IMPROVING IRRIGATED AGRICULTURE IN THE FERGANA VALLEY, UZBEKISTAN

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ABSTRACT

Water scarcity and severe environmental degradation are causing water managers in Central Asia to reevaluate irrigation water use. The objective of this research was to investigate cropping systems that could improve food security in rural areas of the Fergana Valley of Uzbekistan given the constraints of limited water, increasing salinization of land resources and a rigid state order system which requires farmers to produce cotton and wheat. Growing short season food legumes after winter wheat harvest using alternate furrow and regulated deficit irrigation is proposed.

Increasing water use efficiency (WUE) associated with crop production is a way for arid and semi-arid areas to increase their agricultural production where there is little or no prospect for expansion of water resources. The WUE of common bean (*phaseolus vulgaris*) and green gram (*vigna radiata*) irrigated with deficit and alternate furrow irrigation was evaluated in a field experiment in the Fergana Valley. The results indicate the WUE for both commercial yield and biomass were approximately twice as high for green gram as common bean. Conversely, the water use efficiency for root biomass in common bean (0.15 kg m^{-3}) was slightly higher than green gram (0.13 kg m^{-3}). WUE increased in green gram when deficit irrigation or alternate furrow irrigation were practiced, whereas it remained constant in common bean for all treatment combinations.

The different response of the two legumes to regulated deficit irrigation and alternate furrow irrigation is explained by examining components of the plant-soil-water system. Both strategies resulted in water savings and reduced crop evaporative consumption, with larger reductions in green gram than common bean. Severely stressed common bean extracted more water at 60 cm than non-stressed plants, whereas severely stressed green gram used less water at all depths. Transpiration rates were generally lower in green gram than common bean and decreased in both crops as soil water deficit increased. However, after irrigation, common bean's water use was higher than the non-stressed treatments while green gram's transpiration rate only increased slightly from the before-irrigation value. Collectively, these results suggest alternate furrow irrigation and deficit irrigation are appropriate methods to increase WUE, allowing application of less

irrigation water, particularly, for green gram production. Use of the FAO's water stress coefficient in predicting evapotranspiration under water limiting conditions appears to over-predict water use for green gram and could lead to over-irrigation.

A greenhouse study was conducted to assess how these crops will respond to soil salinity when produced in the gypsiferous soils of the region. The study evaluated various growth components of common bean and green gram irrigated with deficit irrigation in soils with and without gypsum and at three levels of soil salinity. Results showed that biomass and leaf area were decreased by approximately 20% for both crops, as EC_e increased from 2.8 dSm^{-1} to 7.5 dSm^{-1}. Yields were higher at all salinities for green gram than in common bean. However, relative yield reductions with increasing salinity were greater for green gram (43%) compared to common bean (19 – 31%). The presence of gypsum enabled both crops to maintain reasonable yield at EC_e values which would be lethal in soils dominated by other salts.

The CROPGRO model was modified to include a salinity response function. An iterative process was used to modify the CROPGRO code for root water uptake in an approach very similar to the empirical reduction functions found in hydrological models. This approach has been evaluated in the literature as largely superior to the approach found in the current CROPGRO model under conditions of soil salinity. A qualitative analysis of the model indicated the model performed as expected under a range of atmospheric, irrigation and crop tolerance scenarios. Model simulations compared very favourably to results obtained in the greenhouse for yield and seasonal ET with values of the Willmott agreement index (i) of 0.98 for both variables evaluated at different levels of salinity and deficit irrigation (a value of 1.0 indicates perfect agreement). Final biomass predictions were less satisfactory, though the modified model performed as well as the original model. The modified model was successfully tested with field data, on common bean from an experiment in the Fergana Valley (i of 0.75 for ET and 0.74 for final yield), though the sensitivity of the model to a soil fertility function and relative nodule number made it difficult to assess the model performance.

RÉSUMÉ

La pénurie d'eau et la dégradation sévère de l'environnement obligent les gestionnaires de l'eau en Asie centrale à réévaluer l'utilisation de l'eau d'irrigation. L'objectif de cette recherche était d'examiner des systèmes de production qui pourraient améliorer la sécurité alimentaire en milieu rural dans la vallée de Fergana en Ouzbékistan, compte tenu des contraintes que posent le manque d'eau, la salinisation grandissante des sols et la rigidité d'un régime étatique qui exige la production du coton et du blé. Cultiver des légumineuses après une récolte de blé d'hiver en utilisant l'irrigation alternante et l'irrigation déficitaire a été proposée.

Augmenter l'efficacité de l'utilisation en eau (EUE) associée avec la production est une façon de permettre aux milieux arides et semi-arides d'augmenter leur production agricole, là où il y a peu ou pas de perspectives d'expansion des ressources en eau. L'EUE du haricot commun (*phaseolus vulgaris*) et du haricot mung (*vigna radiata*) avec l'irrigation alternante et l'irrigation déficitaire a été évaluée dans une expérience en champs dans la Vallée de Fergana. Les résultats indiquent que l'EUE pour le rendement commercial ainsi que pour la biomasse ont été approximativement deux fois plus haute pour le haricot mung que pour le haricot commun. Inversement, l'efficacité de l'utilisation en eau pour la biomasse racinaire du haricot commun (0.15 kg m^{-3}) était légèrement plus haute que pour le haricot mung (0.13 kg m^{-3}). L'EUE a augmentée pour le haricot mung lorsque l'irrigation déficitaire ou l'irrigation alternante ont été pratiquées, alors qu'elle est restée constante pour le haricot commun pour toutes les combinaisons de traitements.

