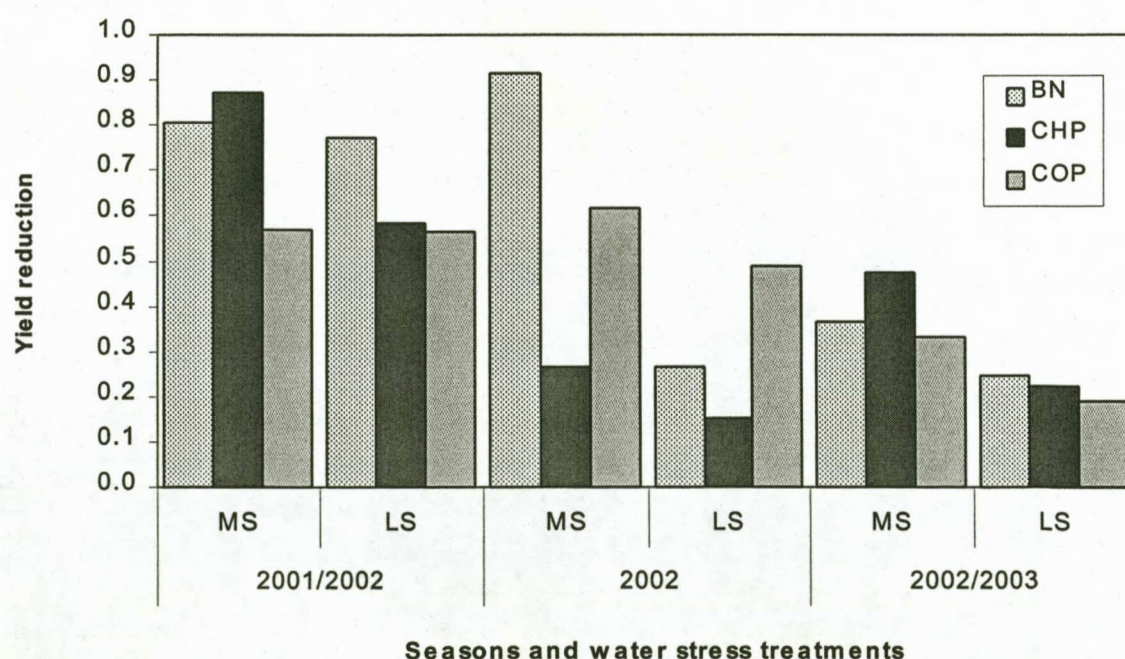
Although the lowest grain yield was recorded in the MS treatment, there was no significant difference in grain yield between the MS and LS treatments in any of the species and seasons except in 2001/2002 (Tables 7.3 and 7.4). In 2001/2002, the MS treatment resulted in significantly lower yield than the LS treatment in beans (Table 7.3). Relative to the control, yield reduction of the species over season ranged from 34-92% in

beans, 26-87% in chickpea and 33-61% in cowpea in the MS treatment, and 22-77% in beans, 15-58% in chickpea and 19-56% in cowpea in the LS treatment (Fig. 7.1).

**Table 7.2.** Mean squares in the analysis of variance of biomass, seed yield, number of pods (NP) and number of seeds (NS) per meter square, 100 seed mass (SW) and harvest index (HI) for three grain legume species grown under three water regimes in three seasons.<sup>+</sup>

Source	df	NP m <sup>-2</sup>	NS m <sup>-2</sup>	SW	Biomass	Seed yield	HI
<b>2001/2002</b>							
REP	2	29789.1	404196.8	5.208	144721.6	88356.5	0.001
Water regime (W <sub>R</sub> )	2	621575.7***	7956288.1**	81.8*	12463024.5*	6826001.8*	0.150*
Error	4	9816.3	214890.6	6.5	1182788.4	437537.9	0.005
Species (S <sub>P</sub> )	2	866587.8***	1534872.4**	283.7***	1535775.8*	28723.9	0.020
W <sub>R</sub> × S <sub>P</sub>	4	313564.1***	752279.1**	19.7*	1075428.3*	315170.9	0.015
Error	12	5242.8	131160.5	5.7	263670.1	181429.4	0.007
Total	26						
<b>2002</b>							
REP	2	217.9	84137.4	6.3	748600.3	6708.0	0.016
W <sub>R</sub>	2	410234.7**	7047980.3***	57.9**	16454573.1***	2704967.6*	0.025
Error	4	21705.9	92801.3	2.1	239192.1	252060.4	0.024
S <sub>P</sub>	2	586748.5***	6042233.4***	147.6***	1222957.7**	891557.1**	0.011
W <sub>R</sub> × S <sub>P</sub>	4	71563.8**	1975375.4***	14.5***	2397078.9***	830180.5**	0.034
Error	12	11638.2	156819.1	0.60	175329.9	114650.8	0.019
Total	26						
<b>2002/2003</b>							
REP	2	104474.7	374127.1	21.2	596573.4	67948.9	0.000
W <sub>R</sub>	2	379524.5*	10948589.4*	1.4	6822149.0	1680161.2*	0.020*
Error	4	50326.3	691061.6	3.5	1591115.2	129919.1	0.002
S <sub>P</sub>	2	2471188.6***	87999971.7***	150.7***	4428756.3**	4202278.2***	0.081***
W <sub>R</sub> × S <sub>P</sub>	4	133767.6	146463.8	7.9	265839.1	46027.7	0.001
Error	12	57177.4	325397.9	7.0	353142.5	148617.7	0.004
Total	26						

<sup>+</sup> \*, \*\*, \*\*\* variation significant at 5, 1 and 0.01% P levels, respectively.



**Figure 7.1.** Relative yield reduction of three grain legumes due to mid-season (MS) and late season (LS) water stress with respect to well-watered conditions in three seasons.

Except for 2002, chickpea was more sensitive to flowering period water stress than beans and cowpea. The lowest relative yield reduction in 2002 in chickpea was mainly due to the high temperature condition which affected the yield of plants in the control treatment. On the other hand, yield reduction in beans was the highest in this season (Fig. 7.1) when flowering water stress was coupled with high temperature.

Both beans and chickpea were more sensitive to the MS than the LS stress across all seasons. As compared to beans and chickpea, the gap in yield reduction due to the MS and LS stresses in cowpea is closer suggesting that water stress at either of the stages could have a similar effect on final grain yield. Moreover, except in the LS treatment in 2002, cowpea was less sensitive than beans to yield reductions due to both the MS and LS stresses. Under the LS stress, beans was more sensitive than cowpea and chickpea in the first season whereas cowpea was more sensitive than the other species in the second season. The yield response of the three species to the LS stress was almost similar in the third season because of low intensity of the stress as explained above.

Although the amount of yield reduction varied among species and time of water stress, the present results indicated a significant amount of yield reduction due to both the MS and LS stresses in all three grain legumes. A significantly higher reduction of grain yield due to reproductive than vegetative season drought has also been reported in a number of grain legumes including chickpea (Singh, 1987; Sivakumar and Singh, 1987), beans (Acosta Gallegos and Shibata, 1989; Tesfaye, 1997), cowpea (Turk *et al.*, 1980a), mung bean (Pannu and Singh, 1993; De Costa *et al.*, 1999) and peanut (Wright *et al.*, 1991).

Compared to the control, both the MS and LS treatments reduced  $\text{NP m}^{-2}$  and  $\text{NS m}^{-2}$  in all the species (Fig. 7.2 and 7.3). However,  $\text{NP m}^{-2}$  was more affected by the MS treatment while  $\text{NS m}^{-2}$  was equally affected by the MS and LS treatments in the milder temperature seasons (2001/2002 and 2002/2003). In the higher temperature season (2002), nevertheless, the MS treatment had significantly lower NS than the LS.

Water stress also affected SW in 2001/2002 and 2002 but not in 2002/2003 which could be as a result of low VPD of the air during this particular period. The reduction of SW from the control was significantly higher in the MS than in the LS treatment in 2002 but similar for both the MS and LS treatments in 2001/2002 (Table 7.3).

**Table 7.3. Mean biomass production at harvest, grain yield, number of pods (NP) and number of seeds (NS) per meter square, 100 seed mass (SW) and harvest index (HI) of three grain legumes under three water regimes in 2001/2002 and 2002 seasons.**

Variable <sup>*</sup>	Water regime	2001/2002			2002		
		Bean	Chickpea	Cowpea	Bean	Chickpea	Cowpea
NP m <sup>-2</sup>	C <sup>Δ</sup>	A 488.0 b*	A 1489.3 a	A 281.3 c	A 417.0 b	A 1162.7 a	A 446.7 b
	MS	B 328.7 a	C 246.0 ab	A 173.3 b	B 165.0 b	C 423.3 a	B 159.0 b
	LS	B 250.0 b	B 683.0 a	A 179.0 b	A 450.7 b	B 702.7 a	A 295.3 b
NS m <sup>-2</sup>	C	A 2906.3 a	A 2979.0 a	A 2643.3 a	A 2849.3 b	A 1162.7 c	A 4015.3 a
	MS	B 1944.3 a	B 246.0 b	B 1382.7 a	B 808.3 a	B 846.0 a	C 1137.0 a
	LS	B 1476.0 a	B 683.0 b	B 1557.3 a	A 3043.0 a	B 848.3 c	B 2281.0 b
SW (g)	C	A 20.7 b	A 34.5 a	A 21.0 b	A 22.7 b	A 27.7 a	A 20.7 c
	MS	B 16.3 c	B 25.7 a	A 20.7 b	C 12.8 c	B 23.7 a	A 19.3 b
	LS	B 14.7 c	B 24.3 a	A 20.0 b	B 17.0 c	B 25.0 a	A 20.3 b
Biomass (kg ha <sup>-1</sup> )	C	A 4619.8 a	A 4057.3 a	A 4182.3 a	A 5690.2 a	A 3748.6 b	A 4960.7 a
	MS	C 1468.7 b	C 1348.9 b	B 3213.0 a	C 1560.0 b	B 2491.6 a	B 2300.8 a
	LS	B 2546.9 a	B 2453.1 a	B 2890.6 a	B 4096.5 a	B 3075.2 b	B 2312.0 c
Grain yield (kg ha <sup>-1</sup> )	C	A 2361.3	A 2276.0	A 1704.2	A 2368.7 a	A 1117.6 b	A 1330.9 b
	MS	B 460.9	B 292.7	B 733.2	C 199.6 b	A 822.9 a	B 513.4 ab
	LS	B 540.6	B 953.5	B 746.0	B 1744.9 a	A 949.1 b	B 682.5 b
HI	C	A 0.50	A 0.56	A 0.41	0.41	0.29	0.27
	MS	B 0.30	B 0.22	B 0.23	0.13	0.37	0.22
	LS	B 0.21	B 0.39	B 0.26	0.43	0.30	0.29

\* Each value is the mean of three replicates; <sup>Δ</sup> Water regime: C = control, MS = mid-season stress, LS = late-season stress

\* Within species, values across water regimes preceded by the same capital letter are not significantly different at P≤0.05; within a water regime, values across species followed by the same lower case letter are not significantly different at P≤0.05.

**Table 7.4. Mean biomass production at harvest, grain yield, number of pods (NP) and number of seeds (NS) per meter square, 100 seed mass (SW) and harvest index (HI) of three grain legumes under three water regimes in 2002/2003.\*<sup>Δ</sup>**

Variable	Water regime	Bean	Chickpea	Cowpea
NP m <sup>-2</sup>	C	651.0 ± 7.87	1794.7 ± 209.24	346.3 ± 42.61
	MS	509.7 ± 53.49	1074.7 ± 298.93	258.0 ± 29.38
	LS	468.3 ± 34.14	972.3 ± 206.09	196.7 ± 17.15
NS m <sup>-2</sup>	C	4819.7 ± 94.41	2879.0 ± 449.09	3957.7 ± 537.79
	MS	3000.0 ± 538.69	1074.7 ± 298.93	1690.3 ± 314.40
	LS	3238.3 ± 377.86	1261.7 ± 309.80	1599.3 ± 138.70
SW	C	24.0 ± 0.00	30.3 ± 1.20	22.7 ± 0.33
	MS	23.3 ± 0.33	28.7 ± 2.03	23.7 ± 1.20
	LS	21.3 ± 0.33	32.0 ± 3.79	24.7 ± 1.33
Biomass	C	6798.2 ± 603.69	5641.6 ± 104.17	4912.4 ± 187.79
	MS	5235.7 ± 722.87	4006.2 ± 625.00	3840.2 ± 668.39
	LS	4670.9 ± 660.19	4037.4 ± 700.71	3903.0 ± 180.42
Grain yield	C	3221.5 ± 350.14	1765.4 ± 98.00	1907.6 ± 163.11
	MS	2117.8 ± 379.02	931.9 ± 268.54	1274.3 ± 223.17
	LS	2449.0 ± 308.05	1373.1 ± 269.11	1544.9 ± 94.96
HI	C	0.47 ± 0.02	0.31 ± 0.02	0.39 ± 0.02
	MS	0.41 ± 0.01	0.23 ± 0.02	0.33 ± 0.00
	LS	0.54 ± 0.05	0.31 ± 0.04	0.40 ± 0.01

\* Explanations as in Table 7.2. <sup>Δ</sup> According to the ANOVA analysis, the W<sub>R</sub> × S<sub>P</sub> interaction was not significant and hence mean separation was not conducted for the interaction means. Values indicated next to means are standard errors.



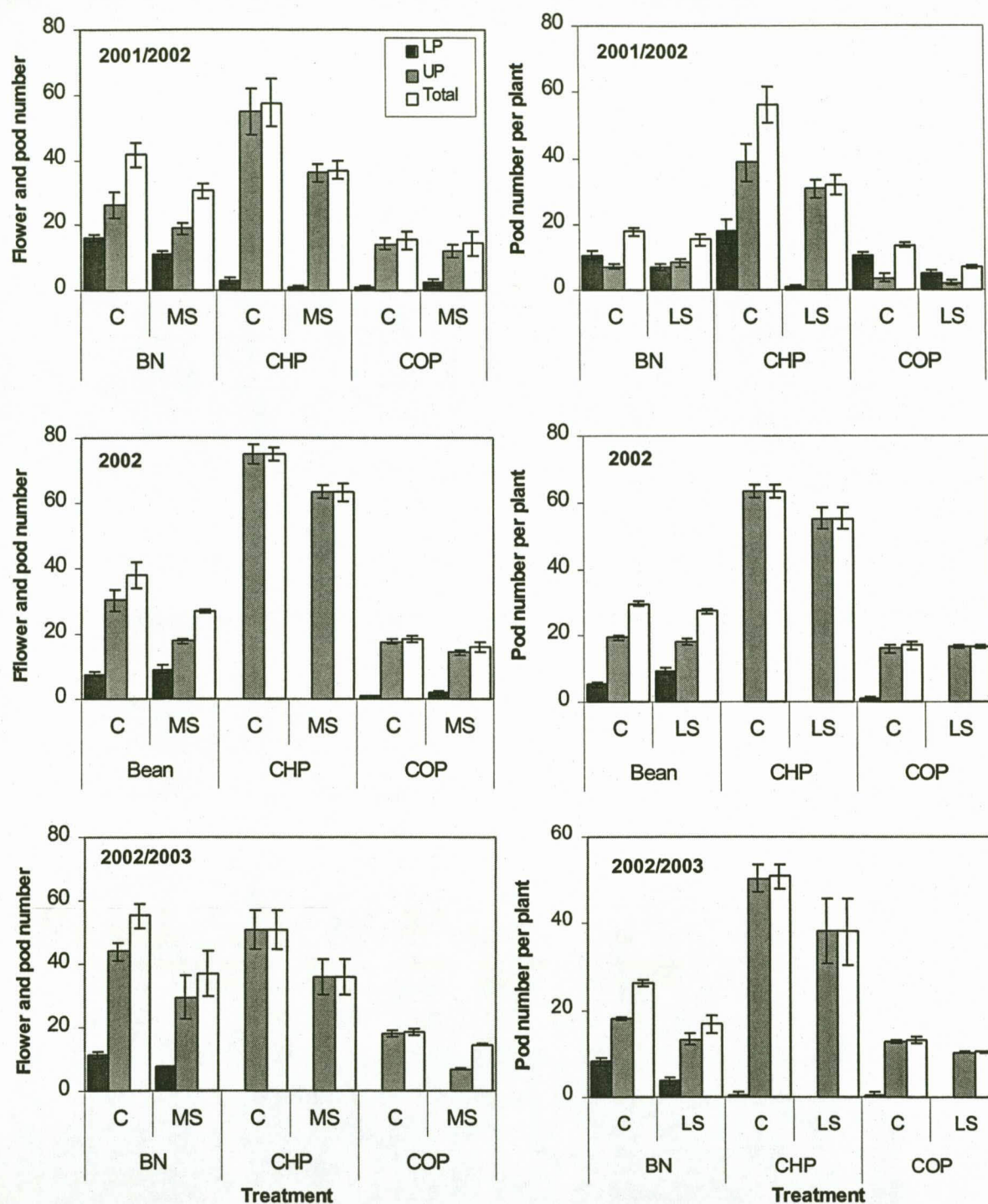
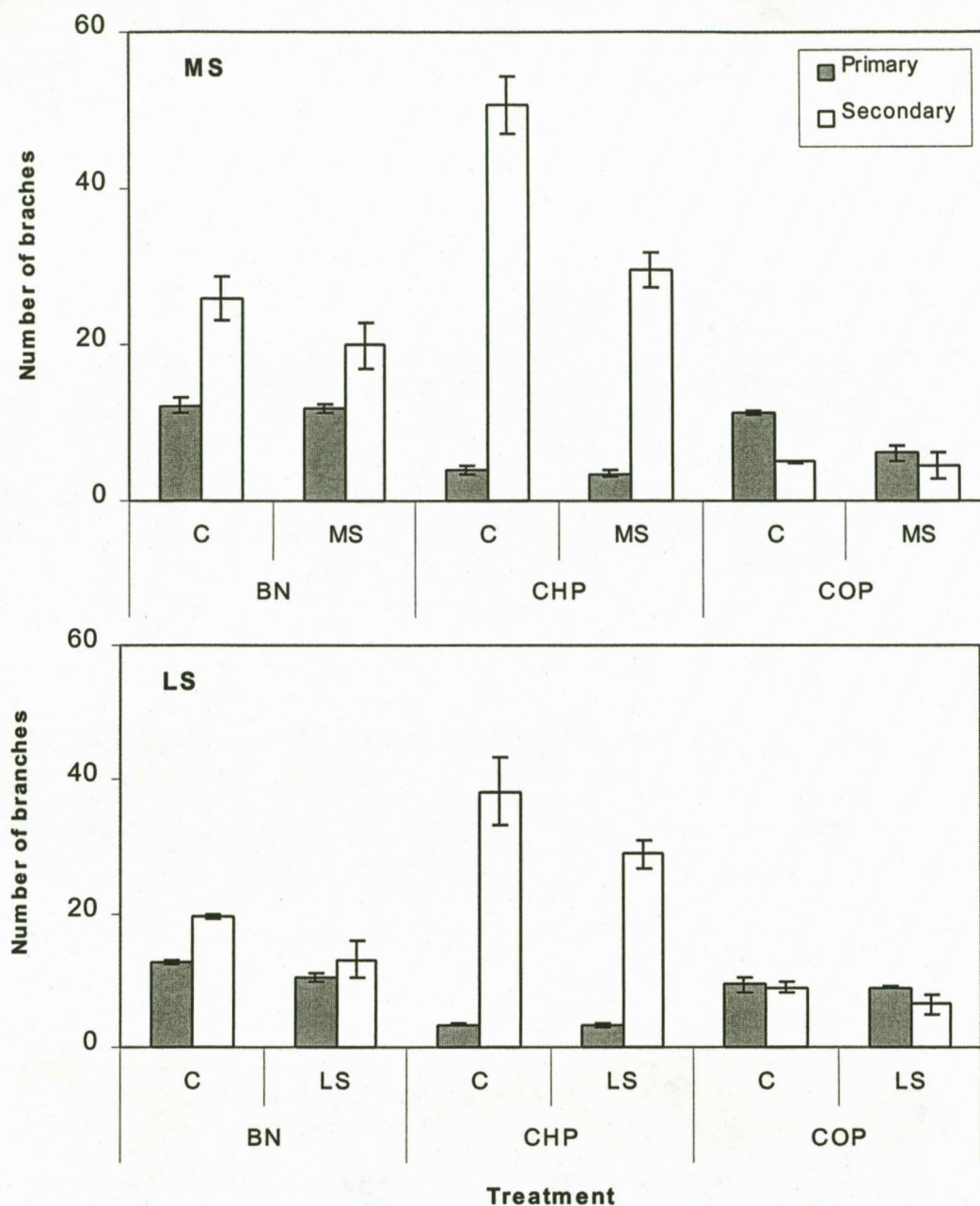


Figure 7.2. Number of flowers and pods per plant at the end of the mid-season (MS) stress (left) and number of pods per plant at maturity in the late season (LS) stresses (right) as compared to the control (C) for three grain legume species in three seasons. BN = beans, CHP = chickpea, COP = cowpea, LP = lower half of the plant canopy, UP = upper half of the plant canopy. When visible, vertical bars indicate standard error of means.



**Figure 7.3.** Number of primary and secondary branches per plant after the mid-season stress (MS) and maturity of the late-season stress (LS) as compared to the control (C) for three grain legume species in 2002/2003. When visible, vertical bars indicate standard error of means.

Yield component response of the species to the water deficit treatments was not consistent across seasons (Table 7.3 to 7.4). In cowpea,  $NP\ m^{-2}$  was affected by the MS and LS treatments in 2002 and 2002/2003 seasons, respectively but not affected in 2001/2002. In beans and chickpea, however, NP was mostly sensitive to MS water stress whereas NS was sensitive to both the MS and LS stresses.



In addition to data collected at harvest, number of flowers and pods were counted at the end of the stress period in the MS and at maturity for the LS treatment. The count of flowers and pods in the lower and upper half of the plant canopy indicated that the majority of the reproductive organs were located in the upper half of the plants, particularly in chickpea and cowpea. As shown in Fig. 7.2, the numbers of reproductive organs were significantly reduced by the water stress treatments in beans and chickpea as a result of flower abortion and/or dropping of flowers and pods. The reduction in the number of flowers and pods, (6-21% in the MS and 2-48% in the LS treatment) was minimal in cowpea in all the seasons. Beans was more sensitive to reduction of reproductive organs as a result of stress during flowering (seasonal mean of 30%) than stress during the pod filling period (19%) when compared to chickpea which is equally sensitive to reduction of reproductive organs under both flowering (27%) and pod filling (27%) period water deficits.

As the numbers of branches in many grain legume species determine the number of pods that a plant can carry, a count of primary and secondary branches was made after each stress period in 2002/20003 to investigate the effect of reproductive period water stress on branch number. The data showed that cowpea had more primary branches than secondary branches while chickpea and beans had higher number of secondary branches than primary ones (Fig. 7.3). Unlike secondary branches, primary branches were not affected by either of the water stress treatments in all species suggesting that these branches were mostly produced during the vegetative growth period. Dramatic reduction of secondary branches was observed in chickpea due to the MS stress (42%) while the reduction in beans was moderate (23%) and that of cowpea was minimum (<10%). The reduction of secondary branches (due to early drying and/or stunted growth) as a result of the LS treatment was highest in beans (32%) followed by cowpea (28%) and chickpea (25%). Generally, reduction in the number of flowers and secondary branches by the water stress treatments was reflected in significantly lower NP m<sup>-2</sup> in all species. Previous studies also indicated reductions in NP due to reproductive stage water stress in cowpea (Wien, *et al.*, 1979; Turk *et al.*, 1980a), beans (Acosta Gallegos and Shibata, 1989; Tesfaye, 1997), peanut (Harris *et al.*, 1988; Wright *et al.*, 1991), soybean (Wien *et al.*, 1979) and mung bean (Pannu and Singh, 1993). In addition to low number of pod bearing branches, the negative effect of water stress on meiosis and pollen fertility could have contributed to the reduction of NP as observed in many cereals (Saini and Westgate, 2000).