Les réactions différentes des deux légumineuses face à l'irrigation déficiente et l'irrigation alternante s'expliquent en examinant les composés du système plante-sol-eau. Les deux stratégies ont eu comme résultats la conservation d'eau et la réduction de la consommation d'eau des cultures, avec de plus grandes réductions pour le haricot mung que pour le haricot commun. Le haricot commun plus sévèrement stressé a extrait plus d'eau à 60 cm que les plantes non-stressées, alors que le haricot mung sévèrement stressé a utilisé moins d'eau à toutes les profondeurs. Les taux de transpiration étaient généralement plus bas pour le haricot mung que pour le haricot commun et ont diminué

dans les deux cultures en fonction de l'augmentation du déficit d'eau. Toutefois, après l'irrigation, l'utilisation d'eau par le haricot commun stressé était plus grande que les traitements non-stressé, alors que le taux de transpiration du haricot mung n'a augmenté que légèrement en comparaison avec la valeur avant-irrigation. Collectivement, ces résultats suggèrent que l'irrigation alternante et l'irrigation déficitaire sont des méthodes appropriés pour accroître l'EUE, permettant l'utilisation de moins d'eau d'irrigation, particulièrement pour la production du haricot mung. L'utilisation du coefficient de stress en eau de la Organisation des nations unies pour l'alimentation et l'agriculture (FAO) pour prédire l'évapotranspiration sous des conditions de limitation en eau semble surévaluer l'utilisation d'eau pour le haricot mung et pourrait résulter en une irrigation excessive.

Une étude en serre a été effectuée pour évaluer comment ces cultures réagissent face à l'augmentation de la salinité du sol lorsqu'elles sont produites dans les sols riches en gypse de la région. L'étude a évalué des composants variés de la croissance du haricot commun et du haricot mung irrigués avec l'irrigation déficitaire dans des sols sans gypse et à trois niveaux de salinité de sol. Les résultats indiquent que la biomasse et la surface du feuillage ont diminuées par approximativement 20% pour les deux cultures, quand EC_e (salinité) a augmenté de 2.8 dSm^{-1} à 7.5 dSm^{-1}. Les rendements étaient plus élevés pour le haricot mung à tous les niveaux de en comparaison avec le haricot commun. Toutefois, des réductions de rendements relatives avec la salinité croissante étaient plus grandes pour le haricot mung (43%) comparé au haricot commun (19 – 31%). La présence de gypse a permis aux deux cultures de maintenir des rendements raisonnables à EC_e, des valeurs qui pourraient être fatales dans des sols dominés par d'autres sels.

Le modèle CROPGRO a été modifié pour inclure une fonction de réponse à la salinité. Un processus itératif a été employé pour modifier le code CROPGRO pour l'absorption de l'eau par les racines, une approche semblable aux fonctions de réductions empiriques trouvées dans des modèles hydrologiques. Cette approche a été évaluée dans la littérature comme étant largement supérieure à l'approche trouvée dans le modèle courant du CROPGRO. Une analyse qualitative des modèles a démontré que le modèle fonctionne tel qu'attendu sous divers scénarios atmosphérique, d'irrigation et de tolérance de la culture. Des simulations de modèle ont comparé très favorablement aux résultats obtenus dans le serre pour le rendement et le ET saisonnier avec des valeurs de Willmott agreement index of (i) de 0.98 pour les deux variables évaluées à différents niveaux de salinité et d'irrigation déficitaire. Les prédictions de la biomasse finale ont été moins satisfaisantes, bien que le modèle modifié a performé aussi bien que le modèle original. Le modèle modifié a été testé avec succès avec les données obtenues avec le haricot commun lors d'une experience dans la vallée de Fergana (i de 0.75 pour ET et 0.74 pour rendement final), malgré que la sensibilité du modèle à une fonction de fertilité du sol et au nombre relatif de nodules aie rendu difficile l'évaluation de la performance du modèle.

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NOMENCLATURE

α	albedo
$\alpha(h,h_o)$	empirical reduction function
a	relative decline in water use per unit of salinity/regression coefficient
a	regression coefficient
ABA	abscisic acid
AFI	alternate furrow irrigation
ASCE-ET	American Society of Civil Engineers Task Committee on Standardized Reference ET
b	regression coefficient/ relative rate of reduction in water use due to salinity
c	regression coefficient
C	calibration dataset
c_1	constant in root water uptake calculation
$c_2(L)$	constant in root water uptake calculation
c_3	constant in root water uptake calculation
Ca^{2+}	calcium ion
$CaSO_4 \cdot H_2O$	gypsum
CFI	conventional furrow irrigation
Cl^-	chlorine ion
CO_2	carbon dioxide
d(L)	thickness of soil layer L (cm)
d_{GWT}	depth of groundwater table (m)
D_r	actual rootzone depletion (mm)
$d_{rootzone}$	depth of rootzone (m)
e_a	actual vapour pressure (kPa)
EC_e	electrical conductivity of a saturated soil paste extract (dS m^{-1})

$EC_{threshold}$	salinity value beyond which water use is reduced (dS m^{-1})
EF	modelling efficiency
e_i	vapour pressure inside leaf (kPa)
E_{op}	potential plant ET (mm d^{-1}) in CROPGRO
e_s	saturation vapour pressure (kPa)
ET	evapotranspiration
$ET_{balance}$	crop consumptive water use (mm)
ET_{FAO}	estimated evapotranspiration from FAO Penman-Monteith equation (mm)
ET_M	maximum crop evapotranspiration
ET_o	reference crop evapotranspiration
ET_{re}	tall reference crop evapotranspiration
$ET_{reduced}$	potential plant transpiration reduced due to salinity
e_z	vapour pressure of atmosphere surrounding leaf (kPa)
f(salt)	salinity reduction function
FAO	Food and Agriculture Organization of the United Nations
$FC_{\%vol}$	volumetric soil moisture at field capacity (cm^3 cm^{-3})
f_o	steady state infiltration rate (m^3/min m)
G	soil heat flux (MJ $m^{-2}d^{-1}$)
GLM	general linear model
GWC_i	ground water contribution on day i (mm)
h	matric potential (cm)
H	sensible heat (MJ $m^{-2}d^{-1}$)
H^+	hydrogen ion
h_3	matric potential at which soil water uptake is reduced (cm)
h_4	matric potential at permanent wilting point (cm)
h_o	osmotic potential (cm)
h_o*	threshold osmotic potential beyond which yield declines due to salinity (cm)

i	Willmott agreement index/ day index
IRR_i	irrigation requirement (mm)
j	treatment index
K	crop coefficient
$K(h)$	soil hydraulic conductivity (cm d^{-1})
K^+	potassium ion
K_{cb}	transpiration component of crop coefficient
K_e	evaporation component of crop coefficient
k_s	water stress coefficient
λ	latent heat of vaporization (2.45 MJ kg^{-1} at 20ºC)
L	layer index
LAI	leaf area index
LL(L)	soil water content at permanent wilting point (cm^3 cm^{-3}) in CROPGRO
$LL_{salt}(L)$	new value of LL(L) used to determine RWU(L) under saline conditions (cm^3 cm^{-3}) in CROPGRO
MAE	mean absolute error
MD_j	maximum depletion of available soil water (mm)
Mg^+	magnesium
N	sunshine hours (h)
Na^+	sodium ion
NaCl	sodium chloride
OA	osmolyte accumulation
Ψ	water potential (MPa)
P	significance level
p	depletion factor
pH	soil acidity measure
P_i	effective precipitation (mm)
p_j	nominal depletion factor of treatment j

$p_{nominal}$	nominal depletion factor
$PWP_{\%vol}$	volumetric soil moisture at permanent wilting point
PWU(L)	proportion of water uptake from each layer calculated in previous iteration
R_a	extraterrestrial radiation (MJ $m^{-2}d^{-1}$)
RAW	readily available water (mm)
R_b	thermal radiation (MJ $m^{-2}d^{-1}$)
RDF(z)	rooting density distribution at depth, z (cm cm^{-3})
RDI	regulated deficit irrigation
RE	relative error
RH_{max}	maximum daily relative humidity (%)
RH_{min}	minimum daily relative humidity (%)
RLV(L)	root length density (cm cm^{-3})
RMSE	root mean square error
R_n	net radiation (MJ $m^{-2}d^{-1}$)
RRD	partial root drying
R_s	solar radiation (MJ $m^{-2}d^{-1}$)
R_{so}	cloudless day radiation (MJ $m^{-2}d^{-1}$)
RWU(L)	root water uptake in layer L (cm)
$RWU_p(L)$	potential root water uptake in layer L (cm)
$\mathit{RWU_p(L)}$	previous estimate of RWU(L) (cm)
S_1	salinity model parameter for controlling stomatal conductance
S_2	salinity model parameter for controlling stomatal conductance
SALRDCT	relative rate of reduction in water use per unit of salinity (% dS^{-1} m^{-1})
$SAT_{\%vol}$	volumetric soil moisture at saturation
SLPF	soil fertility factor
$SM_{\%vol}$	measured volumetric soil moisture
SW(L)	soil water in layer L (cm^3 cm^{-3})

SWFAC	water stress factor reducing photosynthesis
$SWFAC_{saline}$	water stress factor reducing photosynthesis under saline conditions
$SW_{use,i}$	soil water use on day i (mm)
T_{max}	maximum daily temperature (ºC)
T_{min}	minimum daily temperature (ºC)
TRWUP	total root water uptake (cm)
$TRWUP_o$	original estimate of TRWUP
$TRWUP_p$	previous estimate of TRWUP (cm)
TURFAC	water stress factor reducing expansive growth
u	wind speed (m s^{-1})
u_2	wind speed measured 2m above ground level (m s^{-1})
V	validation dataset
VPD	vapour pressure deficit of atmosphere surrounding leaf (kPa)
WUE	water use efficiency (kg m^{-3})
$WUE_{biomass}$	above ground biomass water use efficiency (kg m^{-3})
WUE_{seed}	commercial yield water use efficiency (kg m^{-3})
WUE_{seed}	root biomass water use efficiency (kg m^{-3})
x	relative water deficit
z	depth in soil profile (cm)
z_{max}	effective depth of groundwater table (m) when GWC < 1 mm d^{-1}

CONTRIBUTIONS OF AUTHORS

All the manuscripts in this thesis (Chapters 3, 4, 5, and 6) have been authored by Heidi Webber, Dean Chandra Madramootoo, Maryse Bourgault, Mikhail Horst, Galina Stulina and Professor Don Smith. Heidi Webber is the primary author as she prepared all manuscripts in this thesis. She was involved with the design of the field experiment and designed all aspects of the salinity, soil, drainage, irrigation and soil moisture monitoring components of the greenhouse experiments. She was responsible for the planning, executing and monitoring of irrigations for the field and greenhouse experiments. She collected all of the data related to irrigation volumes and durations, soil moisture, soil salinity, advance and recession times and aided in data collection for leaf area, biomass and yield components. She designed and coded the changes to the CROPGRO model and performed the model evaluation presented in the thesis. Finally, she performed any data analysis presented in this thesis and prepared all manuscripts.