SW of cowpea was not affected by any of the stress treatments in any the seasons. This contradicts with the report of Wien *et al.* (1979) who found an increase in SW under water deficit during the reproductive stage of cowpea. The contradiction could be either due to cultivar or climatic differences between the studies. Chickpea normally had the highest SW and NP  $\text{m}^{-2}$  under all water regimes in all seasons which are compensatory for its low number of seeds per pod. As compared to the control, SW in beans and chickpea was significantly reduced by the MS and LS treatments in the first two seasons.

Although beans and cowpea had similar SW under well-watered conditions, bean had lower SW but significantly higher NP and NS  $\text{m}^{-2}$  than cowpea under the MS and LS treatments in two of the three seasons (Table 7.3 to 7.4). The influence of water stress on seed number and mass, generally, depends on its timing and intensity during the reproductive growth. For example, in pea, seed abortion occurred when water stress coincided with the initiation of linear seed filling while seeds that reached this stage before water stress maintained normal growth (Ney *et al.*, 1994). Therefore, in agreement with the results of Ney *et al.* (1994), the present species respond to seed-filling water stress either by reducing seed number (e.g. cowpea) or mobilizing reserves to maintain a constant seed growth rate (e.g. beans). Generally, environmental stresses such as water deficit can induce a compensation growth between yield components indicating the developmental plasticity of plant yield systems under environmental stress (Adams *et al.*, 1967).

Biomass at harvest was significantly affected by the water stress treatments in 2001/2002 and 2002 seasons but not in 2002/2003 (Table 7.3 and 7.4). It was severely reduced by the MS treatments in beans and chickpea in 2001/2002 and in beans in 2002. Biomass production ranged from 3749 (chickpea) to 6798 (beans), 1349 (chickpea) to 3840 (cowpea) and 2312 (cowpea) to 4671 (beans)  $\text{kg ha}^{-1}$  in the C, MS and LS treatments, respectively over the three seasons (Table 7.3 to 7.4). As shown in Chapters 3 and 4, the lowest biomass in the MS treatment is a result of low LAI, RUE and WUE. This is in agreement with other reports on chickpea (Sivakumar and Singh, 1987), beans (Acosta Gallegos and Shibata, 1989), cowpea (Turk, and Hall, 1980 a, b) and mung bean (Pannu and Singh, 1993).

HI was significantly higher in the C treatment in 2001/2002 while it was similar between the C and LS treatments in 2002 and 2002/2003 (Table 7.3 and 7.4). Differences between

species in HI was observed only in the 2002/2003 in which beans had significantly higher HI than cowpea, and cowpea had significantly higher HI than chickpea (Table 7.4). The lowest HI was recorded in the MS treatment in all the seasons. HI varies on the ability of a genotype to partition current assimilate to the seed and the reallocation of stored or structural assimilates to the same sink (Turner *et al.*, 2001). The lack of significant difference between the species in the two seasons could be explained by the different assimilate partitioning pattern of the species as shown in Chapter 3. For example, beans and cowpea had similar seed number and seed mass under well-water supply conditions, but bean had relatively higher number of seeds than cowpea, and cowpea had higher seed mass than bean in the LS treatment. Both beans and cowpea had higher partitioning ( $p$ ) in the LS treatment (Table 7.5). This shows that partitioning in bean is used to maintain seed number (fill all the available seeds) rather than mass whereas in cowpea partitioning seems to be used to maintain seed mass rather than number (i.e. fill most of the available seeds).

Chickpea had low  $p$  in the latter two seasons but also had similar HI to that of beans and cowpea under the different water regimes. This could be due to higher partitioning of current assimilate to the seed than reallocation of stored dry matter in chickpea. In other studies, differences in chickpea grain yield were associated with differences in crop growth rate ( $C_r$ ) rather than variation in dry matter partitioning,  $p$  (Williams and Saxena, 1991). Therefore, the lack of significant differences in HI among the species could be a result of the different strategies used by the plants to maintain their HI at high level. The lowest HI in the MS treatment could partly be a result of lower partitioning to the pods (Table 7.5) and resumption of vegetative growth after re-watering at a cost of pod growth and also generally low crop growth rate owing to low LAI and RUE recorded in the same treatment.

### 7.3.3. Partitioning

Dry matter partitioning among plant parts was discussed in detail in Chapter 3. Here, the mean total growth rate ( $C_r$ ) and pod growth rate ( $C_p$ ) and mean dry matter partitioning to the pod ( $p$ ) and its importance as a yield component is presented. As shown in Table 7.5, the control treatment had higher  $C_r$  than the stress treatments in most of the cases though the LS treatment excelled the control in some cases (e.g. beans) because of its shorter growth period. In beans, both  $C_r$  and  $C_p$  in the MS were lower than the LS treatment in all

**Table 7.5. Mean crop growth rate ( $C_r$ ), pod growth rate ( $C_p$ ) and partitioning coefficient ( $p$ ) of three grain legumes grown under three water regimes in three seasons.**

Parameter	Water regime	Beans	Chickpea	Cowpea
<b>2001/2002</b>				
$C_r$ ( $\text{g m}^{-2} \text{ } ^\circ\text{Cd}^{-1}$ )	C	$0.831 \pm 0.271$	$1.02 \pm 0.174$	$1.020 \pm 0.126$
	MS	$0.692 \pm 0.060$	$0.693 \pm 0.098$	$0.520 \pm 0.049$
	LS	$0.890 \pm 0.109$	$0.575 \pm 0.069$	$0.509 \pm 0.061$
$C_p$ ( $\text{g m}^{-2} \text{ } ^\circ\text{Cd}^{-1}$ )	C	$0.395 \pm 0.197$	$0.582 \pm 0.142$	$0.559 \pm 0.093$
	MS	$0.190 \pm 0.042$	$0.275 \pm 0.065$	$0.269 \pm 0.013$
	LS	$0.690 \pm 0.307$	$0.395 \pm 0.043$	$0.318 \pm 0.144$
$p$	C	0.475	0.571	0.548
	MS	0.275	0.397	0.517
	LS	0.775	0.687	0.625
<b>2002</b>				
$C_r$ ( $\text{g m}^{-2} \text{ } ^\circ\text{Cd}^{-1}$ )	C	$1.05 \pm 0.132$	$0.822 \pm 0.051$	$0.923 \pm 0.137$
	MS	$0.450 \pm 0.098$	$0.633 \pm 0.068$	$0.778 \pm 0.146$
	LS	$1.260 \pm 0.092$	$0.855 \pm 0.051$	$0.814 \pm 0.188$
$C_p$ ( $\text{g m}^{-2} \text{ } ^\circ\text{Cd}^{-1}$ )	C	$0.940 \pm 0.165$	$0.484 \pm 0.094$	$0.445 \pm 0.007$
	MS	$0.163 \pm 0.029$	$0.423 \pm 0.004$	$0.358 \pm 0.171$
	LS	$1.07 \pm 0.225$	$0.355 \pm 0.031$	$0.324 \pm 0.023$
$p$	C	0.895	0.589	0.482
	MS	0.362	0.668	0.460
	LS	0.849	0.415	0.398
<b>2002/2003</b>				
$C_r$ ( $\text{g m}^{-2} \text{ } ^\circ\text{Cd}^{-1}$ )	C	$1.600 \pm 0.185$	$0.990 \pm 0.067$	$1.143 \pm 0.157$
	MS	$0.799 \pm 0.091$	$0.502 \pm 0.047$	$0.501 \pm 0.063$
	LS	$0.991 \pm 0.106$	$0.683 \pm 0.062$	$0.987 \pm 0.082$
$C_p$ ( $\text{g m}^{-2} \text{ } ^\circ\text{Cd}^{-1}$ )	C	$0.739 \pm 0.491$	$0.393 \pm 0.143$	$0.509 \pm 0.159$
	MS	$0.004 \pm 0.144$	$0.154 \pm 0.112$	$0.055 \pm 0.142$
	LS	$0.718 \pm 0.286$	$0.456 \pm 0.136$	$0.681 \pm 0.097$
$p$	C	0.462	0.397	0.445
	MS	0.005	0.307	0.110
	LS	0.725	0.668	0.690

the seasons. When compared to the LS, both chickpea and cowpea also had lower  $C_r$  in the MS only in 2002 and 2002/2003 seasons.  $C_p$  in both chickpea and cowpea was higher in the LS than in the MS in the milder temperature seasons but lower in the higher temperature season. This difference in  $C_r$  is mainly attributed to differences in canopy development and energy interception between environments and the crops (Greenburg *et al.*, 1992). Therefore,  $C_r$  gives an integrated measure of the source use capacity of a crop and can be further evaluated through the effect of radiation interception and RUE (Turner *et al.*, 2001). Under water-limited environments,  $C_r$  is a result of the crop's ability to capture and transpire water and its efficiency of water use (Passioura, 1977). Therefore, differences in  $C_r$  indicate differences in resource utilization among species in a given environment. The correlation of  $C_r$  with grain yield (data not shown) was variable across seasons. Unlike  $C_r$ , however,  $p$  was strongly positively correlated with grain yield in the control (0.76 to 0.98) and LS (0.98) treatments in 2002 and 2002/2003 while the

correlation in the MS treatment was weak and variable among seasons (-0.56 to 0.79). Beans, followed by chickpea in 2001/2002 and 2002 and by cowpea in 2002/2003, had the highest  $p$  in the LS treatment (Table 7.5).

Remobilisation of assimilates from shoot to seed is reported for beans (Acosta Gallegos and Shibata, 1989) and cowpea (Hall and Patel, 1985). Except in chickpea in 2002,  $p$  was generally low in the MS treatment in all species and seasons. The lowest partitioning in the MS treatment could be a result of reduced reproductive organ establishment which decreased pod set (smaller sink strength) resulting in reduced partitioning, sink limitation (Greenburg *et al.*, 1992). This partitioning difference between the water regimes indicates differences in the ability of the crops to initiate enough sink to utilize the carbon assimilate available under different environments (Greenburg *et al.*, 1992). As shown in peanut, drought at the pod filling stage maximizes partitioning because established fruit generally has priority for the available assimilate in the event of stress (Greenburg *et al.*, 1992).

The present study shows differences in  $p$  among species in that beans had higher  $p$  in the LS and C treatments than the MS in all seasons unlike chickpea and cowpea where the  $p$  in the water regimes was varied across seasons. The contribution of  $C_r$  and  $p$  towards stress adaptation can vary among plant species. For example, tolerance of  $p$  to high temperature is considered more important to peanut adaptation than  $C_r$  under severe water deficit (Greenburg *et al.*, 1992) while in chickpea  $C_r$  was the major source of yield variation under water stress rather than  $p$  or length of reproductive period (Williams and Saxena, 1991). In the present study, however,  $p$  was consistently correlated with grain yield while the correlation of  $C_r$  with grain yield was variable across seasons. Therefore,  $p$  seems to be a good indicator of yield performance under varying water and temperature conditions. In general, attainment of high biomass followed by high partitioning to the seed is the major requirement of a high grain yield in many grain legumes including chickpea (Saxena *et al.* 1990; Singh, 1991; Leport *et al.*, 1999), cowpea (Wien *et al.*, 1979), lentil (Silim *et al.* 1993a), pea (Silim *et al.*, 1985), soybean (Westgate *et al.*, 1989), mung bean (Bushby and Lawn, 1992), peanut (Wright *et al.*, 1991) and narrow leafed lupin (French and Turner, 1991). The enzyme sucrose synthase is reported to be responsible for controlling the rate of seed filling, seed size and finally sink activity (Mohapatra *et al.*, 2000).

### 7.3.4. Yield component framework

Grain yield is determined by both reproductive components (e.g. NP per plant, NS per pod and SW) and components that integrate many plant functions at a higher level (e.g. WUE, RUE, HI, length of phenological development periods). In this study, some of these parameters were correlated with grain yield (Table 7.6) in order to find the major yield determining components in grain legumes under different water supply conditions during the reproductive periods.

**Table 7.6. Correlation (Pearson) of the grain yield of three-grain legume species with some plant parameters under three water regimes for three seasons.<sup>a</sup>**

Water regime	Parameters*	2001/2002 <sup>++</sup>	2002	2002/2003
Well-watered	Biomass	-0.02	0.87	0.89
	HI	0.86	0.96	0.91
	Number of seeds per m <sup>2</sup>	0.95	0.26	0.88
	Days to flowering	-0.57	0.63	0.24
	Days to podding	-0.80	0.20	0.09
	Days to maturity	0.83	-0.78	0.97
	Reproductive period	0.73	-0.98	-0.44
	Pod filling period	0.99	-0.63	-0.46
	WUE <sub>d</sub>	0.47	0.92	0.91
	WUE <sub>g</sub>	0.98	0.99	0.51
	RUE	-	0.90	0.99
Mid-season stress	Biomass	-0.99	0.95	0.92
	HI	0.24	0.99	0.95
	Number of seeds per m <sup>2</sup>	0.55	0.11	0.99
	Days to podding	0.79	-0.50	0.61
	Days to maturity	-0.14	-0.86	-0.13
	Reproductive period	-0.99	-0.86	-0.36
	Pod filling period	-0.99	-0.93	-0.34
	WUE <sub>d</sub>	0.92	0.99	0.45
	WUE <sub>g</sub>	0.99	0.97	0.13
	RUE	-	0.69	0.98
Late season stress	Biomass	-0.57	0.98	0.93
	HI	0.97	0.93	0.98
	Number of seeds per m <sup>2</sup>	-0.42	0.59	0.99
	Days to podding	-0.76	-0.24	0.47
	Days to maturity	-0.87	-0.97	-0.67
	Reproductive period	0.82	-0.80	-0.44
	Pod filling period	0.87	-0.45	-0.52
	WUE <sub>d</sub>	0.20	0.50	-0.92
	WUE <sub>g</sub>	0.99	0.99	0.88
	RUE	-	0.99	0.94

<sup>a</sup> n = 9 (three species with three replications)

\* WUE<sub>d</sub> = water use efficiency of total above ground dry matter, WUE<sub>g</sub> = water use efficiency of seed yield, RUE = radiation use efficiency. <sup>++</sup> Correlation coefficients with values greater than 0.72 or less than -0.72 are significant at 5 % P level.

Under well-watered conditions, grain yield was strongly positively correlated with HI, NS  $\text{m}^{-2}$ ,  $\text{WUE}_d$ ,  $\text{WUE}_g$  and RUE (Table 7.6). Days to maturity was positively correlated with grain yield in 2001/2002 and 2002/2003 seasons but both days to maturity and pod filling period correlated negatively to yield in 2002. This negative correlation indicated the importance of early maturity and short period of pod filling for high grain yield under high temperature conditions. In other studies, high temperature during the reproductive period in late sown chickpea led to reduced seed size, lower yield and lower WUE (Sivakumar and Singh, 1987).

Under mid-season water stress, grain yield was positively correlated with HI, NS  $\text{m}^{-2}$ ,  $\text{WUE}_d$ ,  $\text{WUE}_g$  and RUE although the strength of correlation varied across seasons. Except for the high temperature season, the period from sowing to podding was positively correlated with seed yield. However, grain yield was strongly negatively correlated with the period of pod filling in all the seasons suggesting the need for a short pod-filling period under mid-season stress for high seed yield. Days to maturity was negatively correlated with grain yield in 2002 indicating the importance of early maturity for high grain yield when water stress at mid-season is combined with high temperature conditions. Under late season water stress, grain yield was strongly positively correlated with HI,  $\text{WUE}_g$  and RUE in all the seasons (Table 7.6). Pod filling period was negatively correlated with grain yield in 2002 and 2002/2003 but positively correlated in 2001/2002. Length of maturity period was negatively correlated with grain yield in all the seasons indicating the need to select early maturing cultivars for high grain yield in grain legumes under terminal drought environments. The correlation of  $\text{WUE}_d$  with grain yield under late season stress was variable across seasons, being positive in 2001/2002 and 2002 and negative in 2002/2003.

Total above ground biomass at harvest was strongly positively correlated with grain yield in 2002 and 2002/2003 in all the water regimes but correlated negatively in 2001/2002 suggesting the seasonality of its association with seed yield. This could be due to some environmental factors that reduce initiation of reproductive primordia during the transition period from vegetative to reproductive phase. However, similar to the observations in 2002 and 2002/2003 seasons, several reports indicated strong positive correlation of biomass with grain yield in many crops such as chickpea (Silim and Saxena, 1993b), beans (Acosta Gallegos and Shibata, 1989) and a range of other legumes

(Thomson *et al.*, 1997; Siddique *et al.*, 1999). Similar to the present results, positive correlation of grain yield with HI, seed number and mass, and early flowering has been reported in chickpea under severe water deficit (Silim and Saxena, 1993b). Positive correlations of grain yield with biomass at maturity (Thomson *et al.*, 1997; Siddique, *et al.*, 1999) and harvest index (Thomson *et al.*, 1997) were reported in a range of grain legume species in Australia. In agreement with the present study, phenology was strongly negatively correlated with grain yield under the dry year while it was weakly correlated under the wet year in lentil (Silim *et al.*, 1993a). Earliness is considered to be important in cowpea, pea, and other grain legumes (Hall and Patel, 1985; Subbarao *et al.*, 1995; Sharma and Khan, 1997; Siddique *et al.*, 1999). Strong positive correlation of grain yield with HI and RUE is reported in mung bean (De Costa *et al.*, 1999).

The analysis of yield components showed that high yield of grain legumes under different water supply conditions was a result of high total biomass at harvest, high NS, high HI and high RUE. In agreement with the present study, Chapman *et al.* (1993), Pannu and Singh (1993) and De Costa *et al.* (1999) have observed a positive response of HI to irrigation in mung bean that irrigation during flowering and pod filling periods increased HI through greater pod initiation and higher pod growth. High biomass production is a function of high radiation interception, RUE and WUE, all of which are influenced by LAI which is a parameter very sensitive to water deficit in grain legumes (Acosta Gallegos and Shibata, 1989; Chapman *et al.*, 1993; De Costa *et al.*, 1997). Favourable water supply during flowering and pod filling stages is, therefore, required to maximize RUE by maintaining high LAI, and thereby increase biomass and seed yield. RUE is a measure of the efficiency of canopy photosynthesis (Norman and Arkebauer, 1991; Loomis and Connor, 1992) and is highly sensitive to water deficits (Lawlor, 1995) particularly during flowering and pod filling stages when LAI and transpiration are very high (De Costa *et al.*, 1999). Therefore, high LAI and high RUE and WUE are important morphological and physiological component of seed yield, respectively in grain legumes.

Although, the genotypes used in the present correlation study are few in number, the observed relationships between grain yield and yield determining parameters showed interesting environment dependent (water regime in this case) relationships which insight further investigation on grain legumes.



#### 7.4. Conclusion

Water deficit during the reproductive period is a major factor for the low yield of grain legumes. In this study, the most water stress sensitive stages of each species and yield determining parameters in each water regime were identified.

Beans and chickpea are more sensitive to flowering than pod-filling water stress while the yield response of cowpea is similar under the two periods of stress. Therefore, minimizing the water stress at these most sensitive phenological stages through management or breeding methods could help maximize the yield of these crops. Moreover, such information can also be used to set irrigation priorities based on critical growth stages and thereby increase water saving and yield in areas where the crops are grown under irrigation conditions. In most of the cases, the yield of cowpea is less sensitive to both MS and LS stresses than that of beans and chickpea. This information is useful in the practice of crop choice based on environmental constraints such as water stress.

Grain yield was greatly reduced when stress occurred during the flowering period which is mainly associated with the adverse effect of the stress on growth of reproductive organs, LAI, efficiency of radiation and water use, and partitioning of dry matter to the seed. The reduction of yield under pod-filling water stress is mainly due to a shorter reproductive period and to some extent reduction of the numbers of reproductive organs such as number of seeds per pod and numbers of pods per plant. Therefore, management or breeding activities which improve one or more of these characters are expected to improve the yield of grain legumes under drought prone environments.

Unlike the mean crop growth rate, dry matter partitioning to the pod during the reproductive periods was strongly correlated with grain yield. High dry matter partitioning during late season water stress is found to be an important mechanism by which species maintain high HI and grain yield under terminal drought environments. Accordingly, crops such as beans, which have high dry matter partitioning capacity during late season water stress, could be grown in areas where water is available during the vegetative and early reproductive season while it is scarce towards the end of the season.

Yield determining factors in grain legumes varied along water regimes and temperature conditions. Yield, however, was strongly positively correlated with HI and RUE across all water regimes in both seasons. High NS  $\text{m}^{-2}$  and high WUE and longer maturity time are important for high grain yield in well-watered and mild temperature environments. On the other hand, short reproductive period and high WUE are important in mid-season drought environments with intermediate temperature. Under less extreme temperatures, yield was strongly positively correlated with  $\text{WUE}_g$ ,  $p$  and early maturity in the LS treatment indicating the importance of these characters in terminal drought environments to improve grain yield. Moreover, as observed in the 2002 season, short pod filling period, early maturity, high biomass, HI and WUE are important for obtaining high grain yield under high temperature environments with variable water supply. The relationships found between yield and yield component characters in each water regime can be used by breeders as a guide to improve the yield of grain legumes in the different environments.

## CHAPTER 8

### Evaluation of the CROPGRO-Dry Bean and Chickpea Model in a Semi-Arid Environment

#### 8.1. Introduction

Dynamic crop growth simulation started in the early 1960s, with successful application to well defined growth processes such as canopy photosynthesis (e.g. de Wit, 1965; Duncan *et al.*, 1967). Since then, the rapid development of computing power has led to models on many aspects of crop growth and development. Since there exist an almost infinite number of combinations of soil type, weather and agricultural practices, experimenting in all desirable situations is impossible. Therefore, there is a need to use models to increase the human capacity in understanding the different possible interaction of these factors (Penning de Vries *et al.*, 1988). A crop model can be used as a quantitative scheme for predicting the growth, development and yield of a crop, given a set of genetic coefficients and relevant environmental variables (Monteith, 1996).

Crop growth models are increasingly being used to support field research and extension in many countries (Carberry *et al.*, 2002; Jagtap *et al.*, 2002). Applying models can lead to a more effective way of using existing knowledge for extension, agronomic and cropping systems research and breeding. It also leads to a more effective experimentation and integration of the scientific disciplines involved in crop production (Penning de Vries *et al.*, 1988). As outlined by Boote *et al.* (1996), models can assist in synthesis of research undertaking about the interactions of genetics, physiology and environment, as well as integration across disciplines, and organization of data. They can assist in pre-season and in-season management decisions on cultural practices, fertilization, irrigation, cultivar choice and pesticide use. Crop models can also assist policy makers by predicting soil erosion, leaching of agrochemicals, effect of climate change, and also by giving large area yield forecasts (Boote *et al.*, 1996). Moreover, variability in yields of sensitive crops or cropping sequences due to variations in weather can be tested with long-term weather data, which speeds up crop assessment. Analysis of yield variability across season has been undertaken for certain crops such as faba bean (Grashoff *et al.*, 1987 as cited in Penning de Vries *et al.*, 1989), rice (Morris, 1987) and wheat (Aggrawal and Kalra, 1994). This type of analysis helps establish the impact of year-to-year weather variability on the crop much faster than with more conventional field experimentation methods (e.g.

Penning de Vries *et al.*, 1989; Matthews *et al.*, 2002; Jones *et al.*, 2003). In general, models are currently being applied to solve several agricultural problems. Matthews *et al.* (2002) described a number of models and their applications in tropical agricultural systems.

The DSSAT (Decision Support System for Agrotechnology Transfer) comprises a set of annual crop simulation models and a data base management system, together with utilities analysis program (Tsuji *et al.*, 1994; Thornton *et al.*, 1994), and is being used in many countries. For example, in Africa, the DSSAT models have been applied in the study of crop management (e.g. Vos and Mallett, 1987; Mbabaliye and Wojtkowski, 1994; Wafula, 1995), irrigation management (e.g. Kamel *et al.*, 1995; MacRobert and Savage, 1998), fertilizer management (e.g. Singh *et al.*, 1993; Thornton *et al.*, 1995; Jagtap *et al.*, 1999), climate change (Muchena and Iglesias, 1995), climate variability (Phillips *et al.*, 1998), food security (Thornton *et al.*, 1997) and so on. The model can be used for storing information concerning field trials, extracting data from crop models for the purpose of validation or comparing management strategies and performing simple analysis of the results of simulation runs (Thornton *et al.*, 1994; Tsuji *et al.*, 1994).