Dean Chandra Madramootoo is the second author of all manuscripts. He was the research supervisor and funded all of the research. His role included guidance in formulating the research plans, coordination of various authors, and constructive reviews of all manuscripts.

Maryse Bougault, a Ph.D. student in Plant Science is the third author on the manuscripts. She was involved with the experimental design of all experiments, collected and analyzed leaf area, biomass, yield and yield components for both the field and greenhouse experiments and provided useful insight on the statistical analysis and review of the manuscripts.

Mikhail Horst, the forth author of the manuscripts, is an irrigation researcher with the Interstate Coordination Water Commision (ICWC) in Uzbekistan. He provided invaluable guidance with all aspects of irrigation planning and execution for the field work in Uzbekistan and critical review of thesis Chapters 1 and 2.

Galina Stulina is a soil scientist with the ICWC in Uzbekistan. She provided project management of the field experiments in Uzbekistan, soil analysis, and valuable input on formulating the research questions.

The last author on all of the manuscripts is Professor Don Smith of the Plant Science department. Professor Smith's role was as a research co-supervisor, and he was involved in the experimental design of the experiments as well as providing important critical review of the manuscripts.

CHAPTER 1: GENERAL INTRODUCTION

1.1 BACKGROUND

Like many arid and semi-arid regions, drought and water scarcity impact and influence many aspects of life in Central Asia. This is particularly true for Uzbekistan, the country located in the middle of the region. Irrigation is required for almost all cropping systems and agricultural production forms the backbone of the country's economy. As part of the Soviet Union, intensive land and infrastructure development during the 1960's resulted in the rapid doubling of its irrigated area and Uzbekistan gained the status as the world's second largest cotton exporter. The consequence of this development has been extensive land degradation, such as waterlogging and soil salinity, due to over irrigation and the drying of the Aral Sea in what is considered one of the most serious anthropogenic environmental disasters in history.

The Fergana Valley is one of the main agricultural regions in the country. The region receives only 200 mm of precipitation annually, though its fertile soils and continental climate lead to its development as an ancient irrigated oasis. The Fergana Valley is located at the base of the Tian Shan mountains, which are the source of irrigation water via the Syr Darya river. Cotton and winter wheat, the main crops grown, are both irrigated using furrow irrigation. Secondary soil salinization in the Fergana Valley is widespread and increasing as the water table rises to within 1 to 5 m of the soil surface due to heavy leaching and old, poorly functioning drainage systems (EC-IFAS, 1999). The population in the Valley is largely rural and employed in agriculture. Unemployment rates are high and food insecurity has increased markedly in recent years. The rapidly growing population is expected to increase demands on water resources.

The improvement of on-farm irrigation systems and the introduction of low cost, water saving irrigation technologies are identified as key and realistic components of reducing agriculture's water demand (Horst et al., 2005). Deficit irrigation and alternate furrow irrigation are two irrigation strategies that are relatively easy to adopt and enable water savings. To increase food production, short season grain legumes, such as green gram (*Vigna radiata* (L.)) and common bean (*Phaseolus vulgaris*), can be grown after winter wheat harvest. However, adopting new technologies and changing established cropping patterns represents a risk not many farmers in the region can afford. As farmers are required to produce cotton and wheat, any food crops they grow must use scarce additional water and increase cropping intensity. Finally, crop sensitivity to soil salinity may make some cropping systems unfeasible. Appropriate crop models offer farmers and decision makers a low risk method of evaluating different management scenarios.

1.2 HYPOTHESIS

The first stage of the research involves identifying and testing appropriate water-conservation irrigation strategies in the Fergana Valley. Growing the legumes green gram and common bean as second crops after the wheat harvest offers farmers the possibility to improve both their food security and land productivity, while still fulfilling their commitment to produce cotton and wheat. Optimal irrigation with alternate furrow and deficit irrigation can be implemented to grow these legumes with minimal irrigation water.

The next phase of this research investigates the crop response of green gram and common bean to salinity in gypsiferous soils and the possible interactions of water-conservation irrigation strategies and soil salinity. Cotton and wheat are salt tolerant (Maas, 1985) and by the time these crops show symptoms of salt stress, the land will already be rendered too saline for cultivation of many other crops. Compiled information of crop tolerance to salinity (Tanji and Kielen, 2002; Maas, 1985) is not easily transferable to the gypsiferous soils of the region (Szabolcs, 1989).

The next stage of the research is to modify the CROPGRO model to be applicable in the Fergana Valley. Specifically, a crop growth response factor to salinity is developed and tested. The current theory on how non-halophytes respond to salinity is considered in two distinct phases (Munns et al., 2000). The first response is that of water stress, as leaf expansion rates are reduced long before ions accumulate to toxic levels in cells. The second stage of the crop response to salinity is leaf death due to the accumulation of Na^+ and Cl^- to toxic levels in cytoplasm.. In gypsiferous soils, calcium moderates the effects of sodium salinity, limiting growth reductions. As such, the salinity response factor developed for CROPGRO acts in a manner analogous to water stress.

1.3 OBJECTIVES

The goal of this research is to identify alternate cropping systems and irrigation strategies for producing food crops optimizing limited water supplies in the Fergana Valley of Uzbekistan. Deficit irrigation and alternate furrow irrigation will be evaluated in terms of their water use efficiency, soil water dynamics and crop water requirements for common bean and green gram grown as second crops. The legumes' response to soil salinity and the interaction between these technologies and salinity will be quantified in gypsiferous soils. A salinity response factor will be incorporated into the CROPGRO model and the appropriateness of this model to predict growth and water use of common bean in the Fergana Valley will be evaluated. Specifically, the research objectives are:

1. Quantify the water use efficiency, water use and growth response of common bean and green gram to deficit and alternate furrow irrigation and propose optimal irrigation schedules and strategies for these crops
2. Compare the patterns of water use of the two crops when irrigated with deficit and alternate furrow irrigation.
3. Evaluate the estimates of ET predicted by the FAO 56 (Allen et al., 1998) methodology and the appropriateness of the suggested depletion levels for irrigation.
4. Determine the salinity tolerance thresholds, relative growth reductions and relative rates of reduction in water use of common bean and green gram to soil salinity dominated by gypsum salts.
5. Investigate interactions between the use of deficit irrigation techniques and the level of soil salinity for sandy loam soils dominated by gypsum salts.
6. Develop a salinity response factor for incorporation into the CROPGRO model.

1.4 SCOPE

The work contained in this thesis is focused on irrigation water management in the Fergana Valley, Uzbekistan. The technologies and cropping systems investigated were identified together with research and technical specialists in Uzbekistan. The technologies and cropping systems were field tested over two seasons on a private farm in the Fergana Valley and received feedback from members of the local community, including farm workers, irrigators, technicians and local heads of government. Further greenhouse and modeling studies were conducted to complement and extend the results obtained from field trials in Uzbekistan. For various logistical reasons, this work was conducted in Canada at the Macdonald Campus.

CHAPTER 2: LITERATURE REVIEW

2.1. INTRODUCTION

This review begins by providing background information on irrigation and water resources in Uzbekistan. The scope encompasses the other Central Asian countries to provide the geographical, historical and political context. Subsequently, a review of recent scholarship on crop water requirements, crop response to water and salinity stress, water saving irrigation technologies, crop models, and soil salinity modeling is presented.

2.2 BACKGROUND AND CONTEXT: IRRIGATED AGRICULTURE IN CENTRAL ASIA

In Central Asia, the majority of renewable surface water sources are of a transboundary nature. Generally, the countries in which the water originates do not coincide with the countries that are the heaviest users. The resulting situation, difficult for any group of nations to resolve, is further complicated by the established patterns and priorities of water use and distribution dating to the Soviet Era.

2.2.1 Available water resources

Much of the land area of the five Central Asian Republics forms the drainage basin for the Aral Sea (Fig. 2.1) and likewise the main rivers draining into the Aral Sea cross national borders. The total average surface runoff of the basin is 116.9 km^3yr^{-1}, of which the largest proportions originate in Tajikistan (43.4%) and Kyrgyzstan (24.4%), with the remainder coming from Afghanistan and Iran (18.5%), Uzbekistan (9.6%), Kazakhstan (2.1%) and Turkmenistan (1.3%) (Micklin, 2000). Surface water flows to the Aral Sea by way of one of two main rivers and is associated with natural variability. The Amu Darya (79.4 km^3 yr^{-1}) derives its runoff primarily from the Pamir Mountains in Tajikistan and then flows along the Afghanistan – Uzbekistan border, into Turkmenistan and finally back into Uzbekistan where it enters into the western portion of the Large

Aral Sea (southern end of the former Aral Sea) (Micklin, 2007). The Syrdarya (37.2 km^3 yr^{-1}) originates in Kyrgyzstan with runoff from Tian Shan mountains and then flows into Uzbekistan, Tajikistan and Kazakhstan where it empties into the Small Aral Sea, or the northern section of the former Aral Sea (Severskiy, 2004; Micklin, 2000; Micklin, 2007). Total groundwater resources in the basin are estimated to be 43.5 km^3 yr^{-1} (Severskiy, 2004), while the proportion which is usable and transnational is estimated at 5 km^3 yr^{-1}, bringing the total available water resources in the basin to 121.9 km^3 yr^{-1} (Micklin, 2000). Collectively, the Amudarya and Syrdarya basins contain over 4000 lakes with a total storage capacity of 50 km^3 (Severskiy, 2004). The volume of constructed water-storage reservoirs is 74 km^3, with Tokhtogul (19.5 km^3) in Kyrgyzstan and Nurek (10.5 km^3) in Tajikistan, the largest. These reservoirs, like most other large structures, are for both power generation and irrigation (Severskiy, 2004). Additionally, return waters such as drainage water from irrigated fields and industrial wastes which are discharged into surface water bodies are reused, constituting somewhere between 24 km^3 yr^{-1} (Micklin, 2000) and 32.4 km^3 yr^{-1} (Severskiy, 2004) of available water. The higher estimate includes water discharged into large desert depressions. These waters are high in pollutants and salts, which together result in progressively degraded water and land quality downstream.

Figure 2.1. The Aral Sea Basin.