Therefore, it seems that simulation of crop growth can help strengthen regional development and agricultural planning in many countries. An obvious question, however, is whether simulation modelling has a real role to play in developing countries. To clarify such queries, it is necessary to test and evaluate the performance of already developed models with experimental data collected in developing countries. Along this line, Hensley *et al.* (1997) and Botes (1994) made comparisons between the Putu model (de Jager *et al.*, 1981) and other models. In comparing DSSAT3 and Putu maize and wheat, Hensley *et al.* (1997) reported that these models mostly gave reliable yield predictions although they were sometimes unreliable, and further pointed out weaknesses observed in both models. Therefore, crop models proposed for broader crop management applications should be tested widely and against diverse field experiments to assess their ability of answering practical questions (Boote *et al.*, 1996).

In general, in sub-Saharan Africa where unpredictable fluctuations of weather and climate has made many crop field trial experiments a risky exercise, the involvement of crop models in the decision support system of a given production system becomes more imperative than before. However, candidate crop models should be validated under the

specific environments before they are adapted to solve practical problems in such countries (Hoogenboom *et al.* 1994). Therefore, the main objective of this study was to validate the CROPGRO grain legume model of DSSAT in a semi-arid environment using experimental data collected for beans and chickpea during three seasons in Ethiopia.

## 8.2. Input Data and Methodology

### 8.2.1. CROPGRO model

Crop growth models, which share a common input and output data format, have been developed and embedded in a software package called DSSAT (Tsuji *et al.*, 1994; Jones *et al.*, 1994; Hoogenboom *et al.*, 1994). The models under DSSAT umbrella include CROPGRO which is a mechanistic, process-oriented model for grain legumes with weather, crop development, carbon balance, crop and soil N balance and soil water balance subroutines (Boote *et al.*, 1998a, 1998b; Hoogenboom *et al.*, 1994b). Crop development includes processes like vegetative and reproductive development, duration of root and leaf growth, onset and duration of reproductive organs, and dry matter partitioning to plant organs over time. The crop carbon balance includes daily simulation of photosynthesis, conversion and incorporation of carbon into crop tissues, carbon losses to abscised parts, and growth and maintenance respiration. The carbon balance also includes simulation of leaf area expansion, growth of vegetative tissues, pod and seed addition, shell and seed growth, nodule growth, senescence and carbohydrate mobilization (Boote *et al.*, 2002). The crop N balance includes daily soil N uptake, N<sub>2</sub> fixation, mobilization of N from vegetative tissues to reproductive organs, rate of N use for new tissue growth and rate of N loss in abscised parts. Soil water balance processes include infiltration of rainfall and irrigation, runoff, soil surface evaporation, root water uptake, drainage of water below the root zone, and crop transpiration (Hoogenboom *et al.*, 1994b; Boote *et al.*, 1998a; 1998b; 2002). Model state variables are simulated and output on a daily basis for crop, soil water, and soil N balance processes.

The generic CROPGRO model (v3.5) uses a common FORTRAN code to simulate the growth of grain legumes such as dry bean, soybean, peanut and chickpea using input files that define species traits and cultivar attributes (Boote *et al.*, 1998a; 1998b). DSSAT also provides a seasonal analysis system (including crop rotation and different management options) to simulate possible long-term adaptation measures so as to analyse those management scenarios that can decrease potential agricultural productivity under

expected climate change conditions (Thornton and Hoogenboom, 1994). In the present study, CROPGRO was used to simulate the growth and yield of common bean (*Phaseolus vulgaris* L.) and chickpea (*Cicer areitinum* L.).

### 8.2.2. Input data

The DSSAT crop models are designed to use a minimum set of soil, weather, crop and management information. The models integrate at daily time steps, and hence require daily weather data, consisting of maximum and minimum temperature, solar radiation, and rainfall as input. The models also require a soil profile description.

#### 8.2.2.1. Soil data

Soil profile description was made from a 2 m deep pit on the experimental site following the USDA soil classification system (Appendix 6A & 6B). Soil texture, bulk density, colour, pH, organic matter and organic carbon, total nitrogen, and cation exchange capacity (CEC) were analysed at the Soil Laboratory of Alemaya University following established methods while soil water at field capacity and permanent wilting point were determined at the National Soil Laboratory of Ethiopia (Appendix 6C & 6D). The soil parameters used in the model are listed in Table 8.1.

**Table 8.1. Soil parameters for the experimental site at Dire Dawa, Ethiopia.**

Soil horizon	Depth (cm)	DLL <sup>a</sup> (cm <sup>3</sup> /cm <sup>3</sup> )	DUL <sup>a</sup> (cm <sup>3</sup> /cm <sup>3</sup> )	$\theta_s^a$ (cm <sup>3</sup> /cm <sup>3</sup> )	pH (H <sub>2</sub> O)	RGF <sup>a</sup>	BD (g/m <sup>3</sup> )	OC (%)	Total N (%)	Clay (%)	Silt (%)
Ap	0-10	0.181	0.305	0.377	8.5	1.00	1.24	1.18	0.10	33.0	36.0
A	11-40	0.211	0.336	0.384	8.6	0.75	1.23	1.36	0.12	40.0	37.0
Ba	41-70	0.205	0.335	0.409	8.6	0.20	1.27	1.20	0.10	38.0	44.0
Bt	71-90	0.218	0.348	0.406	8.4	0.10	1.41	1.14	0.10	41.0	43.0
BC	91-180	0.196	0.317	0.364	8.5	0.00	1.36	1.00	0.09	36.0	27.0

<sup>a</sup>DUL = drained upper limit, DLL = Drained lower limit,  $\theta_s$  = saturation (upper limit), RGF = root growth factor, BD = bulk density, and OC = organic carbon.

<sup>a</sup>calculated by DSSAT from other input soil parameters

#### 8.2.2.2. Weather data

Three field experiments with three water regime treatments were conducted in 2001/2002, 2002, and 2002/2003 season at Dire Dawa, Ethiopia (see previous chapters for detail description of site and experimental design). Daily maximum and minimum temperatures, solar radiation and rainfall were collected from a class A weather station at Dire Dawa airport (latitude = 9°4'N, longitude = 41°5'E, altitude = 1260m), which is 500 m away from the experimental site, in 2001/2002 and 2002 seasons and from an automatic

weather station placed at the experimental site (latitude = 9°6'N, longitude = 41°8'E, altitude = 1197m) in 2002/2003 starting from 1 October 2002(Appendix 7A to 7C).

### 8.2.2.3. Crop genetic coefficients

The bean cultivar planted was Roba-1 and the chickpea cultivar was ICC-4958 (see Chapter 3 for description). In 2001/2002, both beans and chickpea were planted on a 10m x 10m plot each adjacent to the main experimental area for the determination of minimum crop data sets (phenology, growth and yield) for calibration. Previous data collected for beans at the same site (Tesfaye, 1997) was also used for the calibration. The genetic coefficients of each variety were estimated by repeated iterations using the "Gencalc" program of DSSAT as described by Hunt and Pararajasingham (1994) until a close match between simulated and observed phenology, growth and yield was obtained. The calculated genetic coefficients are shown in Table 8.2.

**Table 8.2. Genetic coefficients of cultivars 'Roba-1' and 'ICC4958' obtained from "Gencalc" of DSSAT using 2001/2002 season and previous experiment data from Dire Dawa.**

Description	Genetic coefficient	
	Roba-1	ICC4958
<b>Developmental aspects</b>		
Critical short day length (h)	12.2	11.0
Slope of relative response of development to photoperiod (h)	0.0	-0.143
Time between plant emergence and flower appearance in photothermal days (PTD)	36.0	30.0
Time between first flower and first pod (PTD)	2.0	8.0
Time between first flower and first seed (PTD)	9.0	15.0
Time between first seed and physiological maturity (PTD)	29.0	35.0
Time between first flower and end of leaf expansion (PTD)	18.0	42.0
Seed filling duration for pod cohort at standard growth conditions (PTD)	14.0	29.0
Time required for cultivar to reach final pod load under optimal conditions (PTD)	8.0	18.0
<b>Growth aspects</b>		
Maximum leaf photosynthesis rate at 30 °C and high radiation ( $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ )	1.0	1.7
Specific leaf area of cultivar under standard growth conditions ( $\text{cm}^2 \text{ g}^{-1}$ )	220.0	150.0
Maximum area of full leaf (three leaflets, $\text{cm}^2$ )	133.0	10.0
Maximum fraction of daily growth that is partitioned to seed + shell	1.0	1.0
Maximum weight per seed (g)	0.247	0.403
Average seed per pod under standard growing conditions	6.20	1.30

### 8.2.3. Model evaluation (validation)

The cultivars were grown under three water regimes namely, mid-season (stage R1) stress, late season (stage R4) stress and well-watered condition (see previous chapters for details) for three seasons. Data collected on crop evapotranspiration, phenology, growth, yield and yield components from all three seasons were used for evaluation of the models.

The data included in the evaluation part of the model for 2001/2002 was from a different data set used for the calibration.

Model performance was evaluated based on five statistical indexes: the index of agreement ( $d_a$ ), the mean deviation (MD), the root mean square error (RMSE), the coefficient of variation (CV) and the modelling efficiency (ME) following Willmot (1982), Hoogenboom *et al.* (1999), Gabrielle *et al.* (1995), and Loague and Green (1991).

$$d_a = 1 - \left[ \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (|P_i| + |O_i|)^2} \right] \quad (8.1)$$

where  $P'_i = P_i - \bar{O}$  and  $O'_i = O_i - \bar{O}$ .

$$MD = n^{-1} \sum_{i=1}^n (P_i - O_i) \quad (8.2)$$

$$RMSE = \left[ n^{-1} \sum_{i=1}^n (P_i - O_i)^2 \right]^{0.5} \quad (8.3)$$

$$CV = \frac{RMSE}{\bar{O}} * 100 \quad (8.4)$$

$$ME = \frac{\sum_{i=1}^n (O_i - \bar{O})^2 - \sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (8.5)$$

where  $O$  is observed value,  $P$  is model-predicted value,  $\bar{O}$  is observed mean value,  $i$  is observation and  $n$  is number of observations.

The values of MD indicate whether there is a systematic bias in the simulated values. The RMSE reflects the magnitude of the mean difference between predicted and measured values. The CV is a relative measure of the amount of unexplained variation and is independent of the unit of measurement used (Wang *et al.*, 2003). The simulation is considered excellent if the CV is < 10%, good if it is within 10-20%, fair if it is between 20-30% and poor if it is >30% (Jamieson *et al.*, 1991). The maximum value of ME is 1 (optimal value) and it compares modelling variability with experimental variability. A negative value of ME refers to the fact that the modelling variability is greater than the experimental variability, and hence the simulation is not satisfactory (Rinaldi *et al.*, 2003). Higher values of  $d_a$  indicate better model performance whereas lower values



indicate poor performance. Evaluation of model performance was also performed by plotting “simulated vs. measured” values and calculating the parameters of the regression line (slope, intercept, and  $R^2$ ) and comparing them with a 1:1 line.

### 8.3. Results and Discussion

#### 8.3.1. Model validation

##### 8.3.1.1. CROPGRO-DRY BEAN

The seasonal course of measured and simulated leaf area index (LAI), above ground matter production (ADM), and cumulative evapotranspiration (ET) of beans for two seasons are shown in Fig. 8.1 to 8.3. As indicated by the closer match between the regression and the 1:1 lines and a high  $d_a$  value (0.97), the model predicted LAI well in 2002 but over estimation was observed after flowering in 2002/2003.

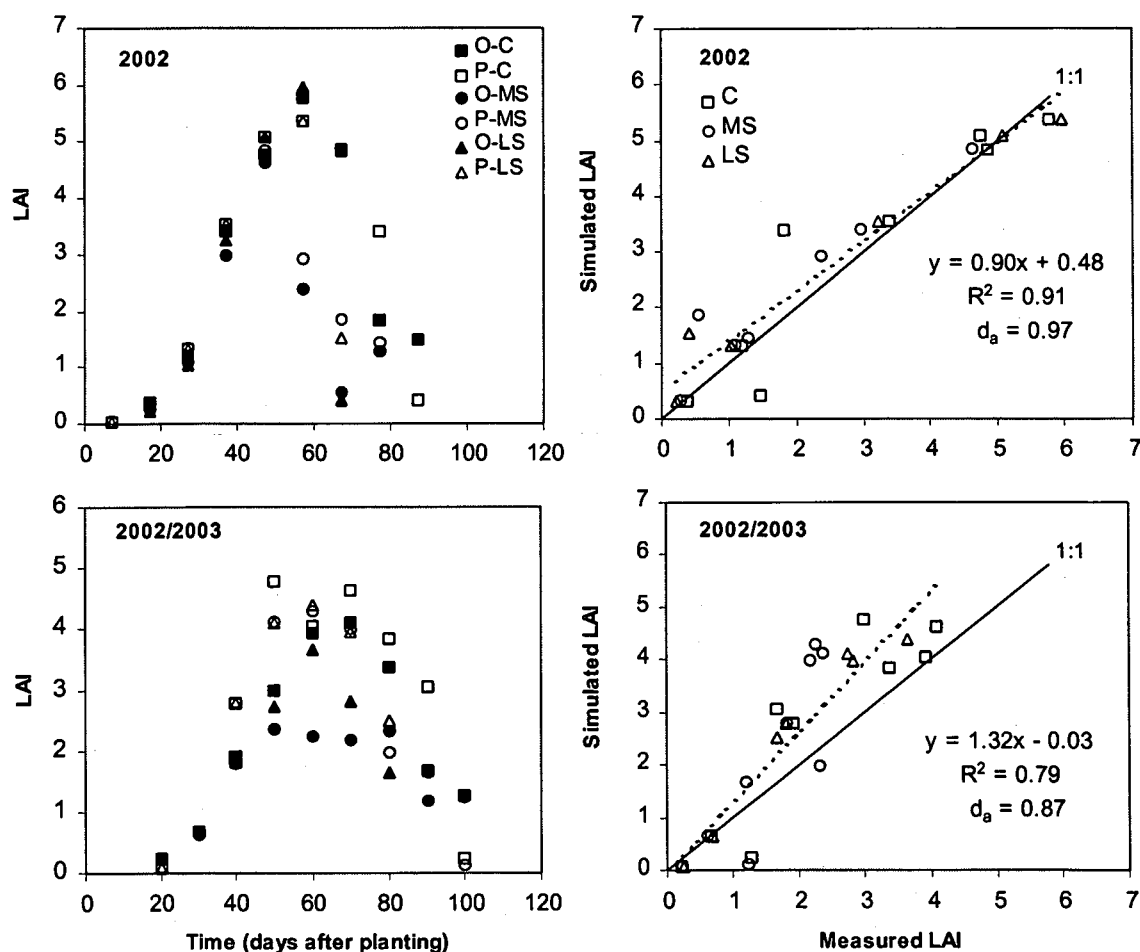
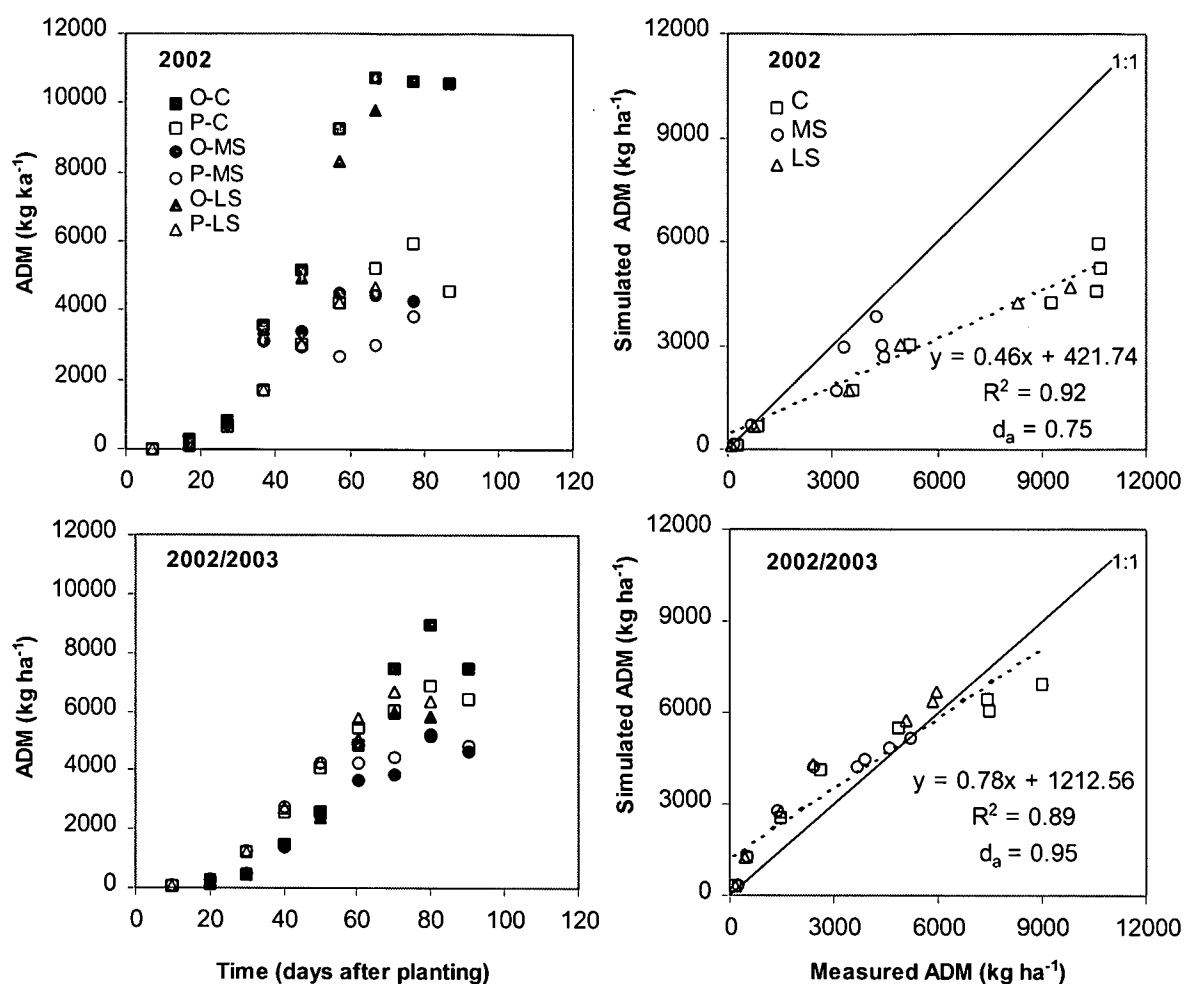


Figure 8.1. Seasonal course of measured (O) and simulated (P) LAI of beans under water stress (MS, LS) and well-watered (C) conditions (left), and regression of simulated vs. measured values (right) for 2002 and 2002/2003 seasons.



**Figure 8.2.** Seasonal course of measured (O) and simulated (P) above ground dry matter production (ADM) of beans under water stress (MS, LS) and well-watered (C) conditions (left), and regression of simulated vs. measured values (right) for 2002 and 2002/2003 seasons.

On the other hand, ADM was underestimated in 2002 whereas the estimation is closer to the 1:1 line in 2002/2003 with a high index of agreement (0.95). Although the same  $d_a$  value (0.90) was obtained in both seasons, cumulative ET after flowering was overestimated in 2002 while it was underestimated in 2002/2003. The results indicate that the model overestimates LAI and cumulative ET but underestimates ADM under higher temperature conditions (2002) compared to the more milder temperature season (2002/2003).

The main statistical indexes used to evaluate the accuracy of the models are reported in Table 8.3. Regression coefficients,  $R^2$  and probability values for the test of the regression are also presented in Table 8.4 for phenology, yield and yield component variables. The

CROPGRO-DRYBEAN model was able to simulate time to anthesis (flowering) but not the time to maturity. Despite a lower CV (14%), the value of  $d_a$  was 0.46 and the ME was negative (-0.36) for maturity date indicating more variability in the simulation than in the actual measurements. As shown by small MD and RMSE values and a high  $d_a$  value (0.86) and a positive ME, the model simulated maximum LAI with reasonable accuracy. Simulation of above ground dry matter at harvest was also fair with a RMSE of 21.4%, a  $d_a$  value of 0.92 and ME of 0.73, which is closer to the optimal value (1.0). Regression of the ADM data indicated a slope closer to the 1:1 line with  $R^2$  value of 0.77, which is significant at 1% probability level (Fig. 8.4, Table 8.5). The model also simulated mass per seed and HI fairly well with a CV of < 30% (Table 8.3).