Water use in the basin is essentially at (or beyond) maximum capacity. Uzbekistan is the largest user with withdrawals of 53 km^3 yr^{-1}; Turkmenistan (23.1 km^3 yr^{-1}), Tajikistan (12.0 km^3 yr^{-1}), Kazakhstan (11.0 km^3 yr^{-1}) and Kyrgyzstan (5.1 km^3 yr^{-1}) all use considerably less (Severskiy, 2004). Irrigated agriculture consumes more water than any other sector; the percentage of total withdrawals used for irrigation ranges between 86% in Tajikistan and 97% in Turkmenistan. Annual groundwater withdrawals, estimated at 11 km^3, are used mainly for drinking water in Kazakhstan, Turkmenistan and Uzbekistan and for irrigation in Kyrgyzstan and Tajikistan (Severskiy, 2004). Despite having fully utilized available water resources, each of the five republics plans to expand their irrigated area (Micklin, 2007). The problems associated with the transboundary nature of the two largest rivers in the basin are compounded by a high degree of variability in annual runoff and the important fact that when the rivers were first developed for large scale extraction, the Central Asian Republics were a part of the former Soviet Union, whereas they are presently independent republics (Severskiy, 2004).

Intensive agriculture has created severe water quality problems in downstream reaches of the Syrdarya and Amudarya, as well as in the Aral Sea. This is a result of the reduced water flow in the rivers and into the Aral Sea, which concentrates the salt and pesticide loads introduced with drainage water. Water salinity in the Large Aral Sea exceeds 100 g L^{-1}, which is more than three times higher than that of sea water and is lethal to all fish, and most other life forms. The situation is much better, and improving, in the Small Aral Sea; salinity levels in 2006 had dropped to 12 g L^{-1} and the lake again supports many fish species (Micklin, 2007).

2.2.1 Agriculture and irrigation

Agriculture forms the backbone of the Uzbek economy. The country is the world's second largest cotton exporter, after the US. Cotton exports account for close to 30% of the country's GDP and 60% of its foreign currency income (Kandiyoti, 2003). Agriculture employs 45% of the population while the national unemployment rate is estimated at close to 25% (CIA World Fact book, 2007). Finally, much as in Soviet times, farmers have little choice to produce cotton or wheat if they want access to any inputs such as chemicals, seed, fuel, machinery or fertilizers. However, unlike during the Soviet era, the government invests little back into the system, leaving farmers with a burden they can ill afford or manage.

Water availability limits agricultural production, as total cultivatable land resources total 25.4 Mha, but current production of approximately 4.5 Mha requires 115% of average annual renewable water resources (Food and Agriculture Organization of the United Nations, 2007). Drainage water is typically reused downstream, allowing for greater water use than is available. Additionally, industrial and municipal demand currently account for less than 10% of water withdrawals, but are expected to grow with population growth.

Serious land degradation such as salinization and waterlogging and large scale environmental disasters like the drying of the Aral Sea, which are the direct results of irrigation development, limit productivity and societal well-being. Massive irrigation development was undertaken by the former Soviet Union in the 1950's – 70's to make Uzbekistan an important world cotton producing centre. Irrigated area doubled to over four million hectares by the mid-eighties. Formerly, small field sizes of less than a hectare and crop rotations including alfalfa and fallow, were successful at controlling salinity and waterlogging. These were increasingly replaced by large fields as massive collectivization occurred in the 1930's (Micklin, 2000). Coupled with the expansion in irrigated area was the near complete regulation of both the Amu Darya and Syr Darya rivers. By the early 1980's years are recorded with no flow reaching the Aral Sea (Micklin, 2000). The drying of the Aral Sea has had severe environmental, economic and health impacts on the communities near the sea. The problems of land salinization and rising watertables reduce land productivity and, in the long term, render it unsuitable for cultivation. Inefficient irrigations due to lack of land leveling and flow monitoring, heavy leaching water application and old, non-functioning drainage systems accelerate the process of land degradation. Addressing the needed upgrade of all these factors would require substantial investment. A change of cropping systems to one utilizing less water-intensive crops is unlikely in the short term due to the country's economic dependence on cotton and wheat production. The improvement of on-farm irrigation systems and the introduction of low cost water-saving irrigation technologies have been identified as key and realistic components of reducing agricultural water demand (Dukhovny et al., 2002; Horst et al., 2005).

2.2.2 Food production issues

Since the collapse of the Soviet Union at the end of 1991, food security has worsened in Uzbekistan. In the period between 1991 and 1993, an estimated 8 % of people were undernourished compared to 26 % in 2001 to 2003. The dramatic increase in food deprivation is explained by a negative annual growth rate in food production (-0.2 %) and a growing population (+ 1.8 % per annum) (FAO, 2006). The proportion of the population living beneath the poverty line reaches 31% in rural areas and 23 % in urban centres. The current highly regulated and controlled agricultural situation leaves little opportunity for farmers to diversify their cropping pattern. However, growing vegetable crops for personal consumption is a possibility if it can be done with relatively few inputs and using minimal water. Legume crops offer this possibility.

2.3 CROP WATER USE

Crop water use is governed by two factors, evapotranspiration (ET) and the plant's ability to transport water from soil to atmosphere. ET is evaporation of water at the plant and soil surfaces and constitutes the climatic demand for water, setting the upper limit for crop water use. While climatic factors drive water use, soil water deficit, soil water salinity and plant nutrition may prohibit the plant from meeting the climatic demand for water, resulting in crop stress. This review covers the basic physics of ET and highlights the state of current research and engineering treatment of the process. A subsequent section presents the case when environmental stresses prevent plants from meeting the climatic demand for water. To begin, the role of water in plants and concepts related to water flow (water potential) in the soil – plant – atmosphere continuum are presented.

2.3.1 Role of water in plants

Water is essential to plant life, vital for maintaining the structure and function of membranes and enzymes, acting as a solvent for chemical reactions, providing turgor for plant growth, and regulating plant temperatures through transpiration (Volkmar and Woodbury, 1994). However, 99% of the water that passes through the plant is lost to the atmosphere as water evaporates at the stomata, in the process termed transpiration. Closure of the stomata to regulate water loss also restricts CO_2 entry into cells for photosynthesis.