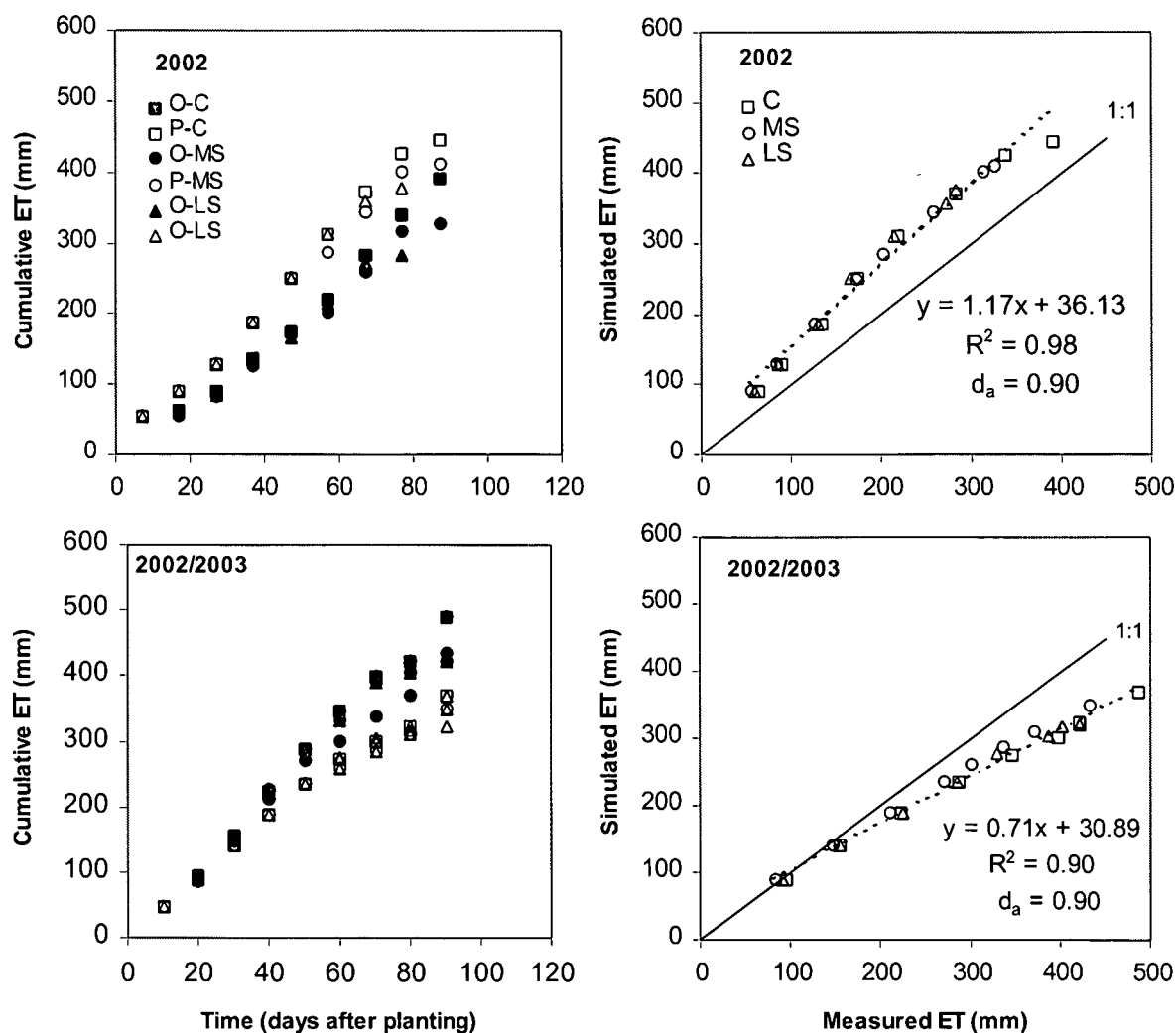
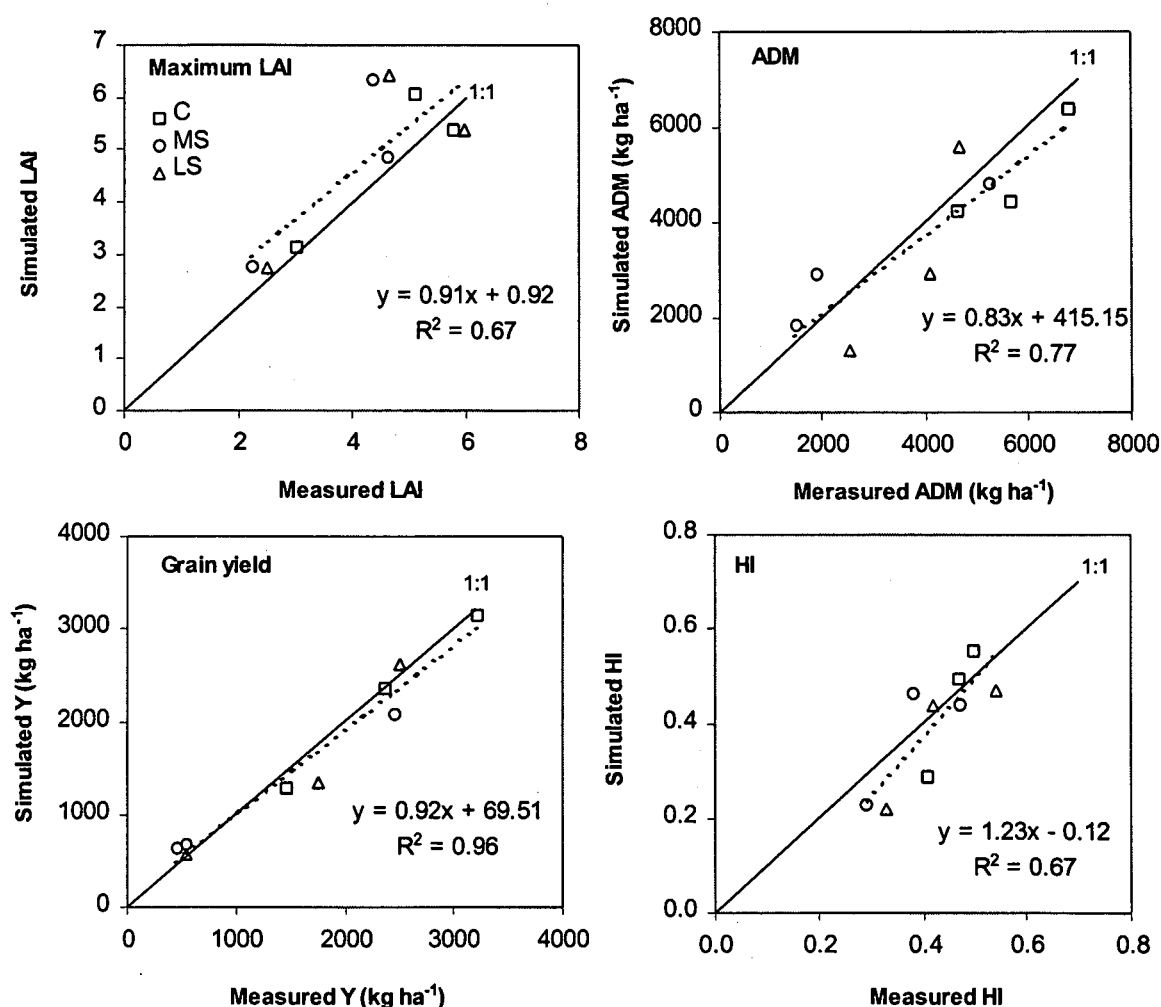


Figure 8.3. Seasonal course of measured (O) and simulated (P) cumulative crop evapotranspiration (ET) of beans under water stress (MS, LS) and well-watered (C) conditions (left), and regression of simulated vs. measured values (right) for 2002 and 2002/2003 seasons.

**Table 8.3. Statistical indexes of measured and simulated parameters of beans for data combined over three water regimes and three seasons (n = 9).**

Variable	Observed		Simulated		MD	Statistical indices			
	Mean	S.D*	Mean	S.D		RMSE	CV (%)	ME	d <sub>a</sub>
Anthesis date (DAP)	48.4	7.50	44.3	3.60	-4.10	5.50	11.5	0.39	0.76
Maturity date (DAP)	86.4	10.8	84.0	5.50	-2.90	11.8	13.7	-0.36	0.41
Max. LAI (m <sup>2</sup> m <sup>-2</sup> )	4.20	1.37	4.80	1.52	0.50	0.99	23.2	0.41	0.86
Grain yield (kg ha <sup>-1</sup> )	1699.0	1014.2	1631.1	953.00	-67.9	212.1	12.5	0.95	0.99
ADM (kg ha <sup>-1</sup> ) <sup>++</sup>	4113.9	1798.6	3819.2	1700.0	-294.7	878.8	21.4	0.73	0.92
HI	0.42	0.08	0.40	0.12	-0.02	0.09	20.8	0.09	0.85
Weight per seed (g)	0.19	0.04	0.17	0.05	-0.04	0.05	26.2	-0.76	0.69
No. of seeds per m <sup>2</sup>	2254.0	1295.7	948.3	411.3	-1305.8	1613.3	71.6	-0.74	0.55
No. of seeds per pod	6.31	0.72	5.99	0.43	-0.32	0.75	12.0	-0.24	0.44

\* S.D = standard deviation, MD = mean deviation, RMSE = root mean square error, CV = coefficient of variation for RMSE, and ME = modelling efficiency. <sup>++</sup> above ground dry matter at harvest.



**Figure 8.4. Comparison of simulated and measured maximum leaf area index (LAI), above ground biomass at harvest (ADM), grain yield (Y) and harvest index (HI) of beans for three water regimes over three seasons. The broken lines refer the regression line (equations indicated) while the solid lines refer the 1:1 line between the simulated (with CROPGRO-DRY BEAN model) and measured values with n = 9.**

Grain yield was simulated well with a CV between 10-20% and values of  $d_a$  and ME very close to the optimal value (Table 8.3). A regression equation, which is significant at 0.1% P level with slope of 0.92, confirms that the model performed well in simulating bean grain yield (Fig. 8.4, Table 8.4). However, the model underestimated number of seeds per  $m^2$  and number of seeds per pod with a very poor ME (Table 8.3). Therefore, further calibration and testing of the model may be required to increase its accuracy in simulating seed number.

**Table 8.4. Regression coefficient for beans and chickpea from simulated and observed data combined over three water regimes and three seasons (n = 9).**

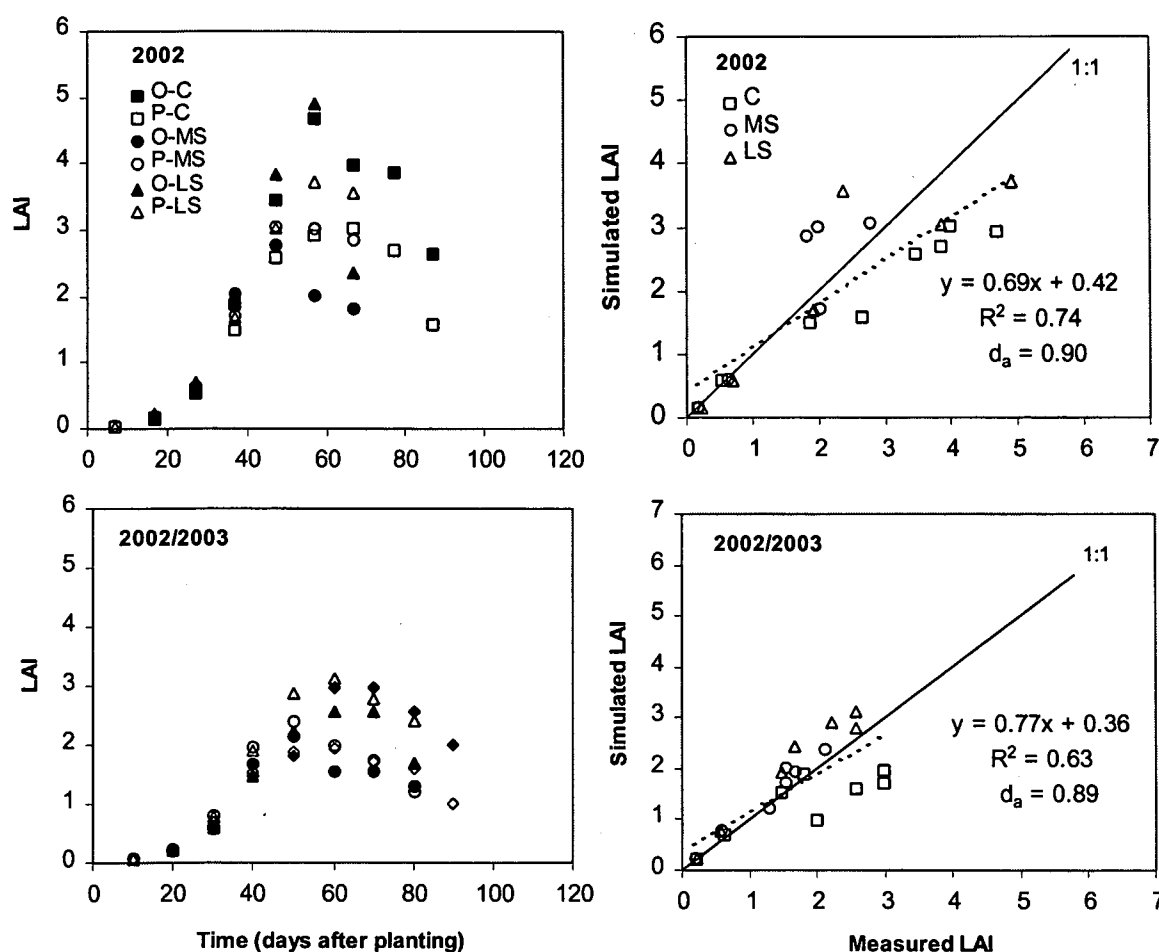
Variable	a	b	R <sup>2</sup>	Probability
<b>Beans</b>				
Anthesis date (DAP)	21.2±0.69	0.48±0.01	0.99	0.000
Maturity date (DAP)	84.0±16.96	-0.01±0.20	0.00	0.982
Maximum LAI (m <sup>2</sup> /m <sup>2</sup> )	0.92±1.06	0.91±0.24	0.67	0.007
Grain yield (kg/ha)	69.5±142.9	0.92±0.07	0.96	0.000
Biomass at harvest (kg/ha)	415.1±768.10	0.83±0.17	0.77	0.002
HI	-0.12±0.14	1.23±0.33	0.67	0.007
Weight per seed (g)	-0.014±0.06	0.74±0.33	0.77	0.002
Number of seeds per m <sup>2</sup>	385.8±189.9	0.25±0.07	0.62	0.012
Number of seeds per pod	4.9±1.36	0.17±0.21	0.08	0.456
<b>Chickpea</b>				
Anthesis date (DAP)	31.5±0.55	0.13±0.01	0.94	0.000
Maturity date (DAP)	72.8±6.73	0.10±0.08	0.20	0.226
Maximum LAI (m <sup>2</sup> /m <sup>2</sup> )	0.36±0.66	0.78±0.24	0.60	0.015
Grain yield (kg/ha)	-101.6±230.0	1.11±0.17	0.87	0.000
Biomass at harvest (kg/ha)	704.6±837.3	0.74±0.22	0.61	0.013
HI	0.01±0.13	1.02±0.35	0.56	0.021
Weight per seed (g)	-0.29±0.19	1.67±0.66	0.48	0.039
Number of seeds per m <sup>2</sup>	1674.7±495.8	0.06±0.38	0.04	0.876
Number of seeds per pod	0.95±0.18	0.22±0.14	0.26	0.158

### 8.3.1.2. CROPGRO-CHICKPEA

The simulated values of LAI during the crop cycle were generally close to the measured values in the 2002 and 2002/2003 seasons with underestimation towards the end of the growing period in 2002 (Fig. 8.5). Underestimation of seasonal LAI by the model was higher under the well-watered conditions than the stressed ones in both seasons (Fig. 8.5).

However, as shown by high  $d_a$  values greater than 0.88 for the combined data over the water regimes, the model simulated seasonal growth of LAI fairly well under both well-watered and water stress conditions during the R1 and R4 growth stages. Although the model tended to underestimate seasonal ADM in the 2002 and 2002/2003 seasons, particularly under well-watered conditions (Fig. 8.6), the index of agreement was high (>0.85) indicating that the simulation of above ground dry matter production during the

(>0.85) indicating that the simulation of above ground dry matter production during the crop growth cycle was acceptable. The model simulated cumulative crop ET with a better accuracy ( $d_a > 0.95$ ) in both seasons (Fig. 8.7) indicating that the simulation of cumulative ET was very good.



**Figure 8.5.** Seasonal course of measured (O) and simulated (P) LAI of chickpea under water stress (MS, LS) and well-watered (C) conditions (left), and regression of simulated vs. measured values (right) for 2002 and 2002/2003 seasons.

Unlike in beans, the model for chickpea simulated maturity date well with a CV of <20% and a positive ME value (0.06) whereas the simulation of anthesis date was very poor (ME = -2.87). The  $d_a$  value, on the other hand, is the same (0.47) for both maturity and anthesis dates suggesting that ME may be a more sensitive indicator of model performance than  $d_a$ .

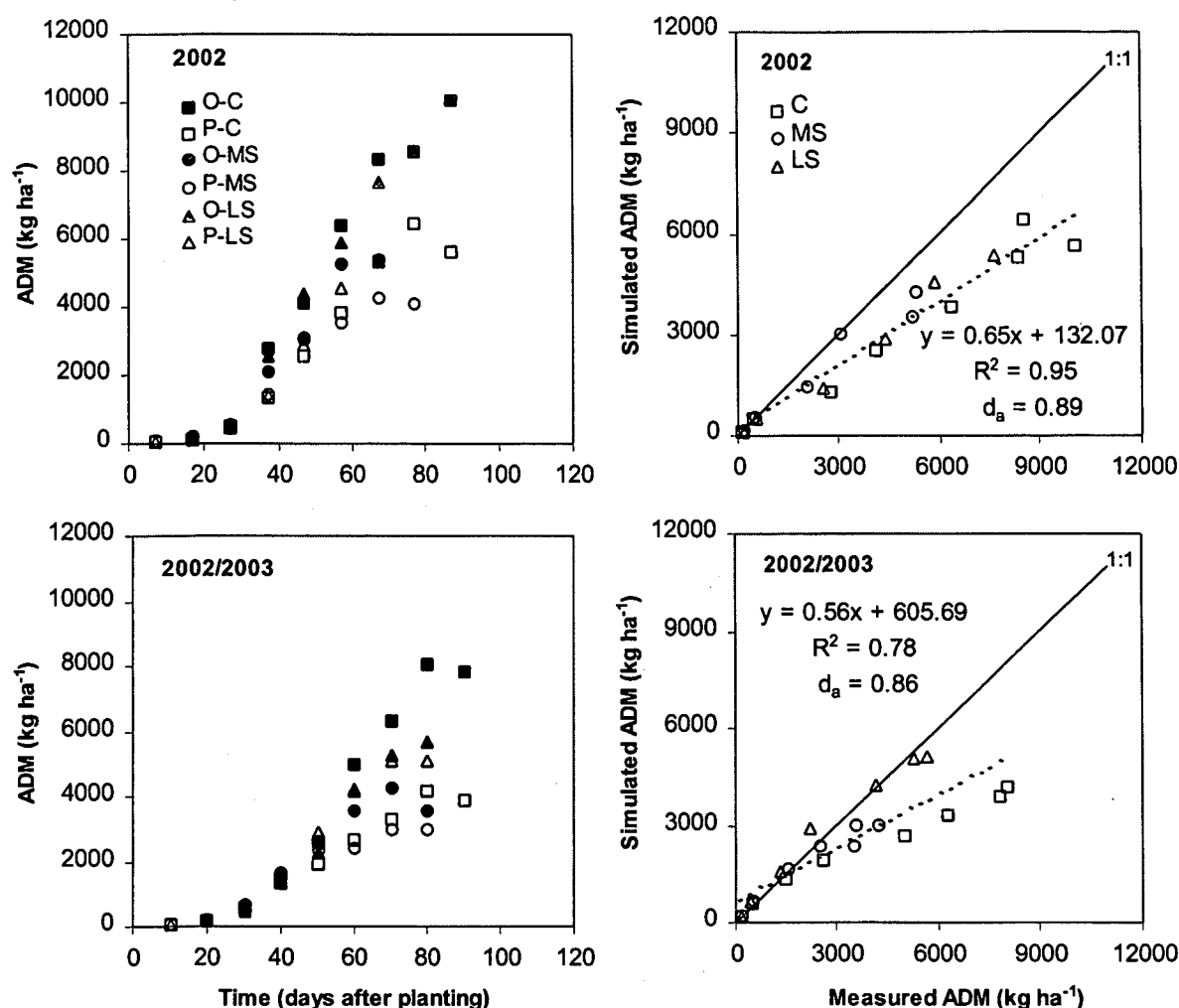


Figure 8.6. Seasonal course of measured (O) and simulated (P) above ground dry matter production (ADM) of chickpea under water stress (MS, LS) and well-watered (C) conditions (left), and regression of simulated vs. measured values (right) for 2002 and 2002/2003 seasons.

The model simulated maximum LAI and above ground dry matter at harvest fairly well with a CV of <30% and ME of value 0.49 and 0.37, respectively (Table 8.5). The regression equation between simulated and measured values of maximum LAI and final ADM were significant ( $P < 0.05$ ) with  $R^2$  value greater than 0.60 (Table 8.4, Fig. 8.8).

The model was successful in simulating grain yield at harvest (CV <20%, ME = 0.79,  $d_a$  = 0.96) and HI (CV <25% and ME = 0.55,  $d_a$  = 0.84) (Table 8.5). The slopes of the regression lines were very close to the 1:1 line with an  $R^2$  value of 0.87 and 0.56 for grain yield and HI, respectively (Fig. 8.8) indicating the best fit between observed and simulated values. The regression equations were highly significant ( $P < 0.01$ ) for grain yield and significant ( $P < 0.05$ ) for HI (Table 8.4).

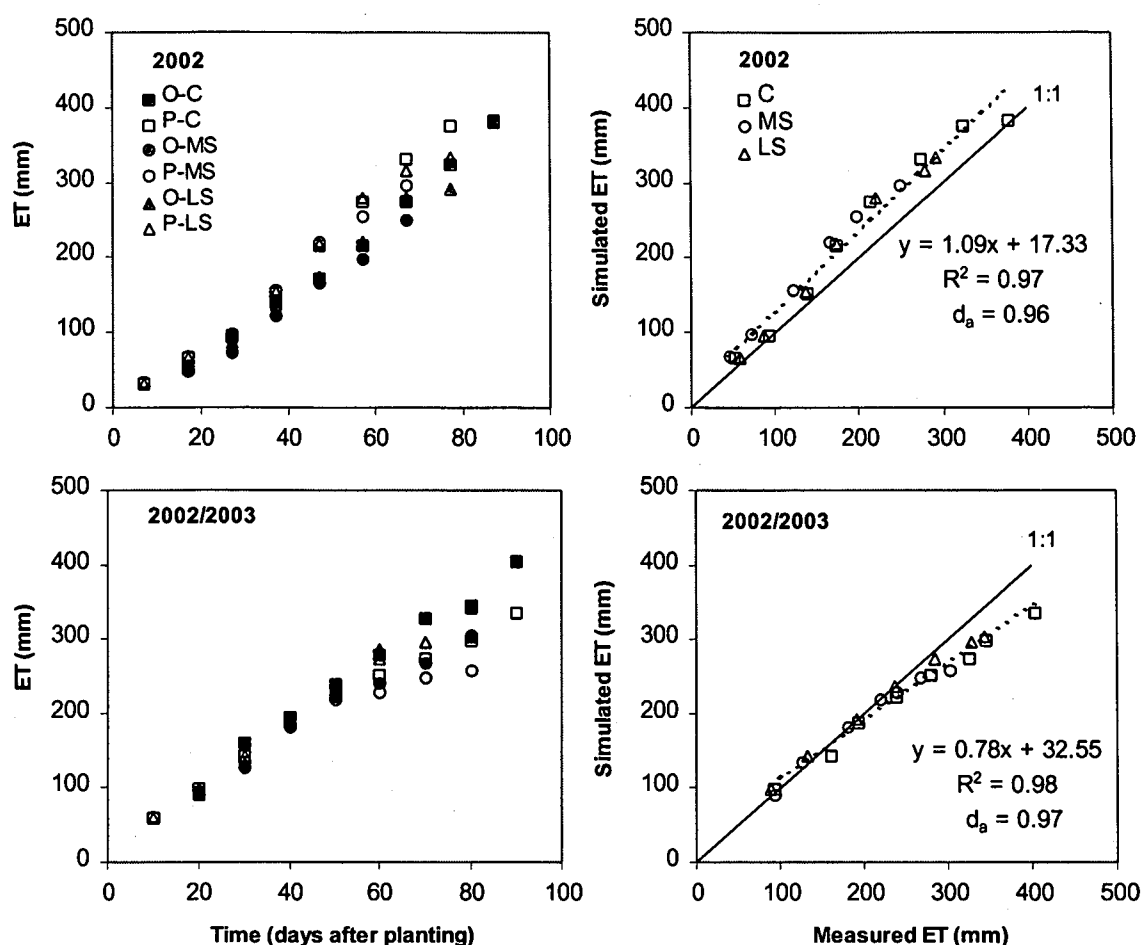


Figure 8.7. Seasonal measured (O) and simulated (P) cumulative crop evapotranspiration (ET) of chickpea under water stress (MS, LS) and well-watered (C) conditions (left), and regression of simulated vs. measured values (right) in 2002 and 2002/2003 seasons.

Table 8.5. Statistical indexes of measured and simulated parameters of chickpea for data combined over three water regimes and three seasons ( $n = 9$ ).

Variable	Observed		Simulated		Statistical indices				
	Mean	S.D.*	Mean	S.D	MD	RMSE	CV (%)	ME	$d_a$
Anthesis date (DAP)	43.00	3.61	37.00	0.50	-6.00	6.70	15.4	-2.87	0.47
Maturity date (DAP)	86.00	14.12	82.00	3.24	-4.10	12.90	15.1	0.06	0.47
Max. LAI ( $m^2 m^{-2}$ )	2.60	0.98	2.37	0.98	-0.22	0.66	25.5	0.49	0.86
Grain yield ( $kg ha^{-1}$ )	1284.20	570.63	1323.90	680.72	39.70	245.70	19.1	0.79	0.96
ADM ( $kg ha^{-1}$ ) <sup>++</sup>	3540.10	1323.7	3305.4	1247.5	-234.67	841.00	23.8	0.37	0.87
HI	0.37	0.09	0.38	0.12	0.01	0.08	21.5	0.55	0.84
Weight per seed (g)	0.28	0.04	0.18	0.10	-0.10	0.12	43.1	-9.30	0.45
No. of seeds per $m^2$	1076.30	809.7	1740.30	806.3	664.0	1237.1	115.0	-1.63	0.32
No. of seeds per pod	1.30	0.31	1.23	0.13	-0.04	0.25	19.9	0.23	0.54

\* S.D = standard deviation, MD = mean deviation, RMSE = root mean square error, CV = coefficient of variation for RMSE, and ME = modelling efficiency. <sup>++</sup> above ground dry matter at harvest.