The water flowing through plants originates in the soil, travels through the roots into the xylem and finally into the stomata where it is evaporated into the atmosphere. The water potential gradient between soil and atmosphere drives the process from regions of high to low potential. When the soil is wet, between saturation and field capacity, the water potential is close to zero, that of free water. Therefore, for water to enter plants, the water potential in roots and leaves must be lower than that of the soil. Three types of forces combine to create the resultant water potential: matric, osmotic and pressure. In leaf cells, pressure and osmotic forces combine to produce the resulting, slightly negative water potential; pressure potentials are positive and result in turgor, giving plant cells a rigid structure to enable cell growth. Osmotic potentials are negative due to the high concentration of solutes in the cells. Water travels through the xylem vessels as a liquid through the plant. It is not until it reaches the leaves that it exits into the intracellular spaces where it diffuses to the atmosphere through the stomata.

The rate of water loss through the stomata is governed by both the evaporative demand of the air, potential ET (discussed in the following section) and stomatal regulation in the plant. The mechanism by which stomata open and close consists of the conversion of organic acids into malic acid and hydrogen ions in the guard cells of the stomata. To maintain near neutral pH, the H^+ ions are pumped out of the cell and potassium ions enter the cell to replace them. The cell quickly achieves a high concentration of solutes that act to lower its osmotic potential and water enters the cell. The result is the cells expand and bend, actually opening the entrance way from the intracellular spaces and mesophyll to the ambient environment. The factors which act to control stomatal opening in non-water limiting conditions are sunlight (stomata open in the morning) and intracellular CO_2 concentrations (when the concentration is too high the stomata close and when it is too low they open). Neither of these has any bearing on plant water status; rather they are mechanisms to ensure maximum carbon assimilation and photosynthesis. This is the paradox of stomatal openings; in opening to allow CO_2 to diffuse in, plants lose large amounts of water through transpiration (Salisbury and Ross, 1992; Srivastava and Kumar, 1995).

2.3.2 Atmospheric demand: potential evapotranspiration

Evapotranspiration consists of two physical processes: the evaporation of water from the soil surface and transpiration from plant leaves. The proportion of evaporation to transpiration varies with plant growth stage and soil water status; evaporation dominates before the plant canopy is fully expanded or in the day following a heavy irrigation or rainfall (Allen et al., 1998).

Evapotranspiration is the vaporization of liquid water to water vapour; energy is required to drive the process. This energy is the latent heat of vaporization (λ = 2.45 MJ kg^{-1} at 20°C) and is provided primarily by the net radiation (R_n) incident on the Earth's surface (minus the portion of R_n that is used to warm the air (H) and soil (G)). A very small portion of the energy would be from sensible heat transfer from the air to the water in the leaves. The source of R_n is solar radiation (R_s), which constitutes direct and diffuse shortwave radiation. R_s can either be measured directly or estimated from values of extraterrestrial radiation (R_a) or cloudless day radiation (R_{so}) and a measure of how cloudy the day is. Both R_a and R_{so} values depend on latitude and date and are compiled in Jensen et al. (1990). The entire incident R_s does not get transmitted to the Earth's surface to vaporize water, or warm the air and soil. Some of R_s is reflected back into the atmosphere; the quantity reflected depends on the albedo (α) of the incident surface (for a perfect reflector α = 1). Another portion of R_s is absorbed by gases in the atmosphere, which in turn re-emit the radiation at longer wavelengths, thermal radiation (R_b). Absorption and emission of radiation is governed by the Stefan Boltzman equation and is highly dependent on the temperature of the body emitting or receiving radiation, and on properties of the material. In summary, the energy to vaporize water for ET is the net radiation incident at the leaf surface. This quantity is highly dependent on the amount of incoming solar radiation, leaf temperature and ambient air temperature (Jensen et al., 1990).

While solar radiation provides the energy to drive ET, for water (liquid or vapour) flow to occur, a potential difference must exist between the vapour in the leaf and the surrounding atmosphere. The vapour pressure inside the leaf (e_i) must be greater than that of the atmosphere outside the leaf (e_z). In practice, e_i is very difficult to measure, so the concept of reference crop evapotranspiration (presented in the next section) has been developed that eliminates the need to measure e_i. With this formulation, it is the vapour pressure deficit (VPD) of the atmosphere which is the difference between the saturation vapour pressure (e_s) and the actual vapour pressure (e_a) that influences the rate of ET (VPD = $e_s - e_a$). Both e_a and e_s increase with increasing temperature, but for conditions typical of the Fergana Valley e_s increases more rapidly with the result that VPD increases with temperature.

Wind speed (u) is another important factor in determining the rate of ET due to the role it plays in removing the water vapour from the air directly surrounding the leaf. Thus wind acts to dissipate water vapour which reduces e_a, therefore increasing the VPD and rate of ET. However, another effect of wind is to lower leaf temperatures and VPD is a function of temperature.

The importance of temperature in determining ET comes from both the role it has in determining thermal heat emission and influencing VPD. Therefore it should not be expected that combined increases in temperatures and VPD would be additive; temperature is an important determinant of VPD.