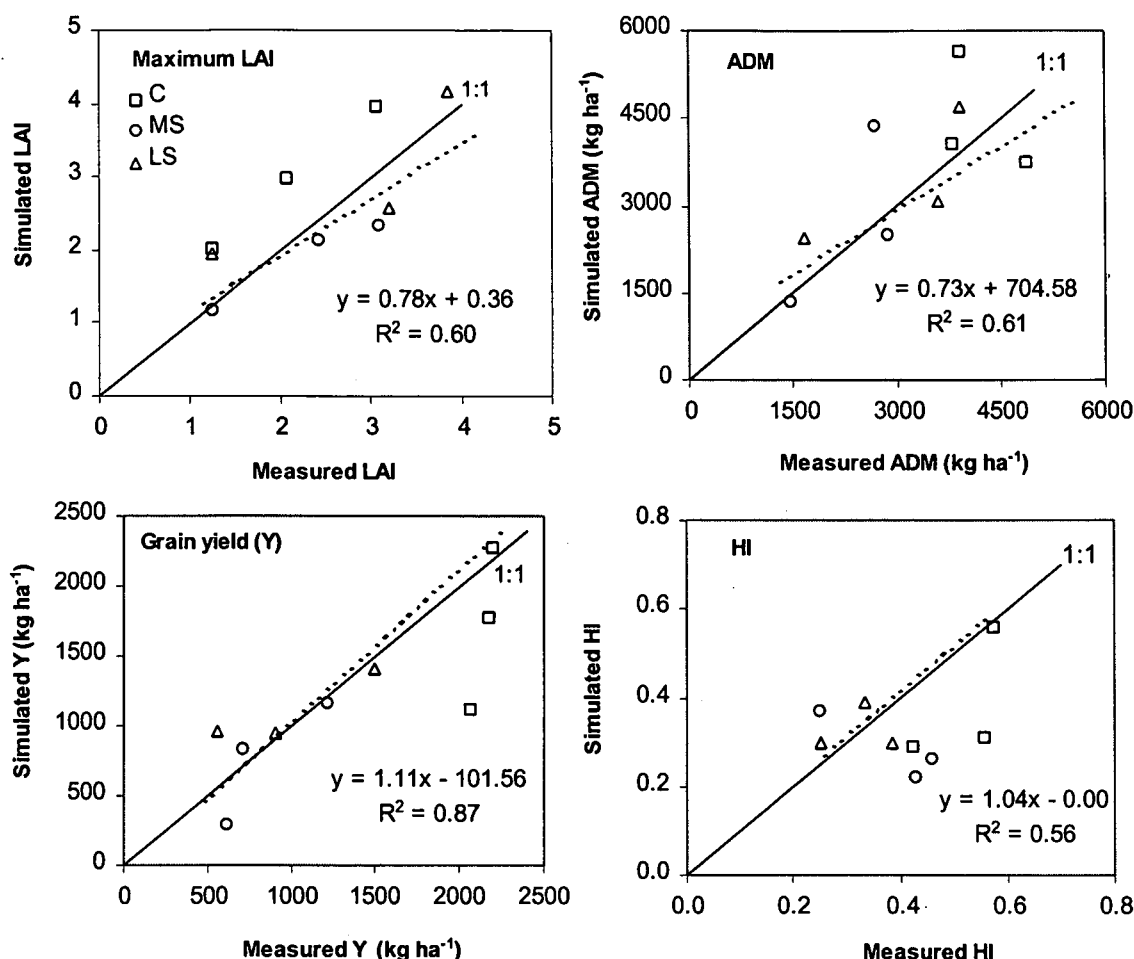


Figure 8.8. Comparison of simulated and measured maximum leaf area index (LAI), above ground biomass at harvest (ADM), grain yield and harvest index (HI) of chickpea for three water regimes over three seasons. The broken lines refer to the regression line (equations indicated) while the solid lines refer to the 1:1 line between the simulated (with CROPGRO-CHICKPEA model) and measured values with  $n = 9$ .

The model failed to simulate weight per seed and number of seeds per m<sup>2</sup> as shown by the high RMSE and CV and low  $d_a$  and negative values of ME (Table 8.5). Moreover, the regression equations had an  $R^2$  value of less than 0.50 and were not significant ( $P > 0.05$ , Table 8.4). Therefore, both the bean and chickpea models showed weakness in simulating yield components.

### 8.3.2. General model performance

CROPGRO was generally successful in simulating grain yield at harvest, maximum leaf area index, aboveground biomass at harvest and harvest index under both well-watered and water deficit conditions during the reproductive period. The success of CROPGRO in

simulating grain yield has also been reported for many grain legumes including beans (Hoogenboom, *et al.*, 1994b; White *et al.*, 1995), soybean (Ruiz-Nogueira *et al.*, 2001; Wang *et al.*, 2003; Mall *et al.*, 2004), and peanut (Singh *et al.*, 1994) under different environmental conditions including water deficit.

Calculation of the crop ET using the "Ritchie's" model (as provided in DSSAT) overestimated the seasonal ET during the high temperature season while a slight underestimation was observed in the milder temperature season for both beans and chickpea (Fig. 8.3&8.7). However, the general trend, as shown by high  $d_a$  and ME values, is acceptable. Despite a higher LAI and crop ET, CROPGRO underestimated accumulation of aboveground dry matter during the growth period of both beans and chickpea in the high temperature season which could be as a result of the lower optimum/maximum temperatures set in the models for optimum/maximum photosynthesis. For example, the optimum (Opt1, Opt2) and maximum temperatures set for pod addition in CROPGRO for beans are 13, 25 and 36°C (Boote *et al.*, 2002). The maximum value set in the model is, thus, by far lower than the maximum air temperature (>39 °C) observed during the experimental period in 2002 such that the model may not have accounted for the photosynthesis above 36°C during pod initiation. Therefore, further improvement in the parameterisation of cardinal temperatures in the models is desirable. The model also clearly underestimated maturity date, number of seeds per m<sup>2</sup> and number of seeds per pod in beans as well as anthesis date and weight per seed in chickpea. Number of seeds per m<sup>2</sup>, however, was overestimated in chickpea. Therefore, further improvement as well as calibration with log-term crop data is necessary to correct the simulation of these components by the model.

#### 8.4. Conclusion

Grain legumes are grown predominantly under rainfed conditions where water is a major limiting factor and the interannual rainfall variability is high. Crop modelling has proven a valuable tool to evaluate the long-term consequences of weather patterns and environmental conditions. However, the candidate crop models must be tested and calibrated for new regions prior to their use as decision support tools in agriculture.

In the present study, the CROPGRO model simulated LAI, crop ET and aboveground biomass at harvest with reasonable accuracy while the simulation for grain yield at

harvest was very good for both beans and chickpea. The models showed good performance in simulating these variables under well-watered and water stress conditions during the reproductive period of the crops. However, the simulation of yield components at harvest in both seasons, and biomass accumulation during crop cycle under high temperature conditions was poor in both crops suggesting further improvements of the models to suit for the study environment. Model weakness was also observed on simulation of maturity date in beans and flowering date in chickpea.

Generally, the performance of CROPGRO in simulating the final yield of beans and chickpea is very good. Therefore, it is concluded that with further calibration using multi-season crop data, the model has good potential to be used as a decision support tool in the semi-arid areas of Ethiopia where long-term field experimentation is costly and less effective due to fluctuating weather conditions.

## CHAPTER 9

### Summary and Recommendations

#### 9.1. Summary

Natural calamities, overpopulation and extreme poverty are threatening the food security of many developing countries, particularly in Africa. The problem is even worse in the SAT regions where water shortage is a recurrent occurrence. Grain legumes are among the major vital crops that can produce sustainable grain yield and biomass in these harsh environments and provide quality protein for the inhabitants besides serving as source of cash income for the households. These crops also play a major role in low input agricultural systems, and have the potential to contribute to the enhancement of the natural resource base used for the production of other raised crops which are the staple foods of the poor communities. However, the yield of grain legumes is generally lower in developing countries than the developed ones, and is the lowest in Africa (Al-Jibouri and Kassapu, 1987; Oram and Agcaoili, 1992; Jeuffroy and Ney, 1997). Water deficit is one of the major constraints that contribute to the low yield of grain legumes in many regions (e.g. Turk *et al.*, 1980a; Graham and Ranalli, 1997; Kumar *et al.*, 1996).

Common bean, chickpea and cowpea are the major grain legume crops traditionally grown in Ethiopia either in the same or different environments. The yield of these crops is very low either because of wrong crop choice or rigid management practices (such as planting the same time every year) in the different growing environments. Successful crop production in the SAT regions entails detail agroclimatic information, proper crop choice and flexible options for management practices according to actual climatic conditions. However, there is no such information in Ethiopia that can assist or advice on choices among these grain legumes for a specific environment in terms of resource utilization and productivity. Therefore, this study was initiated to compare the resource utilization (water and radiation) and productivity of three grain legumes under water stress and non-stress conditions, and to analyse the rainfall behaviour of selected grain legume producing regions of Ethiopia. Information that has been reported in this study will make a valuable contribution to agricultural scientists and extension officers with regard to practical decisions for grain legume production in the semi-arid regions.

Chapter 2 has presented the historical rainfall analysis at ten weather stations in the grain legume producing regions of Ethiopia. The study showed the existence of regional differences in water supply for crop production. In some areas like Bahir Dar, Bako and Bole, management of excess water is the major concern unlike other areas (Jijiga and Dire Dawa) where water shortage is critical. Therefore, maximizing water use and water use efficiency are crucial at Dire Dawa and Jijiga. The regions were categorized into three groups in terms of the length of water availability period (length of effective growing season) for crop production, namely, high water supply (Awassa, Bahir Dar, Bako, Bole, Debre Zeit), intermediate water supply (Alemaya, Mekele, Melkasa) and low water supply (Dire Dawa and Jijiga). In this way, the need for adopting different management practices (strategic and tactical) for optimum resource utilization in each region is emphasized.

The major effects of water stress are reflected in altered growth, phenology and dry matter distribution. Chapter 3 is devoted to investigate and describe possible differences among species in their response to mid-season (MS) and late season (LS) water stress so that the favourable traits identified can be exploited in the improvement of the respective crops. Late season water stress significantly shortened the time to maturity of all three grain legumes in all seasons while the effect in the mid-season stress was dependent on temperature conditions after re-watering. The thermal time requirements of the different phenological stages determined under water stress and non-stress conditions can be used to predict each phenological stage for management decisions in the field and for improvement of crop simulation models. Leaf area growth and above ground dry matter production were only significantly affected by the mid-season stress. Among species, leaf area was least affected in cowpea. Dry matter production is strongly positively correlated with leaf area duration (LAD) in all the three species indicating that factors that reduced the LAD (water stress in this case) also reduced dry matter production. In the present case, the reduction in dry matter in the LS, though not significant, is partly due to a shorter LAD while the reduction in the MS is largely attributed to lower mid-season LAI, and also a shorter LAD under high temperature conditions when compared to the control. Dry matter allocation among above ground parts was influenced by both the timing of water supply (growth stages) and species. High dry matter from the leaves and stem was allocated to the pods during late season water stress followed by well-watered condition. Under LS stress, dry matter allocation to pods was the highest in beans while it was

similar in chickpea and cowpea. Dry matter allocation was lower in the MS treatment (only from leaves), and under such conditions chickpea allocated more dry matter to its pods than beans and cowpea. The relationship between dry matter distribution among above ground parts during the whole growth period was explained using regression equations. These values are expected to be useful in modelling the growth of these crops. Moreover, information on dry matter allocation is helpful to breeders to select and breed crops for specific environments such as the one mentioned here (mid-season and terminal drought environments). Although the relationship was not significant during mid-season water stress conditions, a strong negative linear relationship between specific leaf area (SLA) and water use efficiency (WUE) was found under well-watered conditions in all the three species. Since the determination of WUE involves measurement of soil water which requires expensive instruments, low SLA could be used to select cultivars for high WUE under well watered conditions in these species.

In Chapters 4 and 5, the water and radiation use and the respective use efficiencies of the three grain legumes are presented. Dry matter production in grain legumes is found to be strongly and positively correlated with the fraction of PAR that is intercepted ( $F$ ) which is also strongly positively correlated with LAI. As a result, factors that reduce LAI also reduce  $F$  and consequently result in low dry matter production. In line with this, water stress during the flowering period reduced extinction coefficient ( $K$ ),  $F$  and RUE when compared to well-watered conditions. Species differences were observed on the effect of mid-season water stress on RUE in that water stress during the flowering period significantly reduced RUE in beans and chickpea whereas it had no effect on cowpea. On the other hand, water stress during the late season did not significantly affect these parameters in any of the three species.

Water use was higher under well-watered conditions followed by mid-season stress in all three species than the late season stress. The lower water use in the stress treatments is mainly a result of low seasonal water supply and stomatal closure. However, WUE was the highest in the LS stress and the lowest in the MS due to lower water use in the former and due to lower dry matter production and higher soil evaporation in the latter when compared to the control. Owing to its high seasonal water use as well as high dry matter production, the WUE in the control is intermediate between the MS and LS treatments in chickpea and cowpea while it is similar to the LS in beans. The species' have similar

water use but different WUE (lower in chickpea but similar in beans and cowpea) under well-watered conditions which is mainly as result of differences in canopy cover and resultant soil evaporation. When tested across seasons, the three species had similar WUE under the pod filling period water stress. Nevertheless, chickpea had the lowest WUE when water stress occurred during the flowering period stress. Beans and cowpea had similar WUE under all water regimes when tested across seasons. Unlike chickpea, WUE in beans and cowpea is strongly and positively correlated with HI so that improving the WUE in beans and cowpea is expected to improve the grain yield of these crops. In general, in terms of WUE, beans and cowpea are more productive than chickpea under high water supply and mid-season drought environments while all the species may have similar productivity under terminal drought environments. The differences between the water stress treatments in affecting the radiation and water parameters indicate the importance of the timing of water supply in affecting the resource utilization of grain legumes. In this study, stress during flowering period was found to be detrimental in reducing radiation and water use efficiency. Therefore, the implication of these results is that crop management and breeding practices should focus on increasing the RUE and WUE to improve the yield of grain legumes in sporadic mid-season drought prone environments.

In Chapter 6, the physiological response of the three species to variable water supply and weather conditions, and the inter-relationships among the physiological parameters were investigated. It was found that the leaf water potential of chickpea was more responsive to the decline in soil water than beans and cowpea. This was due to slow stomata closure mechanism as indicated by low stomatal resistance in chickpea. Cowpea closes its stomatal faster than both beans and chickpea which makes it a more drought-avoiding crop than the other two species. The magnitude and rate of photosynthesis decline was higher and faster in the mid-season than in the late-season stress in all species, and among the species the rate of photosynthesis declined faster in chickpea than in beans and cowpea. Cowpea had the lowest reduction in the rate of photosynthesis under severe water stress (available soil water <32%) compared to the other two species. Increase in leaf temperature was found to be the major factor for the decline of diurnal rate of photosynthesis in the stressed plants through its effect on stomatal adjustment, transpiration and possibly enzymatic activities.

Despite low rate of stomatal closure and low level of leaf water potential, chickpea maintained a similar rate of photosynthesis to that of cowpea at the severe stage of the water stress. This indicates that chickpea could have some molecular and cellular adaptation mechanisms that enable it to maintain its photosynthesis similar to the species with high leaf water potential under low available soil water conditions.

The rate of photosynthesis in the three species can be estimated from a few weather and physiological parameters with reasonable accuracy. This will help those who do not have the instruments to measure the photosynthesis of these crops directly. The estimation of transpiration, however, was not encouraging probably because it is affected by more variables than photosynthesis. The relationships established by the regression equations between photosynthesis, transpiration, soil water, leaf water potential and stomatal resistance are useful for modelling or calibrating existing crop growth models for the three species. However, it should be noted that these relationships are cultivar specific.

In chapter 7, the growth stages that are most sensitive to water deficit for each species, and those crop parameters that determine grain yield in each water regime treatment were identified. The grain yield of beans and chickpea is more sensitive to flowering than pod-filling water stress while the yield of cowpea is almost equally sensitive to both periods of water stress, particularly under milder temperature seasons. Therefore, minimizing the effect of water stress at these sensitive phenological stages for each crop through management or breeding methods could help maximize the yield of these crops. When comparing the species, the yield of cowpea is less sensitive to both MS and LS stresses than that of beans and chickpea in most of the seasons. This information can be useful in the practice of crop choice based on environmental constraints such as water stress.

Water deficit during the flowering period resulted in the highest reduction in grain yield which is attributed to the adverse effect of the stress on growth of reproductive organs, LAI, efficiency of radiation and water use, and partitioning of dry matter to the seed. The reduction of grain yield under pod-filling water stress is mainly due to a shorter reproductive period and to some extent a reduction of reproductive organs such as number of seeds per pod and numbers of pods per plant. Therefore, any management or breeding activity which improves one or more of these characters is expected to improve the yield of grain legumes under drought prone environments. Grain yield is positively correlated with HI and RUE under all water supply conditions while its correlation with



WUE and  $p$  varied with water supply. Therefore, it is necessary to design environment dependent selection strategies to improve the yield of grain legumes in a wide of range environments with respect to water supply.

Crop modelling has proven a valuable tool to evaluate the long-term consequences of weather patterns and environmental conditions. However, the candidate crop models must be tested and calibrated for new regions and cultivars prior to their use as decision support tools in agriculture. The DSSAT grain legume crop model (CROPGRO) was evaluated in Chapter 8 for its ability in simulating evapotranspiration, LAI and yield of beans and chickpea using three seasons observed data. Under both well-watered and reproductive period water stress conditions, the model simulated LAI, crop ET and above ground biomass at harvest with reasonable accuracy. The simulation for grain yield at harvest was very good for both beans and chickpea. However, the simulation of yield components at harvest in all seasons, and biomass accumulation during crop cycle under high temperature conditions was very poor in both crops suggesting further improvements of the models to make it suitable for the study environment. Model weakness was also observed on simulation of maturity date in beans and flowering date in chickpea. It is concluded that with further calibration using long-term data, the model has good potential to be used as a decision support tool in the semi-arid areas of Ethiopia where long-term field experiment is costly and less effective as a result of fluctuating weather conditions.

## **9.2. Recommendations**

Based on resource availability (in the various environments) and its use for productivity (among species), the following recommendations are made:

- Site and season specific adjustment of crop choice and other management practices for the regions studied. This will allow proper utilization of resources and minimization of risks in each region unlike the traditional way of employing the same farming practices every year.
- Jijiga, which has a very short growing season with high risk of planting failure, is more suitable for livestock than crop production.
- Chickpea varieties that mature within 80 days or less are needed for Bole and Debre Zeit where the crop is grown as a post-rainy season crop. On the other

hand, there is a huge potential to grow medium maturing chickpea varieties twice in a season at Awassa where the crop is not yet widely grown.

- Common bean, which has a higher RUE and WUE, is more productive than chickpea and cowpea under well-watered conditions. Therefore, whenever high yield is desired from this crop (e.g. large scale production for export), it is advisable to grow beans in the relatively high rainfall areas (with warm temperature).
- Both beans and chickpea are more sensitive to flowering than pod-filling period water stress. Therefore, it is necessary to match the flowering period of these crops to the water availability period in order to maintain yield and/or minimize yield reduction in water limited-environments.
- Cowpea is more adapted to mid- and late- season water limited environments than beans and chickpea because of its ability to maintain LAI, RUE and photosynthesis under water stress conditions. Therefore, cowpea is recommended over the other two species for areas such as Dire Dawa where the growing period is short with possible water shortage during the early reproductive periods.

### 9.3. Future studies

Firstly, agroclimatic information is one of the key elements that are needed for successful crop production in semi-arid regions. However, such information is either lacking or available only as large area recommendation in Ethiopia. The country is very large covering about 1,221,900 sq. km with great terrain diversity and wide variations in climate, soils, natural vegetation and settlement patterns. The country currently has more than 530 first to fourth class weather stations. Of these, only 10 stations were considered in the present study. Therefore, further research on water supply, length of growing season and water balance of the rest of the stations in a GIS (Geographical Information Systems) environment is required to support agricultural decision-making in the country.

Secondly, the current study emphasized on the response of the three species to the different water regimes based only on above ground parts of the plants. This is due to the obvious reason that root measurement under field conditions is very difficult. However, root size, morphology, length, density and hydraulic conductance are basic root attributes to meet the transpiration demand of the shoot (Passioura, 1982). Therefore, in order to

supplement the current study with information about the below ground response of the crops, root growth study, which requires specialized equipment, is suggested for each species under controlled or semi-controlled conditions in the same environment and soil conditions.

Thirdly, crop modeling is now serving as a decision support system in many developed countries. Such a support system is deemed necessary for semi-arid regions in developing countries where long-term field experiments are becoming unaffordable because of economic reasons. Therefore, development of new grain legume crop growth models and also intensive calibration of existing ones with long-term data to suit for semi-arid regions is an immediate area of research to focus on.

**"If you speak of development you have to start with water, it's as simple as that."**

***Carel de Rooy, UNICEF***

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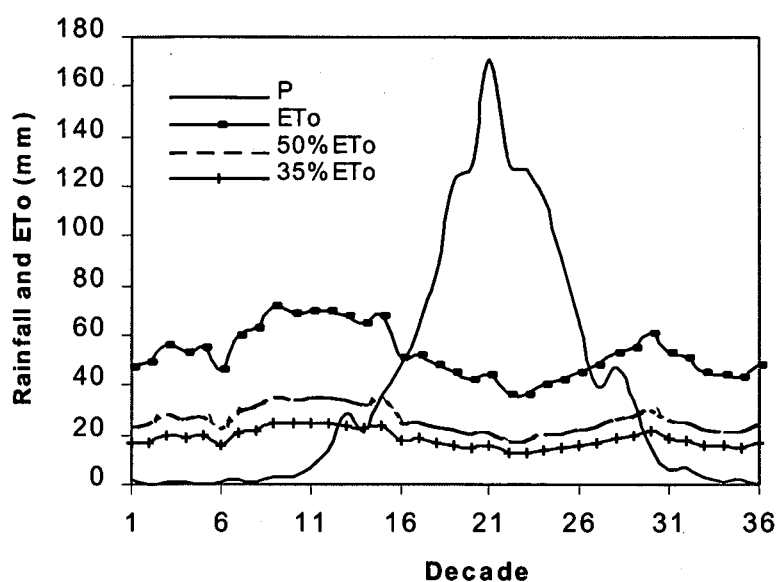
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## Appendix 1

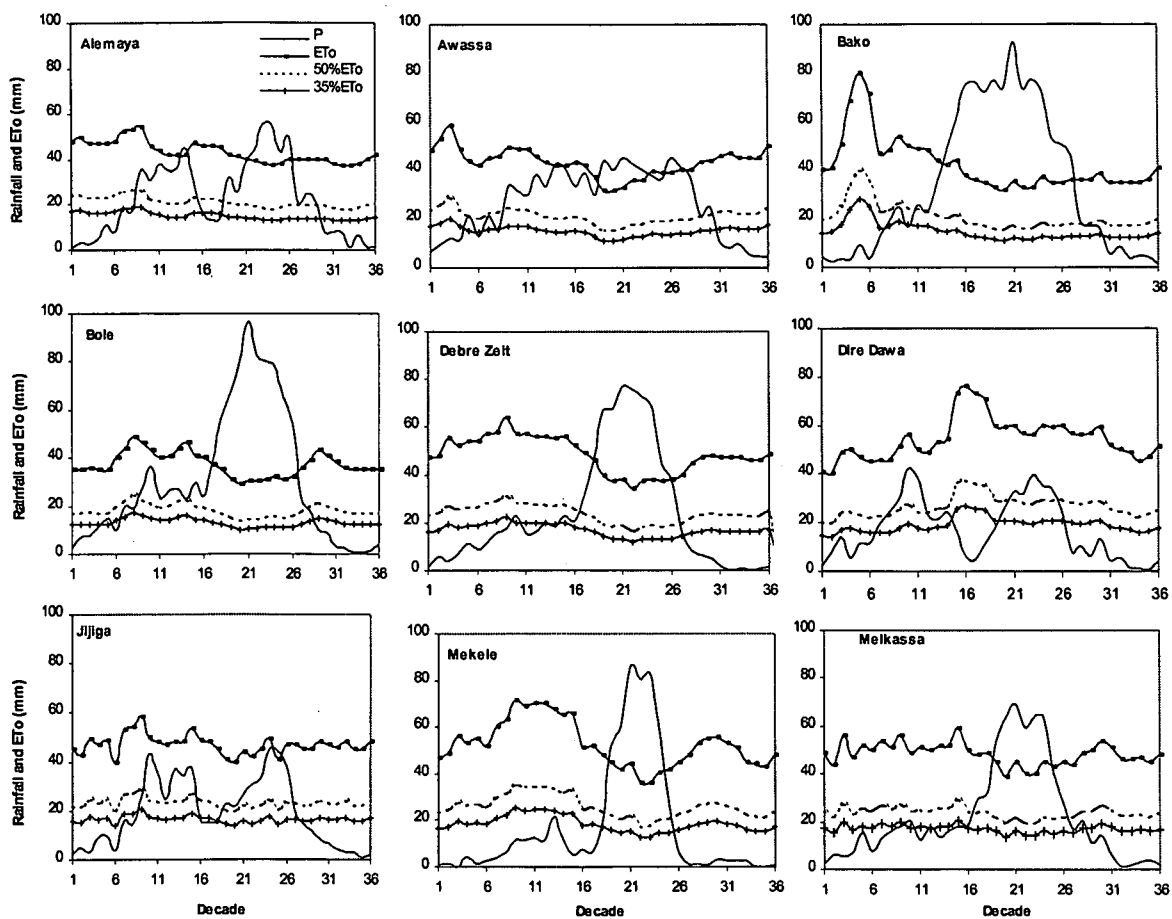
### Appendix 1A. Soil type and soil water relations of the study areas (Eylachew, 1994 and sample analysis)

Location	Soil Type		ST	DUL (mm m <sup>-1</sup> )	DLL (mm m <sup>-1</sup> )	Available (mm m <sup>-1</sup> )	$\theta_s$ (mm m <sup>-1</sup> )
	FAO/UNESCO	USDA					
Alemaya Campus	Eutric Regosol	Typic Ustorhent	C	88	55	33	137
Awassa (Profile-1)	Regosol	NA	CL	108	52	56	150
Bahir Dar	Ferric Luvisol	Typic Rhodustalf	C	132	84	48	150
Bako	Humic Ferralosol	Rhodic Haplustox	C	123	93	30	162
Bole/Akaki	Vertisol	Vertisol	C	157	92	65	185
Debre Zeit	Vertisol	Vertisol	C	139	60	79	180
Dire Dawa	Eutric Regosol	Typic Ustorhent	SL	78	39	38	46
Jijiga	NA	NA	CL	90	63	27	103
Mekele	Calcic Cambisol	Typic Eutrochrept	L	94	64	30	143
Melkassa (Nazareth)	Haplic Andosol	Typic Haplustand	SL	72	38	34	168

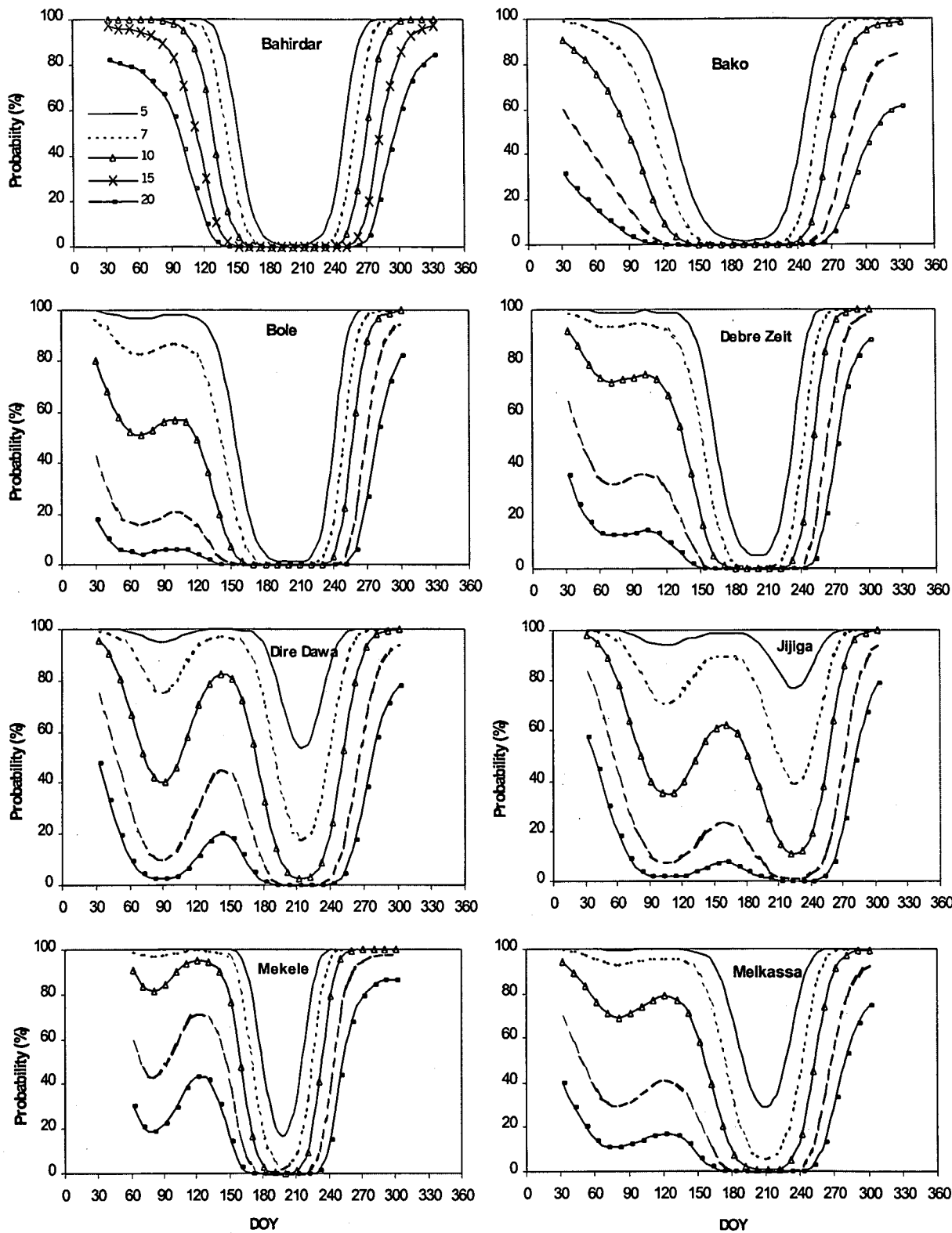
DUL= drained upper limit; DLL=drained lower limit; C= clay; CL= clay loam; L= loam; SL= sandy loam; ST= surface soil texture; NA= information not available.



Appendix 1B. Comparison of long-term decade rainfall (P) and reference evapotranspiration (ET<sub>0</sub>) at 100, 50 and 35% levels at Bahir Dar, Ethiopia.



**Appendix 1C. Comparison of long-term decade rainfall (P) and reference evapotranspiration (ET<sub>0</sub>) at 100, 50 and 35% levels for nine locations in Ethiopia.**



**Appendix 1D. Probabilities of conditional dry spells exceeding 5, 7, 10, 15 and 20 days within 30 days after starting date at 10 locations in Ethiopia.**

## Appendix 2



**Appendix 2A. Meteorological, micrometeorological and physiological instruments used in the study. From left to right are: leaf area meter, pressure chamber, porometer, Infrared Gas Analyzer (LAC4), Time Domain Reflectometry (TDR) and Sun scan canopy analysis system at the back (top), and automatic weather station (bottom).**





**Appendix 2B. Plot layout and an example of soil and micrometeorological data collection during the experimental periods on fields of beans, chickpea and cowpea.**

## Appendix 3

**Appendix 3A. Thermal time from planting to emergence (E), from emergence to flowering (E-F), from flowering to podding (F-P), from podding to maturity (P-M) and from flowering to maturity (F-M) for three grain legumes grown under well-watered (C) and mid-season (MS) and late season (LS) water stresses in two seasons.**

S <sub>p</sub> <sup>a</sup>	W <sub>R</sub>	2001/2002					2002/2003				
		E	E-F	F-P	P-M	F-M	E	E-F	F-P	P-M	F-M
Beans	C	113	581	48	399	457	101	650	23	547	570
	MS	118	559	81	224	305	101	792	28	533	561
	LS	113	577	55	189	245	101	635	39	338	376
Chickpea	C	131	553	146	466	613	132	579	134	725	859
	MS	121	554	160	271	431	132	579	121	754	875
	LS	126	554	141	275	416	132	579	134	451	585
Cowpea	C	86	758	41	402	442	76	792	59	598	657
	MS	81	749	64	252	270	76	778	63	510	572
	LS	75	741	69	210	279	76	764	67	381	447
LSD	WR	n.s.	n.s.	n.s.	93.3**	72.1**	n.s.	n.s.	n.s.	46.1***	62.7***
(P<0.05)	SP	13.4***	38.7***	36.5***	48.5**	70.7***	0.03***	35.7***	34.5***	60.3***	57.8***
	WRxSP	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
CV (%)		12.1	6.0	39.7	16.0	10.3	0.00	5.2	25.3	10.9	9.2

\*\*\*, \*\*, \*: Treatment significant at 0.1, 1 and 5% probability level respectively, n.s: treatment not significant at 5% probability level. <sup>a</sup> S<sub>p</sub> = species, W<sub>R</sub> = water regimes.

**Appendix 3B. Thermal time from planting to emergence (E), from emergence to flowering (E-F), from flowering to podding (F-P), from podding to maturity (P-M) and from flowering to maturity (F-M) for three grain legumes grown under well-watered (C) and mid-season (MS) and late season (LS) water stress in 2002<sup>o</sup>**

S <sub>p</sub>	W <sub>R</sub>	E-F	F-P	P-M	F-M
Beans	C	575	83	696	779
	MS	575	83	549	632
	LS	575	83	422	505
Chickpea	C	594	92	836	928
	MS	594	92	358	450
	LS	594	92	561	653
Cowpea	C	700	132	778	910
	MS	700	132	576	708
	LS	700	132	484	616

<sup>o</sup> measurements were not replicated.

**Appendix 3C. The time course of mean leaf area ( $\text{cm}^2 \text{m}^{-2}$ ) expansion in three grain legumes under three water regimes in 2001/2002.**

Species	DAP	Water regimes with standard errors (SE)					
		C		MS		LS	
		Mean	SE	Mean	SE	Mean	SE
Beans	39	6864	230	8486	1767	7696	1127
	49	10356	1202	8342	1363	8833	735
	57	20098	1141	9415	3984	15087	189
	68	19764	903	11356	888	14584	1098
	78	13237	1640	9670	2880	5429	2337
	88	11527	1965	12396	686	-	-
	98	11854	1111	23802	2103	-	-
Chickpea	38	4977	970	3071	498	4832	481
	48	5725	926	4186	513	5305	567
	56	7159	2540	8101	1780	8235	3243
	67	12131	1912	11675	1543	10128	2881
	77	9944	3418	8477	2588	15408	8623
	87	3366	2147	12049	0	30312	0
	97	2137	2137	11437	-	-	-
Cowpea	35	8119	863	8081	1698	8325	132
	45	9741	2185	9212	415	8930	165
	55	17693	3064	18855	3930	18737	120
	66	22446	5746	15008	578	20051	826
	76	16736	1906	10826	1371	8916	1426
	86	15674	3285	1608	868	-	-
	96	14517	3821	-	-	-	-

**Appendix 3D. The time course of mean leaf area ( $\text{cm}^2 \text{m}^{-2}$ ) expansion in three grain legumes under three water regimes in 2002.**

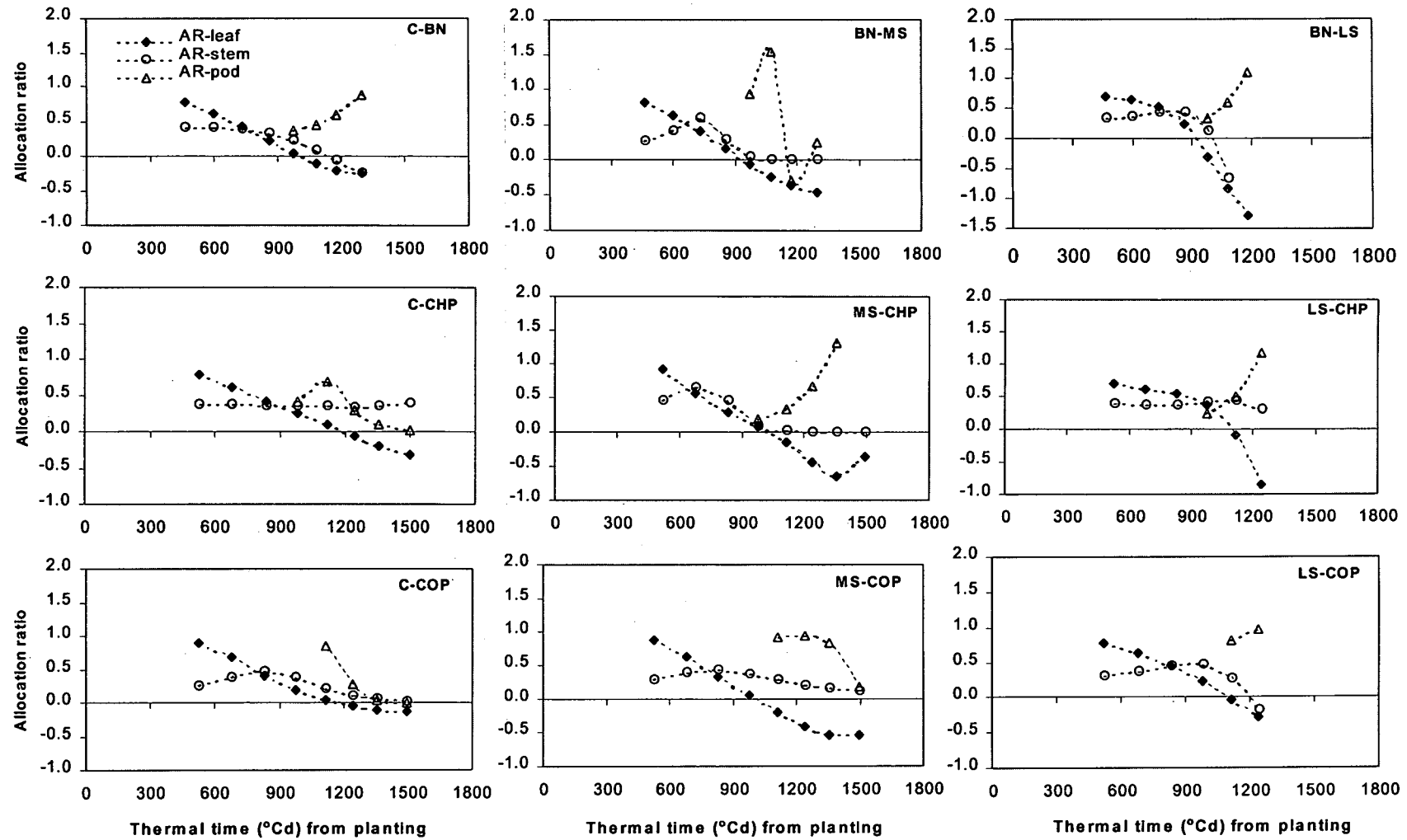
Species	DAP	Water regimes with standard errors (SE)					
		C		MS		LS	
		Mean	SE	Mean	SE	Mean	SE
Beans	17	3800	20	2765	19	2196	21
	27	11830	136	10725	132	10444	126
	37	33938	765	29537	651	32337	375
	47	47486	894	46051	1102	50694	692
	57	57806	587	23688	1107	59682	1105
	67	48391	462	5507	1251	4194	1169
	77	18186	144	12640	112	-	-
	87	14710	136	-	-	-	-
	87	14710	136	-	-	-	-
Chickpea	17	1571	114	1705	112	2274	114
	27	5294	131	6177	126	6973	130
	37	18689	807	20052	798	19130	710
	47	34618	732	27541	1125	38548	1142
	57	46875	1213	19815	1259	49188	1185
	67	39882	409	8028	1179	23641	1214
	77	38615	175	-	-	-	-
Cowpea	87	26370	181	-	-	-	-
	17	3057	32	3189	21	2529	28
	27	6973	127	7925	124	6803	132
	37	22359	1108	18291	1175	21298	1169
	47	36044	1238	37130	1201	40487	1192
	57	48902	2100	39909	1437	56090	1289
	67	34857	877	17986	1103	10768	1104
	77	18015	256	12909	709	-	-
	87	11410	343	-	-	-	-



**Appendix 3E. The time course of mean leaf area ( $\text{cm}^2 \text{m}^{-2}$ ) expansion in three grain legumes under three water regimes in 2002/2003.**

Species	DAP	Water regimes with standard errors (SE)					
		C		MS		LS	
		C	SE	MS	SE	LS	SE
Beans	20	2264	131	2220	44	2387	61
	30	6623	436	6138	517	6782	551
	40	19085	506	17938	717	18071	593
	50	29947	2181	23518	1801	27265	833
	60	39350	4272	22304	3894	36612	2476
	70	41016	1981	21634	1304	28108	1688
	80	33756	719	23265	1674	16496	2942
	90	16655	736	11804	840	-	-
	100	12638	340	12305	1215	-	-
Chickpea	20	2199	86	2159	146	2159	89
	30	6255	278	5727	156	5870	197
	40	14827	607	16599	1315	14802	2580
	50	18129	1379	21164	2065	22276	2260
	60	29759	1111	15268	3314	25703	619
	70	27460	2682	21385	4213	20889	2996
	80	25691	2915	17438	843	16732	803
	90	19862	2140	12813	74	-	-
	100	17338	1734	13524	79	-	-
Cowpea	20	2283	78	2307	24	2288	4
	30	5976	58	5998	67	6371	28
	40	11850	655	12882	288	13828	465
	50	25888	1710	25287	2183	22296	1138
	60	32062	1087	30736	2320	33285	387
	70	36508	3387	20147	1334	26227	1084
	80	28346	2100	18199	2844	20009	2133
	90	16207	882	12291	942	-	-
	100	17058	2379	13999	-	-	-





**Appendix 3G. The time course of calculated allocation ratios (AR) of leaf, stem and pod in beans, chickpea and cowpea under stress and non-stress conditions in 2002/2003. Thermal time to flowering was 749, 711 and 854 °Cd for BN, CHP, and COP respectively.**

## Appendix 4

**Appendix 4A. The time course of mean leaf (LSM), stem (SDM), pod (PDM) and total above ground (ADM) dry matter production of three grain legumes under three water regimes (C, MS, LS) in 2001/2002<sup>++</sup>**

DAP	LDM			SDM			PDM			ADM		
	C	MS	LS	C	MS	LS	C	MS	LS	C	MS	LS
<b>Beans</b>												
39	15.7±3.9	19.7±3.9	15.7±3.9	11.8±0.0	11.8±0.0	11.8±0.0				27.5±3.9	31.5±3.9	27.5±3.9
49	52.7±4.8	34.2±6.5	43.1±2.7	26.8±2.6	20.7±4.5	25.8±2.3				79.5±3.1	54.9±11.0	68.9±3.2
57	91.1±4.4	62.2±6.0	69.8±3.4	54.3±8.9	43.9±5.2	56.7±13.9				145.4±4.5	106.0±8.1	126.5±17.2
68	126.5±11.8	85.2±10.9	107.0±3.0	107.4±10.3	78.1±20.5	118.0±9.3	81.6±17.8	28.1±16.7	85.4±10.1	315.6±35.1	191.4±47.6	310.5±8.7
78	138.7±10.4	81.6±16.3	95.4±16.1	117.5±9.6	86.8±14.7	119.0±5.3	220.5±16.5	78.9±17.3	202.6±57.2	476.7±34.8	247.3±41.6	417.1±71.3
88	192.4±9.5	161.7±10.3		217.2±21.9	169.0±15.4		407.4±152.0	150.5±12.6		817.1±180.3	481.2±37.6	
98	75.0±9.1	195.8±9.9		99.2±21.4	170.0±28.9		213.7±43.5	151.1±46.2		387.8±67.1	464.3±84.3	
108		86.8			243.4±50.2			178.6±33.7			617.8±122.7	
<b>Chickpea</b>												
38	21.4±2.8	22.0±1.0	23.6±8.8	11±3.1	13.4±4.1	11.0±2.9				32.5±5.9	35.4±5.0	34.6±5.0
48	32.1±1.9	25.8±1.0	46.6±7.09	19±2.2	19.3±3.2	27.1±4.4				51.3±3.3	45.1±3.9	73.8±3.9
56	77.5±17.2	70.8±29.0	68.7±2.2	37±8.7	77.9±29.0	45.6±3.8	2.8±1.7	5.9±5.9	1.6±0.9	117.6±27.2	186.7±61.5	115.9±61.5
67	107.2±30.3	112.9±29.6	94.0±13.3	63±18.6	95.4±22.6	74.4±9.3	55.3±25.2	29.7±11.5	48.6±19.3	225.3±73.9	238.1±59.1	217.0±59.1
77	163.7±33.1	135.6±39.4	108.4±23.5	148±35.2	117.1±1.9	115.3±26.8	195.6±67.5	55.3±13.4	121.6±33.5	506.8±131.3	307.9±28.2	345.3±28.2
87	250.1±73.4	162.3*		257±54.4	79.9±79.9		362.2±59.1	136.9*		868.8±180.0	538.9±	
97	157.6±46.6			248±120.2			295.9±96.9			701.6±263.2		
107	118.0*			197*			534.1*			621.8*		
<b>Cowpea</b>												
35	22.8±3.2	23.6±7.3	21.4±3.7	2.8±1.6	3.9±2.05	4.5±2.2				25.6±4.8	27.5±9.4	26.0±1.7
45	39.3±10.4	35.4±6.8	31.5±3.9	19.7±7.9	11.8±0.0	15.7±3.9				59.0±18.0	47.2±6.8	47.2±6.8
55	98.4±12.9	89.5±9.6	88.9±2.3	53.1±9.8	58.8±9.03	60.8±3.1				151.5±22.7	148.3±18.5	149.7±4.7
66	133.8±29.1	96.2±0.9	118.8±11.6	104.3±31.7	90.3±7.5	121.8±15.5	9.4±3.1	13.0±3.5	10.6±4.9	241.2±63.9	190.0±11.3	249.3±25.1
76	142.8±10.9	110.6±15.9	104.1±11.4	174.3±11.3	119.6±14.0	122.8±3.4	147.9±37.4	73.2±6.4	97.8±26.0	465.1±40.7	328.0±35.8	298.8±27.6
86	175.3±19.2	149.6±34.0	73.4±8.9	251.8±35.8	131.3±51.3	141.7*	375.0±40.2	126.3±36.0	108.0±42.1	802.1±90.4	389.0±97.8	162.7±16.7
96	161.7±6.0			204.6±44.5			470.6±112.9			836.9±161.2		

<sup>++</sup> each value, with the respective standard errors, represents a mean of three replications, \* values for only one replication

**Appendix 4B. The time course of mean leaf (LSM), stem (SDM), pod (PDM) and total above ground (ADM) dry matter production of three grain legumes under three water regimes (C, MS, LS) in 2002**