2.3.3. Reference crop ET and crop ET

A number of other factors influence the rate of ET, but these are factors related to the time of year, elevation and latitude and are constant for a given location and date. Also crop properties such as the crop age, height, leaf area, reflectance properties and leaf structure influence ET. To enable ET to be compared across locations and dates, the concept of reference crop evapotranspiration (ET_o) is used. ET_o is the evapotranspiration rate from a reference surface that is not short of water (Allen et al., 1998). As all of the properties of the hypothetical crop are specified, ET_o estimates can be compared across locations and are considered only a climatic factor. The reference crop must be uniform, dense, amply watered, actively growing and surrounded in all directions by the same crop (Allen et al., 2005; Allen et al., 1998). The FAO defines a recommended reference crop as "*a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s* m^{-1} *and an albedo of 0.23*" (Allen et al., 1998). The Environmental and Water Resources Institute of the American Society of Civil Engineers (ASCE – ET) Task Committee on Standardized Reference Evapotranspiration propose the use of two reference crops in an effort to meet the needs of both farmers and landscapers. Their Standardized Reference Evapotranspiration Equation, Tall (ET_{re}) is the reference ET for a tall crop with an approximate height of 0.50 m like full-cover alfalfa (Allen et al., 2005). Both the FAO and ASCE – ET_0 approaches are based on the same Penman – Monteith combination equation (presented in the Estimating ET section) and differ only in the constants used to define the reference crops. The use of the ET_o concept implies that all weather data used in estimating ET_o should be collected over a crop that meets the criteria of the specified reference crop. In practice this is not always possible and Allen (2006) offers strategies to assess, and in some cases, adjust weather data collected under other conditions.

Maximal crop ET (ET_m) for crops other than the reference crops differs from ET_o, and occurs when soil water, salinity, soil conditions or nutrients do not limit growth. The discrepancy is because of differences in leaf structure, stomatal functioning, leaf area, crop height and albedo (Allen et al., 1998; Jensen et al., 1990). To relate ET_m to ET_o crop coefficients, or ratios of $K = ET_m / ET_o$, have been determined over a wide range of lysimeter experiments and tabulated (Pruitt, 1991; Wright, 1991; Bhardwaj, 1991). The K values can be transferred between locations, adjusted for frequency of irrigations, since the climatic factors controlling ET_m are contained in ET_o. The K values can be separated into components dealing separately with evaporation (K_e) and transpiration (K_{cb}), which is often appropriate for research (Allen et al., 2005). Use of the combined K provides adequate estimates of ET_m for engineers and farmers.

2.3.4 Methods of estimating ET

Accurate predictions of ET are used to access climate change impacts on agricultural productivity, irrigation scheduling and water deficits, and examples of the use of ET predictions in the literature are extensive (Richter and Semenov, 2005; Yang et al., 2006; Eitzinger et al., 2003). Direct measurements of ET are not possible, with the exception of plants grown in lysimeters. However, many approaches exist for estimating ET from measured data, with varying levels of difficulty and reliability (Jensen et al., 1990). The accuracy of these estimates or measurements is generally compared to values obtained in lysimeters, which are used as standards. For the ET estimates in lysimeters to be representative of crops grown in fields, the lysimeters must be sufficiently large and deep, filled with the same soil as is found outside it, be surrounded by at least 100 m of similar vegetation (i.e. height and roughness) on all sides (Jensen et al., 1990). However, even ET values obtained from lysimeters are prone to measurement error and the specifications of the lysimeter can have large effects on the ET estimates (Pruitt, 1991). Both the FAO and the ASCE – ET recommend the use of the Penman – Monteith combination equation, in their respective forms, together with appropriate crop coefficients as the sole (Allen et al., 1998) or standardized (Allen et al., 2005) method for estimating ET.

The combination method for estimating ET refers to the joint use of the energy balance and mass transfer/eddy correlation methods. The approach is to combine the energy approach, which estimates the energy needed for evaporation, together with the mass transfer equation which describes the mechanism for removing vapour. Penman (1948) was the first to use such an approach, and both the FAO and ASCE – ET recommended approaches for determining ET_o are modifications of his original combination equation. The main difference in the two approaches is that the FAO method allows for the direct measurement of R_s or its calculation based on latitude, elevation, date of year and the number of sunshine hours (or alternatively a measure of the cloudiness). The ASCE – ET method requires the measurement of R_s with a pyranometer (Allen et al., 2005). Penman's approach eliminated the need to specify the eddy diffusion coefficients and the surface temperature by introducing the concept on a reference surface, and included the first aerodynamic resistance term, albeit in the form of an empirical wind function. Later work by Covey (1959) and Monteith (1965) led to the introduction of surface resistance terms in the combination equation which described the resistance to vapour diffusion at the leaf level due to stomata (Monteith, 1981).

In a massive comparison of thirteen methods of computing daily ET_o, the Penman – Monteith equation consistently ranked first in both humid and arid climates. Data were used from 11 sites including: Victoria, Australia; Denmark; Zaire; and Ohio, Idaho, Nebraska, New Jersey, Colorado and three sites in California in the U.S. Datasets were from 45 site – year combinations. Full details of this evaluation are presented in Jensen et al. (1990). It was on the basis on this evaluation that the FAO and ASCE – ET have advocated the use of the Penman – Monteith equation as the recommended method of computing reference crop evapotranspiration.

2.4 SOIL SALINITY

Soil salinity limits irrigated agriculture worldwide and roughly one third of all irrigated land suffers from some degree of salinity (Kijne et al., 1998). In general terms, a saline soil is a soil in which soluble salts have accumulated to levels that limit agricultural productivity, cause environmental damage or decrease its economic value. A sodic soil is one in which the dominant salt is sodium and is associated with degraded soil physical properties. Worldwide it is estimated that between 831 Mha (Martinez-Beltran and Manzur, 2005) and 955 