DAP	LDM			SDM			PDM			ADM		
	C	MS	LS	C	MS	LS	C	MS	LS	C	MS	LS
<b>Beans</b>												
17	18.9±1.0	11.2±0.3	10.0±1.1	5.9±1.5	3.5±0.5	3.0±1.0				25.0±0.9	14.6±0.5	13.0±0.3
27	60.2±0.7	46.0±2.0	50.8±0.8	24.8±0.9	24.8±1.8	24.2±1.2				85.0±0.3	64.9±3.4	75.2±1.2
37	128.7±2.4	117.5±2.1	129.3±2.3	86.8±1.6	73.8±2.8	83.2±3.6				358.0±2.6	308.7±2.2	345.7±6.0
47	266.2±1.2	180.6±2.7	253.2±2.4	253.2±1.5	152.9±2.6	240.2±2.2	68.5±0.2	33.1±0.3	71.4±0.3	519.4±1.7	334.1±3.3	495.6±5.1
57	282.7±1.7	168.2±3.3	265.0±1.6	333.5±1.7	191.8±2.2	265.0±3.2	193.6±0.6	66.1±0.7	179.4±2.5	924.7±1.7	445.8±2.1	830.2±2.0
67	255.0±3.1	122.2±4.5	167.6±2.5	259.1±2.8	210.7±2.6	208.3±4.4	556.6±0.7	108.0±1.0	545.9±5.9	1069.3±3.6	440.1±1.4	982.5±3.4
77	158.8±2.3	77.9±6.2		251.4±1.3	233.1±1.2		563.7±1.1	112.7±4.9		1063.6±0.7	423.8±0.3	
87	93.3±2.2			283.9±1.3			681.1±2.7			1057.9±0.7		
<b>Chickpea</b>												
17	9.4±0.1	10.6±0.1	11.8±0.2	3.0±0.1	4.1±0.1	4.7±0.1				12.4±0.3	15.0±0.2	16.5±1.0
27	31.3±0.2	34.8±0.2	37.2±0.3	13.6±0.3	15.3±0.1	17.7±0.2				44.7±0.2	48.2±3.2	54.9±0.3
37	76.7±1.2	83.2±1.2	85.6±1.3	42.5±0.4	50.2±0.5	45.4±1.2				277.7±2.1	208.5±2.3	254.3±3.1
47	234.9±2.8	182.4±3.5	263.2±2.9	178.8±1.8	123.4±1.2	177.7±3.1	34.2±3.2	7.1±3.5	34.8±3.2	416.5±7.6	304.6±6.8	440.5±2.1
57	279.2±3.3	213.7±2.1	268.5±3.2	244.9±2.1	185.9±3.8	243.8±2.0	132.2±3.0	87.4±1.8	90.3±3.4	640.0±6.2	521.7±3.1	588.1±3.4
67	387.8±1.5	129.8±8.4	240.2±3.9	250.3±1.0	227.2±3.6	285.7±3.0	208.9±1.5	174.1±9.6	174.7±5.7	834.4±2.4	532.4±19.4	764.7±4.1
77	346.5±1.9			280.9±1.0			227.8±2.2			853.6±4.8		
87	216.6±2.0			335.8±1.2			451.5±2.9			1006.7±4.3		
<b>Cowpea</b>												
17	9.4±0.4	15.3±1.2	10.6±1.1	3.5±0.2	2.4±0.4	4.1±0.3				13.0±0.7	17.7±1.7	14.8±1.7
27	28.3±0.3	36.6±1.9	36.0±1.7	14.8±0.3	14.8±0.6	15.9±0.3				43.3±0.5	50.8±3.3	51.7±4.3
37	108.0±1.1	86.8±1.2	91.5±1.5	54.9±0.7	41.3±0.8	44.3±0.9				161.5±2.6	130.2±1.9	135.7±5.5
47	168.8±2.3	168.2±2.8	175.9±1.8	206.2±1.6	137.5±1.8	213.7±1.2				360.4±5.1	306.5±4.8	390.5±1.9
57	324.0±3.2	240.2±3.5	290.4±5.8	292.2±1.3	286.3±2.9	305.7±3.8	192.4±1.1	155.8±5.2	193.0±8.1	915.8±3.6	784.4±7.9	774.8±10.4
67	367.7±4.1	129.3±2.2	112.1±4.7	309.9±0.8	299.2±1.8	221.3±5.3	291.0±1.5	286.8±5.8	252.6±5.2	968.0±3.3	717.1±2.4	587.6±2.5
77	240.8±2.1	103.3±2.6		373.6±0.8	321.7±1.5		367.7±1.8	293.3±6.7		979.6±1.5	710.6±3.9	
87	212.5±2.0			327.6±1.1			449.7±4.7			988.4±2.3		

**Appendix 4C: The time course of mean leaf (LSM), stem (SDM), pod (PDM) and total above ground (ADM) dry matter production of three grain legumes under three water regimes (C, MS, LS) in 2002/2003<sup>++</sup>**

DAP	LDM			SDM			PDM			ADM		
	C	MS	LS	C	MS	LS	C	MS	LS	C	MS	LS
<b>Beans</b>												
20	10.8±0.5	6.8±2.3	11.8±1.2	4.5±0.7	7.5±1.2	5.9±0.9				15.3±0.7	19.9±1.9	17.7±0.6
30	32.1±3.2	32.9±2.8	31.3±2.2	14.8±1.0	14.4±0.9	14.0±0.5				46.8±4.1	47.2±3.6	45.2±2.6
40	96.6±6.8	87.7±3.5	92.9±4.8	52.5±5.1	47.6±3.1	54.1±5.6				149.1±12.0	135.4±5.2	147.0±8.8
50	152.3±13.8	143.4±18.0	148.3±15.5	110.2±10.0	96.6±8.2	92.5±4.6				262.4±23.7	240.0±26.0	240.8±14.8
60	232.7±18.8	154.4±16.7	196.7±5.3	203.8±24.1	170.2±18.4	207.6±17.6				485.5±43.6	365.1±38.1	505.4±28.6
70	208.9±14.3	114.9±13.5	168.4±12.0	238.5±9.8	148.9±37.4	198.1±20.3	297.5±24.6	61.8±121.4	227.8±18.9	744.9±28.9	385.2±84.7	594.3±30.7
80	197.9±39.8	137.5±25.0	76.9±15.6	250.3±38.8	155.4±22.8	168.0±62.2	449.4±98.8	113.0±223.9	341.1±63.2	1039.6±110.6	705.9±35.7	722.0±63.3
90	119.2±13.2	82.2±4.8		251.8±21.6	144.0±20.3		630.7±53.2	49.56±231.4		1432.6±115.3	715.7±13.9	
100	98.0±3.1	62.8±10.2		195.0±28.3	152.9±32.6		509.4±120.4	82.4±230.0		1352.4±152.6	655.1±80.2	
<b>Chickpea</b>												
20	12.4±1.2	11.8±1.7	11.8±1.4	4.7±0.6	5.7±1.6	5.5±0.8				17.1±1.2	17.5±2.3	17.3±1.6
30	36.6±0.9	33.4±1.6	31.3±1.0	15.9±1.2	14.2±0.0	14.4±0.5				52.5±2.0	47.6±1.6	45.6±0.8
40	94.6±1.3	100.7±3.4	84.0±10.4	55.5±2.5	54.1±1.1	49.4±5.5				150.1±1.9	154.8±4.3	133.4±15.9
50	158.0±7.7	150.3±15.0	136.7±6.5	101.7±9.1	99.0±10.7	88.1±6.5				259.7±26.6	249.3±25.7	224.9±10.4
60	227.0±3.6	146.4±26.7	207.0±16.4	190.4±9.7	150.9±15.5	160.3±15.7	82.4±9.9	54.3±10.8	50.2±12.3	499.9±12.7	351.6±36.2	417.5±23.6
70	212.5±19.8	116.9±21.0	187.7±37.4	197.3±21.7	159.6±26.2	197.5±47.4	220.0±31.1	145.0±55.0	143.0±42.1	629.8±72.6	488.1±72.0	461.6±73.4
80	178.2±16.0	112.7±6.8	131.4±16.3	268.2±27.2	135.2±8.6	220.9±50.1	283.9±65.3	77.9±21.3	168.6±25.7	841.0±51.1	485.2±26.4	591.2±30.7
90	193.8±26.5	95.6±10.3		369.3±10.8	191.4±45.9		214.1±10.0	174.1±67.2		928.2±32.9	474.8±54.6	
100	154.0±16.1	103.9±12.0		364.9±67.3	186.1±24.8		331.3±33.0	138.7±21.0		1028.2±68.9	524.7±82.3	
<b>Cowpea</b>												
20	12.6±0.5	12.0±0.7	12.8±0.7	4.5±0.4	4.3±0.2	4.5±0.4				17.1±0.6	16.3±0.9	17.3±1.1
30	33.6±2.1	34.6±1.9	35.6±1.3	14.6±0.4	16.3±2.2	15.5±0.5				48.2±2.3	51.0±4.0	51.2±1.5
40	85.2±2.1	93.8±7.5	95.2±6.1	37.4±2.0	42.7±2.3	49.2±0.8				122.6±2.6	136.5±9.8	144.4±6.9
50	147.2±14.3	153.7±16.9	147.6±13.0	80.1±3.2	87.7±4.1	86.6±5.0				227.2±17.4	241.4±19.5	234.1±14.9
60	195.0±2.9	165.1±10.0	209.1±9.8	184.7±4.6	156.6±12.6	210.5±7.7	19.7±4.6	22.6±4.9	19.5±0.7	399.4±9.7	344.3±18.4	439.1±16.3
70	184.5±15.9	106.2±7.4	160.3±4.7	232.2±22.3	149.3±18.7	203.6±11.5	222.1±33.1	88.3±7.2	148.3±18.3	638.8±43.3	343.9±24.1	571.3±33.4
80	151.5±2.3	88.9±15.7	149.5±1.4	218.6±7.1	171.2±24.2	201.7±14.9	184.9±12.4	161.3±20.3	223.5±29.2	709.2±20.8	541.8±60.9	707.1±16.8
90	128.1±8.1	57.4±28.7		231.2±39.7	85.4±43.1		304.9±99.7	76.1±38.1		1292.0±37.8	417.6±12.3	
100	135.2±13.1	85.6*		248.5±23.5	72.8±72.5		302.8±39.0	61.8±61.8		1142.7±77.6		

<sup>++</sup> each value, with the respective standard errors, represents a mean of three replications \* values for only one replication

## Appendix 5

**Appendix 5A. Seasonal ( $ET_s$ ), pre-flowering ( $ET_b$ ), post flowering ( $ET_a$ ) and ratio of pre- to post flowering ( $ET_a: ET_b$ ) water use (mm), seasonal transpiration ( $T_s$ , mm), soil evaporation ( $E_s$ , mm), water use efficiency ( $kg\ ha^{-1}\ mm^{-1}$ ) for pre-flowering ( $WUE_b$ ), post flowering ( $WUE_a$ ), above ground dry matter at harvest ( $WUE_d$ ) and grain yield ( $WUE_g$ ) and transpiration efficiency for grain yield ( $TE_g$ ,  $g\ mm^{-1}$ ) of three grain legume species for 2001/2002 seasons<sup>a</sup>**

Species ( $S_p$ )	Water Regime ( $W_R$ )	$ET_s$	$ET_b$	$ET_a$	$ET_b:ET_a$	$T_s$	$E_s$	$WUE_b$	$WUE_a$	$WUE_d$	$WUE_g$	$TE_g$
C	BN	379.3	224.0	155.2	1.45	175.2	204.3	14.2	17.6	12.2	6.3	1.32
	CHP	416.0	203.9	212.0	0.98	136.9	279.0	11.1	17.6	9.8	5.6	1.66
	COP	410.7	246.1	164.5	1.49	192.4	218.0	6.3	33.4	10.2	4.2	0.88
MS	BN	351.3	224.0	134.3	1.63	60.6	290.7	8.7	16.9	4.2	1.3	0.73
	CHP	318.0	203.9	111.0	1.99	49.2	269.0	11.2	21.9	4.3	0.9	0.61
	COP	283.0	246.1	77.7	2.87	150.6	132.3	6.7	25.3	11.4	2.5	0.49
LS	BN	328.3	217.0	95.6	2.31	94.2	234.3	14.2	18.3	7.9	1.7	0.57
	CHP	307.0	207.1	86.7	2.31	89.5	217.7	9.6	25.4	8.4	3.3	1.06
	COP	282.7	218.5	56.5	4.01	137.9	144.7	6.7	29.8	10.3	2.7	0.54
LSD ( $P < 0.05$ )	$W_R$	32.9**	n.s.	15.3**	0.31**	54.6*	n.s.	n.s.	n.s.	n.s.	2.5*	0.22**
	$S_p$	n.s.	14.1**	18.9**	0.34**	19.1**	38.8**	3.2**	4.6**	1.8**	n.s.	0.24**
	$W_R \times S_p$	46.2*	n.s.	32.7*	0.59**	33.4**	67.1*	n.s.	n.s.	3.2**	n.s.	n.s.
CV (%)		7.6	6.3	15.1	15.8	15.4	17.1	31.7	19.6	20.5	40.5	26.5

\*, \*\*: Significant at 5 and 1% probability level respectively; <sup>a</sup>: Soil water was measured to a depth of 30 cm. BN: beans; CHP: chickpea; COP: cowpea

## Appendix 6

### Appendix 6A. Experimental site (Dire Dawa) soil profile description, general

1. Implementing unit:	PhD thesis project
2. 2. Region:	Dire Dawa
3. Village:	Tony Farm
4. Profile No.	1 (200 m south of the main Office of Tony farm administration)
5. Altitude:	1176 m
6. Latitude	09° 36.8' N
7. Longitude	41° 50.4' E
8. Physiography:	Alluvial plain
9. Geology:	Alkaline olivine basalts and tuff of the Ashange group
10. Parent material:	Colluvium derived from basalt
11. Topography:	Level (flat)
12. Rainfall:	612 mm
13. Evaptranspiration:	1964 mm
14. Growing period	60-70 days
15. Slope:	a) Gradient: 8% (11°)      b) Length: 100m
16. Erosion:	None
17. Drainage:	Well drained
18. Water table:	a) dry season: 24 m      b) Wet season: 10m
19. Flooding:	Medium
20. Gravels, stones, rock outcrops:	None
21. Quality of ground water:	Good
22. Degree of degradation:	Non degraded
23. Surface cracks:	None
24. Nature of soil formation:	Alluvial deposition
25. Natural vegetation:	Cultivated land surrounded by different tree species and orange plantation
26. Important crops grown:	cabbage, carrot, egg plant, pepper, cucumber, onion, sorghum, maize, bean
27. Soil Class (FAO):	Eutric Regosol
28. Date:	Jun 19, 2002



# Appendix 6B. Profile description-physical properties

Depth (cm)	Horizon	$\rho$ (g/cm <sup>3</sup> )	Colour		Mottle	Structure		Consistence			Presence of roots	Porosity	Effere- vescence	Cracks and nodules
			Dry	Wet		Size	Type	Dry	Moist	Wet				
0-10	AP	1.24	4/3 5YR	3/4 5YR	None	Fine	Blocky Granular	Soft	Friable	Non sticky	Very high	Very fine	High	None
10-41	A	1.23	3/4 5YR	3/2 7.5YR	None	Very fine	Sub-angular blocky	Slightly hard	Very friable	Slightly sticky	High	Fine	High	None
41-71	BI	1.27	4/3 5YR	3/2 5YR	None	Medium	Angular blocky	Very hard	Very friable	Sticky	Very few	Medium	High	None
71-91	BII	1.41	3/2 5YR	3/4 7.5 YR	None	Medium	Prism like columnar	Very hard	Friable	Slightly sticky	Very fine roots	Medium	High	None
91+	BIII	1.36	3/3 5YR	3/4 5YR	None	Fine	Granular	Very hard	Very friable	Non sticky	None	Fine	High	None

Colour descriptions: 4/3 5YR = Reddish brown; 3/4 5YR, 3/3 5YR, 3/2 5YR = Dark reddish brown; 3/2 7.5YR, 3/4 7.5YR = Dark brown

**Appendix 6C. Soil water relations\***

Depth	Thickness (mm)	DUL (%) 0.33 bar	DLL (%) 15 bar	DUL (mm)	DLL (mm)	ASW (mm)
0-10	100	32.01	15.43	32	15	17
10-41	310	36.24	17.90	112	56	56
41-71	300	36.83	19.10	111	57	54
71-91	300	34.58	18.12	104	54	50
>91	100	32.37	16.19	32	16	16
Total (mm m <sup>-1</sup> )				391	198	193

\* DUL = drained upper limit of soil water, PWP =drained lower limit of soil, ASW = available soil water.

**Appendix 6D. Soil chemical (and some physical) properties\***

Lab.No.	Soil Depth (cm)	pH(H <sub>2</sub> O)	EC (mmhos/cm)	Org. C (%)	OM (%)	Total N (%)	P (ppm)	Exchangeable cations (meq/100gm soil)					Texture (%)			Texture Class
								K	Na	Ca	Mg	CEC	Sand	Clay	Silt	
15195	0-10	8.48	0.634	1.177	2.029	0.101	19.87	0.75	0.50	26.22	10.26	58.6	31	33	36	CL
15196	11-40	8.60	0.533	1.357	2.339	0.117	14.15	1.08	1.11	29.92	9.33	58.6	23	40	37	CL
15197	41-70	8.61	0.496	1.197	2.064	0.103	6.91	0.80	1.37	31.81	10.10	58.8	19	38	44	SCL
15198	71-90	8.45	0.601	1.137	1.961	0.098	5.47	0.56	1.19	33.42	8.82	58.6	16	41	43	SC
15199	>91	8.48	0.477	0.998	1.720	0.086	5.38	0.53	1.23	31.71	5.76	58.2	36	36	27	CL

\* CL= clay loam, SCL= silty clay loam, SC = silty clay

## Appendix 7

Appendix 7A. Daily weather conditions at Dire Dawa ((latitude 9°6'N, longitude 41°8' E, altitude 1197 m), Ethiopia in the 2001/2002 season.

Day	DAP	T <sub>max</sub> °C	T <sub>min</sub> °C	P <sup>+</sup> mm	Ir <sup>**</sup> Mm	Wind speed m s <sup>-1</sup>	n	RH <sub>max</sub> %	RH <sub>min</sub> %	SR <sup>*</sup> MJ m <sup>-2</sup> day <sup>-1</sup>	ET <sub>o</sub> <sup>++</sup> mm
1-Dec		30.2	15.5	0		0.88	10.7	68	23	20.7	4.3
2-Dec		31.2	15	0		0.83	10.7	56	18	20.7	4.5
3-Dec		30.6	13.2	0		0.93	10.4	41	22	20.3	4.2
4-Dec		31	13.6	0		0.93	10.2	58	27	20.1	4.2
5-Dec		30.7	15.8	0		0.93	10.3	48	21	20.2	4.2
6-Dec		31.7	16.4	0		0.83	9.6	60	30	19.3	4.4
7-Dec		30.2	16	0		0.82	7.5	84	39	16.5	3.8
8-Dec	1	28.6	18.5	6		0.6	4.7	90	50	12.8	3.5
9-Dec	2	28.8	15.2	0		0.75	9.3	96	37	18.9	4.1
10-Dec	3	29.8	15.7	0		0.79	8.5	86	30	17.8	4.1
11-Dec	4	31.4	17.8	0	16.7	0.78	10.6	70	18	20.6	4.7
12-Dec	5	31.3	17	0		0.93	10.2	56	25	20.1	4.3
13-Dec	6	30	16.1	0		0.78	7.8	89	42	16.9	3.9
14-Dec	7	30.2	17.6	0		0.92	10.3	90	32	20.2	4.1
15-Dec	8	30.1	15.2	0	16.7	0.82	10.2	81	26	20.1	4.3
16-Dec	9	30.5	15.1	0		0.79	10.1	60	32	19.9	4.4
17-Dec	10	30.7	16.8	0		0.79	10	74	32	19.8	4.4
18-Dec	11	29.7	15	0		0.78	9.4	95	38	19.0	4.1
19-Dec	12	30.1	14.4	0		0.93	10.1	76	27	19.9	4.1
20-Dec	13	28.4	13.6	0		0.87	10.2	80	24	20.1	4.1
21-Dec	14	28.2	13.7	0		0.81	10	80	30	19.8	4.1
22-Dec	15	28.5	14.2	0	16.7	0.8	10	77	30	19.8	4.2
23-Dec	16	29	14.2	0		0.83	10.1	87	22	19.9	4.2
24-Dec	17	28.7	12.1	0		0.83	10.1	71	27	19.9	4.2
25-Dec	18	28.2	13.8	0		0.83	10.1	78	28	19.9	4.1
26-Dec	19	29.4	14.2	0		0.73	10.1	73	27	19.9	4.5
27-Dec	20	29	13.6	0		0.68	9.5	61	28	19.1	4.6
28-Dec	21	28.7	13.5	0		0.75	10.1	80	29	19.9	4.3
29-Dec	22	29	14.9	0		0.73	10.1	72	31	19.9	4.4
30-Dec	23	29.8	14.1	0		0.73	10.1	76	21	19.9	4.6
31-Dec	24	29.9	14	0		0.89	10.1	65	33	19.9	4.1
1-Jan	25	31	14.8	TR	16.7	0.67	8	92	39	17.0	4.2
2-Jan	26	26.3	19.2	5		0.72	2.9	95	58	10.3	2.7
3-Jan	27	24.4	18	13.9		0.45	1.6	98	80	8.6	2.2
4-Jan	28	24.6	18.2	12.7		0.36	1.2	96	68	8.0	2.8
5-Jan	29	26.7	18.4	3.2		0.53	3.4	96	60	11.0	3.1
6-Jan	30	25.5	18.4	TR		0.64	2.8	98	67	10.2	2.5
7-Jan	31	27	16.8	TR		0.66	6.1	100	59	14.6	3.3
8-Jan	32	27.5	17.1	0		0.8	7.3	96	46	16.2	3.5
9-Jan	33	28.9	16.8	0		0.75	10	85	45	19.8	4.2
10-Jan	34	28.7	16	0		0.71	8.8	92	47	18.2	4.0
11-Jan	35	29.6	16.6	0	25.0	0.74	10.2	95	48	20.1	4.2
12-Jan	36	27.5	17.1	TR		1.21	5	92	51	13.2	2.7
13-Jan	37	24.7	17.2	TR		0.75	0.9	98	65	7.8	2.1
14-Jan	38	28	17.5	0		0.76	5.1	96	46	13.4	3.3
15-Jan	39	28.8	15.2	0		0.72	8.8	94	41	18.4	4.1
16-Jan	40	27.7	16.4	0		0.91	7.5	94	41	16.7	3.5
17-Jan	41	28.5	15.3	0	16.7	0.79	9.2	86	41	19.0	4.0
18-Jan	42	28.6	15.8	0		0.89	9.4	83	38	19.3	3.9
19-Jan	43	29.5	15.6	0		0.85	10.4	79	35	20.7	4.3
20-Jan	44	28.2	14.5	0		0.88	10.6	82	34	21.0	4.1
21-Jan	45	27.8	14.4	0		0.89	10.5	79	38	20.9	4.1
22-Jan	46	27.4	14.3	0		0.73	6	87	42	14.9	3.6
23-Jan	47	28.1	14.7	0		0.85	10.7	92	32	21.3	4.2

24-Jan	48	29.1	13.6	0		0.97	10.7	68	25	21.3	4.2
25-Jan	49	29	13	0	25.0	0.99	10.4	53	16	21.0	4.1
26-Jan	50	28.3	12	0		0.98	10.8	61	30	21.6	4.1
27-Jan	51	28.5	12.3	0		0.85	10.8	56	27	21.6	4.4
28-Jan	52	30	14.2	0		0.83	10.4	64	27	21.1	4.5
29-Jan	53	29.1	13.2	0	16.7	0.89	10.5	77	29	21.3	4.3
30-Jan	54	28.9	14.5	0		0.78	10.7	75	28	21.7	4.6
31-Jan	55	29.1	14.6	0		0.87	10.5	78	33	21.4	4.3
1-Feb	56	29.8	12	0	16.7	0.96	10.5	81	20	21.5	4.3
2-Feb	57	29.8	11.7	0		0.81	10.6	63	18	21.7	4.7
3-Feb	58	30.1	12.4	0		0.68	10.6	60	27	21.7	5.0
4-Feb	59	30.8	12.8	0		0.79	10.4	69	29	21.5	4.7
5-Feb	60	29.9	15	0	16.7	0.86	10.4	72	26	21.6	4.5
6-Feb	61	30.5	14.7	0		0.84	10.4	70	24	21.6	4.7
7-Feb	62	30	13.2	0		0.76	10.5	66	23	21.8	4.8
8-Feb	63	30.6	13.1	0	25.0	0.83	10.6	74	19	22.0	4.7
9-Feb	64	30.3	13.1	0		0.77	10.7	53	20	22.2	5.0
10-Feb	65	31	13	0		0.75	10.6	62	14	22.1	5.1
11-Feb	66	30.5	11.8	0		0.67	10.3	66	21	21.8	5.2
12-Feb	67	31	11.6	0	33.3	0.66	10.3	79	26	21.8	5.2
13-Feb	68	30.6	12.8	0		0.82	10.4	90	33	22.0	4.6
14-Feb	69	30.7	16.8	0		0.69	9.9	91	39	21.4	4.9
15-Feb	70	30	18.8	0	16.7	0.8	7	87	41	17.2	4.1
16-Feb	71	30	19.8	0		0.76	6.4	80	43	16.4	4.1
17-Feb	72	32	18	0	16.7	0.87	9.9	85	31	21.5	4.8
18-Feb	73	33.9	18	0		0.92	10	69	29	21.7	4.9
19-Feb	74	32.1	16.6	0		0.99	10.3	95	33	22.2	4.6
20-Feb	75	31.6	17.4	0	25.0	1.04	10.5	92	37	22.6	4.5
21-Feb	76	34.6	18.4	0		0.95	10.4	61	25	22.5	5.0
22-Feb	77	33.5	16.5	0		0.89	10.1	92	31	22.1	4.9
23-Feb	78	33	16.4	0	16.7	0.88	9.4	95	26	21.1	4.8
24-Feb	79	33.2	14.8	0		1.08	10.6	89	20	22.9	4.7
25-Feb	80	34.2	19.7	0		0.88	10.6	32	17	23.0	5.3
26-Feb	81	34.1	17.7	0	25.0	0.93	10.6	67	23	23.0	5.1
27-Feb	82	33.3	17.2	0		1.03	10.4	71	25	22.8	4.8
28-Feb	83	33.5	17.8	0		1.17	10.4	70	25	22.9	4.6
1-Mar	84	32.9	17.5	0		1.04	10.3	50	31	22.8	4.8
2-Mar	85	33.3	17.3	TR	25.0	1.09	8.1	96	32	19.5	4.3
3-Mar	86	22.3	18.8	58		0.9	0	97	79	7.5	1.8
4-Mar	87	25.5	17	TR		0.57	0.4	96	52	8.1	2.8
5-Mar	88	27	18.7	1.7		0.9	4.7	96	62	14.6	3.2
6-Mar	89	29.5	16.5	0		0.81	9.9	95	51	22.4	4.6
7-Mar	90	30.9	17	0		1.05	10.4	84	42	23.2	4.6
8-Mar	91	33.1	18.6	0		1.03	10.7	45	28	23.7	5.0
9-Mar	92	32.2	20	0		1.14	10.4	47	33	23.3	4.8
10-Mar	93	32.3	21.2	0		0.7	9.9	60	39	22.6	5.6
11-Mar	94	31.7	17.7	0		0.82	9.6	83	30	22.2	5.1
12-Mar	95	32.4	16	0		0.86	10.4	89	22	23.4	5.2
13-Mar	96	32	15.6	0		0.71	10.6	77	25	23.8	5.6
14-Mar	97	30.9	14.8	0		0.69	10.6	77	29	23.8	5.5
15-Mar	98	32.1	17	0		1.04	10.4	79	35	23.6	4.9
16-Mar	99	31.9	20.5	TR		2.95	3.8	56	33	13.6	2.5
17-Mar	100	33.8	24.5	TR		3.2	9.2	54	33	21.8	3.6
18-Mar	101	31.1	22	TR		0.98	1.7	88	41	10.4	3.0
19-Mar	102	29.8	21.6	3.4		1.23	5.1	96	45	15.6	3.4
20-Mar	103	30.8	18.8	14.6		0.95	5.1	93	41	15.6	3.8

\* calculated using Angstrom's equation from sunshine duration, \*\* TR = trace, \*\*\* calculated using the Penman-Montieth Equation. \*\* Irrigation amounts are for the control treatments. Water stressed treatments did not receive water for the duration shown in Table 3.1b.

**Appendix 7B. Daily weather conditions at Dire Dawa ((latitude 9°6'N, longitude 41°8' E, altitude 1197 m), Ethiopia in the 2002 season.**

Date	DAP	T <sub>max</sub> °C	T <sub>min</sub> °C	P <sup>+</sup> mm	Ir <sup>**</sup> mm	Wind speed m s <sup>-1</sup>	n hour	RH <sub>max</sub> %	RH <sub>min</sub> %	SR* MJ m <sup>-2</sup> day <sup>-1</sup>	ET <sub>o</sub> mm
20-Mar		30.8	18.8	14.6		0.95	5.1	93	41	15.6	
21-Mar		33.3	17.4	1.3		0.84	7	87	31	18.6	
22-Mar		31.4	19.2	0		0.74	9.1	87	44	21.8	
23-Mar		33.8	20.5	TR		0.74	9.5	82	35	22.5	
24-Mar		33.6	21.4	0		0.74	9	82	33	21.7	
25-Mar		35.2	19.1	0		1.01	10.4	74	25	23.9	
26-Mar		36.4	20.2	TR		2.55	7.3	46	21	19.2	
27-Mar		36.4	25.9	0		1.56	10.4	44	23	24.0	
28-Mar	1	35.4	23.6	1.9		1.03	6.1	72	30	17.4	
29-Mar	2	33.3	18.2	0	25.0	0.89	9.6	90	32	22.8	
30-Mar	3	33.1	19	0		1.04	9.9	76	34	23.3	
31-Mar	4	35.8	20	0		1.03	10.1	74	27	23.6	
1-Apr	5	35.4	21.3	TR	25.0	1	8	49	27	20.4	5.1
2-Apr	6	35.1	21.2	0		1.57	7.4	51	31	19.5	4.3
3-Apr	7	35.4	24.6	1		1.17	6	64	33	17.3	4.4
4-Apr	8	34	21.3	1.4		0.98	6.2	86	41	17.6	4.3
5-Apr	9	34.7	20.5	18.3	25.0	1.18	10.3	92	32	24.0	5.3
6-Apr	10	32.4	19.2	TR		1.03	8.2	83	39	20.8	4.6
7-Apr	11	33.4	20.1	15.5		1.03	7.5	88	33	19.7	4.6
8-Apr	12	34.4	19.7	TR		1.6	8.8	71	32	21.7	4.5
9-Apr	13	34.7	22.6	0		1.35	8	60	28	20.5	4.7
10-Apr	14	32.4	20.4	0		3.9	8.9	94	32	21.9	3.7
11-Apr	15	34.5	24.8	28.8		2.78	10.4	46	28	24.2	4.4
12-Apr	16	30.1	18.1	5		1.49	6.1	85	50	17.6	3.6
13-Apr	17	28	19	2.6		0.63	3.8	95	64	14.0	3.5
14-Apr	18	29	18.2	TR		0.82	6.2	96	51	17.7	4.0
15-Apr	19	30.2	18	0		0.59	8.5	94	44	21.3	5.0
16-Apr	20	29.8	20.7	6.8		1.14	8.4	92	47	21.1	4.5
17-Apr	21	33.4	21	0		2.06	10	64	36	23.6	4.5
18-Apr	22	33.6	23	0		2.28	11.2	61	32	25.5	4.8
19-Apr	23	35.5	23.5	0		0.69	11.2	63	32	25.5	6.5
20-Apr	24	33.5	20.7	0		0.95	11.1	86	33	25.3	5.6
21-Apr	25	31.4	21.1	0		1.16	9.4	88	41	22.7	4.9
22-Apr	26	32	18.1	0		1.1	10.6	69	25	24.6	5.2
23-Apr	27	33.2	17.4	0	33.3	0.76	11	49	23	25.2	6.0
24-Apr	28	34.9	18.5	0		0.97	9.8	45	19	23.3	5.4
25-Apr	29	34.6	17.5	0		1.08	9.3	56	22	22.5	5.1
26-Apr	30	34.3	16.5	0	16.7	1.16	9.3	44	24	22.5	4.9
27-Apr	31	33.2	21	TR		1.12	5.5	57	30	16.6	4.2
28-Apr	32	36.7	22	0		1.71	9.1	43	24	22.2	4.7
29-Apr	33	36.1	24	0	16.7	1.73	10.1	57	23	23.8	5.0
30-Apr	34	36.2	24	3.7		2.1	7.9	88	26	20.3	4.4
1-May	35	35.8	22.4	0		1.69	7.5	55	24	19.7	4.3
2-May	36	36.8	24.2	0		1.7	11.1	57	18	25.3	5.3
3-May	37	36.6	24	0		1.16	11.2	60	22	25.4	5.8
4-May	38	34.8	23.2	0	25.0	1.21	10	64	27	23.6	5.3
5-May	39	35.7	23	TR		1.23	8.8	59	28	21.7	5.0
6-May	40	35.3	22.6	0		1.01	10.8	64	25	24.8	5.8
7-May	41	35.5	22.7	0	16.7	1.51	8.7	62	24	21.5	4.7
8-May	42	34.9	24.5	0		1.03	7.4	58	19	19.5	5.0
9-May	43	36.5	21.2	0		1.12	11	55	15	25.0	5.7
10-May	44	37.7	22.6	0		1.9	11	59	11	25.0	5.1
11-May	45	38.1	24	0	16.7	2.31	11	57	13	25.0	4.9
12-May	46	37.8	24.4	0		1.65	10.8	56	16	24.7	5.3
13-May	47	37.8	24	0		2.05	11.1	58	11	25.1	5.1
14-May	48	38	24.6	0	16.7	2.53	8.2	55	21	20.7	4.2
15-May	49	37.7	25.2	3.1		3.36	10.2	55	15	23.7	4.3

16-May	50	37.9	21.2	1.3		1.73	11	57	20	24.9	5.2
17-May	51	37.3	23.8	0		2.03	9.3	52	18	22.3	4.6
18-May	52	35.3	23.6	0	25.0	2.71	5.6	55	21	16.7	3.4
19-May	53	36.6	24.2	0		2.95	11.3	56	26	25.4	4.6
20-May	54	38.1	24.3	0	16.7	2.11	9.6	53	18	22.7	4.7
21-May	55	37.2	23.7	0		2.95	9.6	57	25	22.7	4.3
22-May	56	35.7	24.4	25.8		2.39	8.6	90	30	21.2	4.4
23-May	57	35.7	18	0		1.47	11.3	71	27	25.3	5.2
24-May	58	36.6	23.4	0		1.67	10.9	59	17	24.7	5.2
25-May	59	37.1	23.8	0		2.35	11.5	54	16	25.6	4.9
26-May	60	37.5	23.6	0		2.42	9.9	58	18	23.1	4.6
27-May	61	37.1	24.2	TR	25.0	2.77	9.3	50	21	22.2	4.2
28-May	62	35.7	23.8	0.4		3.04	8.3	55	27	20.7	3.9
29-May	63	38.1	24.6	TR	25.0	2.15	9.4	45	18	22.3	4.5
30-May	64	37.7	24.2	TR		2.21	8.8	59	19	21.4	4.5
31-May	65	37.5	23.7	2.7		2.74	7.8	65	16	19.9	4.0
1-Jun	66	36.9	24	TR		2.03	10	53	23	23.2	4.7
2-Jun	67	38.2	24	TR		2.63	9.5	51	16	22.4	4.4
3-Jun	68	36.8	24.2	TR		2.26	10.9	50	24	24.5	4.8
4-Jun	69	38.2	24.8	0	25.0	2.03	9.8	41	17	22.9	4.6
5-Jun	70	36.5	24.6	0		2.91	10	46	17	23.2	4.2
6-Jun	71	34.9	23.5	TR		2.83	8.6	55	27	21.0	3.9
7-Jun	72	33.8	23.2	1.8		2.57	8.2	60	31	20.4	3.9
8-Jun	73	33.8	20.6	5	25.0	2.42	9.8	73	29	22.8	4.3
9-Jun	74	35.6	19.8	2.9		2.6	6.5	65	26	17.9	3.6
10-Jun	75	36	20	TR		3.08	8	53	24	20.1	3.7
11-Jun	76	36.9	23.6	0		3.2	10.3	57	18	23.6	4.3
12-Jun	77	36.7	21.5	0		2.95	9.6	56	19	22.5	4.1
13-Jun	78	36.7	22.8	0		3.7	9	55	16	21.6	3.8
14-Jun	79	34.2	23	TR		3.03	2.7	56	27	12.1	2.7
15-Jun	80	36.5	23.2	TR		1.84	8.3	56	24	20.5	4.4
16-Jun	81	36.6	23	TR		2.3	10.2	57	19	23.4	4.6
17-Jun	82	36.8	23.1	0		3.52	9.3	55	17	22.0	3.9
18-Jun	83	35.6	22.2	0		3.33	7.9	56	27	19.9	3.6
19-Jun	84	37.3	23	0		2.84	10.2	52	18	23.4	4.3
20-Jun	85	37.1	22.3	0		3.21	10.5	50	18	23.8	4.2
21-Jun	86	34.8	23	0		3.62	10.7	62	27	24.1	4.1
22-Jun	87	36.5	22.7	0		2.18	10.5	61	20	23.8	4.7
23-Jun	88	36.7	22.6	0		2.65	10.3	52	19	23.5	4.4
24-Jun	89	36.5	22.7	0		2.61	10.6	56	19	24.0	4.5
25-Jun	90	36.4	22.5	0		2.23	10.1	53	18	23.2	4.5
26-Jun	91	36.6	23	0		2.08	9	56	15	21.6	4.4
27-Jun	92	37.4	23.4	0		2.89	10.7	53	16	24.2	4.4
28-Jun	93	38	23	0		3.52	10	49	16	23.1	4.1
29-Jun	94	37.5	23.2	0		3.41	10.4	51	18	23.7	4.2
30-Jun	95	36.8	24.2	TR		2.39	8	50	18	20.1	4.1

\* calculated using Angstrom's equation from sunshine duration, \*TR = trace, \*\* calculated using the Penman-Montieth method. \*\* Irrigation amounts are for the control treatments. Water stressed treatments did not receive water for the duration shown in Table 3.1b.

**Appendix 7C Daily weather conditions at Dire Dawa (latitude 9°6'N, longitude 41°8' E, altitude 1197 m), Ethiopia in the 2002/2003 season.**

Day	DAP	T <sub>max</sub> oC	T <sub>min</sub> oC	P <sup>+</sup> mm	Ir <sup>**</sup> mm	Wind speed m s <sup>-1</sup>	RH <sub>max</sub> %	RH <sub>min</sub> %	SR MJ m <sup>-2</sup> day <sup>-1</sup>	ET <sub>o</sub> <sup>††</sup> mm
5-Oct		30.0	17.4	0.7		0.97			14.1	3.9
6-Oct		33.1	20.0	0		1.13			17.9	4.4
7-Oct		33.6	17.2	0		1.14			22.2	4.3
8-Oct		35	16.9	0		1.01			20.2	4.4
9-Oct		35.4	18.6	0		0.95			19.4	4.3
10-Oct		34.1	18.2	0		1.33			17.8	4.2
11-Oct		35	22.5	0		1.16			18.8	4.4
12-Oct		34.8	19	0		1.35			22.7	4.2
13-Oct		35.2	22.2	0		1.6			23.1	4.3
14-Oct		35.7	21.3	0		1.36			21.4	4.3
15-Oct		35.5	21.9	0		1.26			22.1	4.3
16-Oct		35.8	20.4	0		1.42			19.1	4.2
17-Oct		35.5	21	0		1.3			22.9	4.3
18-Oct	1	35.4	20	0		1.28			21.5	4.0
19-Oct	2	34.6	20.9	0		1.18			22.8	4.1
20-Oct	3	34.7	20.9	0		1.25			22.9	4.5
21-Oct	4	34.4	22	0		1.48			22.8	3.8
22-Oct	5	31.5	22.4	0	25.0	1.59			15.2	4.4
23-Oct	6	34.4	19.5	0		1.03			22.5	4.3
24-Oct	7	33.4	20.5	0		1.14			20.9	4.2
25-Oct	8	33.4	16.8	0	25.0	1.14			22.3	4.3
26-Oct	9	33.4	15.5	0		1.19			20.8	4.4
27-Oct	10	32.2	15.8	0		0.86			21.2	4.3
28-Oct	11	31.9	20.3	TR	25.0	1.05			13.2	4.1
29-Oct	12	33.4	21.4	0		1.06			21.0	4.2
30-Oct	13	34.3	21.5	0		1.28			22.0	4.1
31-Oct	14	33.4	21.1	0	25.0	1.21			21.5	3.4
1-Nov	15	34	17.5	0		1.21			21.6	3.9
2-Nov	16	33.7	17.8	0		1.14			21.7	3.3
3-Nov	17	33.4	17	0		1.07			22.0	3.7
4-Nov	18	32	15.7	TR		0.9			19.3	3.8
5-Nov	19	30.3	19.8	0	33.3	1.04			17.2	4.0
6-Nov	20	30.8	15.3	0		0.83			17.8	3.9
7-Nov	21	32.6	15.4	0		1.11			21.7	3.8
8-Nov	22	32.9	17.1	0		1.07			21.6	3.7
9-Nov	23	33.5	16.8	0	25.0	1.13			20.9	3.6
10-Nov	24	32.2	17.8	0		1.11			20.8	3.9
11-Nov	25	32.2	16.2	0		1.00			21.5	3.7
12-Nov	26	32.2	16.2	0		1.15			21.5	3.8
13-Nov	27	32.5	17	0	25.0	1.08			21.6	3.4
14-Nov	28	32.5	17.6	0		1.07			21.4	3.0
15-Nov	29	33	17.2	0		1.06			21.5	3.8
16-Nov	30	32.4	16	0		1.11			21.3	4.0
17-Nov	31	32.1	14.6	0		1.03			21.7	3.6
18-Nov	32	31.3	14.4	0	25.0	1.14			21.4	3.6
19-Nov	33	30.5	14	0		1.06			21.3	3.4
20-Nov	34	30.6	15.4	0		0.87			21.2	3.2
21-Nov	35	30.2	17.2	0		0.93			16.2	2.1
22-Nov	36	32.2	17	0		0.96			21.1	2.3
23-Nov	37	32	14.3	0		1.00			20.9	2.6
24-Nov	38	31.5	16	0		1.00	56	22	20.7	1.8
25-Nov	39	31.6	17.1	0		1.00	61	19	21.2	2.2
26-Nov	40	31.5	17.5	0		0.95	64	20	21.2	2.4
27-Nov	41	31.6	17.6	0		1.00	76	21	20.7	2.7
28-Nov	42	31.5	17	0	29.2	1.03	78	21	20.0	2.5
29-Nov	43	30.6	15.8	0		0.98	65	24	20.8	2.6
30-Nov	44	31.5	14.8	0		1.02	85	33	20.5	3.9



1-Dec	45	31.39	17.07	0	16.7	1.39	86	34	18.7	3.3
2-Dec	46	30.32	17.73	0		0.99	93	30	19.4	3.3
3-Dec	47	30.8	16.26	0		1.09	98	32	15.8	3.6
4-Dec	48	30.31	15.03	0		1.37	79	26	21.2	3.1
5-Dec	49	30.47	14.4	0		1.26	90	25	20.8	2.7
6-Dec	50	29.01	14.59	0		1.14	85	26	20.5	3.4
7-Dec	51	28.93	11.91	0	25.0	1.24	81	14	21.4	3.9
8-Dec	52	28.63	14.04	0		1.20	72	27	20.6	4.0
9-Dec	53	29.99	16.1	0	12.5	1.12	77	29	20.2	3.7
10-Dec	54	29.96	13.38	0		1.11	93	32	17.8	3.7
11-Dec	55	30.14	16.11	0		1.17	84	27	20.1	3.9
12-Dec	56	29.76	16.99	0		1.35	69	29	20.1	3.9
13-Dec	57	29.99	16.06	0		1.10	80	31	19.4	3.5
14-Dec	58	29.42	16.26	0		0.82	92	41	12.5	4.2
15-Dec	59	27.63	18.01	0		1.38	98	51	16.0	4.0
16-Dec	60	29.83	16.24	0		1.07	96	27	19.6	4.2
17-Dec	61	28.86	14.02	0		1.13	83	23	20.5	3.8
18-Dec	62	28.67	15.95	0	25.0	1.21	69	34	19.8	3.1
19-Dec	63	29.04	17.31	0		1.22	74	38	19.7	3.3
20-Dec	64	29.85	17.16	0		1.02	82	37	17.9	3.5
21-Dec	65	28.31	16.88	0		1.16	82	35	16.7	3.2
22-Dec	66	22.43	17.5	0		0.89	97	67	6.7	3.0
23-Dec	67	25.4	18.69	0		0.99	91	54	8.7	3.8
24-Dec	68	26.55	17.97	0	25.0	0.84	92	55	11.3	3.6
25-Dec	69	22.11	18.1	0		0.72	99	73	3.8	3.9
26-Dec	70	21.41	17.46	0		0.59	99	80	3.5	3.6
27-Dec	71	23.94	16.78	3.6		0.88	99	71	9.9	3.7
28-Dec	72	25.11	16.62	2.6		0.84	99	65	11.4	3.2
29-Dec	73	24.76	18.26	0		1.01	98	60	10.3	3.1
30-Dec	74	24.69	15.12	0		0.93	99	62	9.4	4.0
31-Dec	75	26.72	14.49	5.2		0.73	98	49	16.5	3.7
1-Jan	76	25.35	15.98	0		0.88	96	50	13.1	4.4
2-Jan	77	26.44	15.88	0		0.82	92	45	13.7	4.8
3-Jan	78	27.9	13.91	0		0.86	97	39	18.2	4.5
4-Jan	79	25.52	13.74	0	25.0	0.89	99	48	14.0	4.5
5-Jan	80	25.31	14.65	0		0.98	93	50	10.0	3.6
6-Jan	81	26.55	13.55	0		1.32	97	30	20.1	4.2
7-Jan	82	25.55	8.31	0		1.15	88	26	21.9	4.6
8-Jan	83	26.15	11.16	0		1.06	90	22	21.1	4.8
9-Jan	84	27.8	12.6	0		1.26	65	25	21.0	4.9
10-Jan	85	27.86	14.17	0	25.0	1.28	65	18	21.7	3.9
11-Jan	86	27.29	12.63	0		1.28	69	7	22.7	4.4
12-Jan	87	26.56	12	0		1.21	77	13	22.7	4.4
13-Jan	88	26.63	13.17	0		1.32	76	14	21.8	4.2
14-Jan	89	26.7	10.18	0	16.7	1.06	78	20	22.0	4.3
15-Jan	90	27.89	11.36	0		1.09	76	31	21.4	4.5
16-Jan	91	28.73	11.08	0		0.89	88	33	20.9	4.0
17-Jan	92	28.53	14.49	0		1.05	87	37	20.6	4.5
18-Jan	93	26.65	15.88	0	16.7	0.74	90	46	10.5	4.4
19-Jan	94	28.78	15.78	0		1.00	95	44	15.3	4.6
20-Jan	95	31.01	15.09	5.8		1.10	99	34	19.1	4.5
21-Jan	96	30.18	15.5	0.2		1.16	99	37	16.6	4.4
22-Jan	97	29.08	16.03	12.6		1.45	99	42	16.9	3.3
23-Jan	98	29.38	14.57	0.2		1.06	99	38	21.1	4.8
24-Jan	99	28.65	17.01	0		1.11	87	43	19.6	4.4
25-Jan	100	31.18	15.54	0		1.04	95	33	21.3	4.5
26-Jan	101	30.18	16.04	0		1.07	92	38	20.1	4.2
27-Jan	102	30.85	15.77	0		1.23	98	37	21.2	4.8
28-Jan	103	32.36	21.16	0		1.61	85	32	18.1	3.5
29-Jan	104	31.53	18.85	0		2.09	79	27	19.9	4.6
30-Jan	105	29.93	14.29	0		1.11	93	32	21.7	4.4
31-Jan	106	30.19	18.48	0		1.39	76	30	21.7	4.4

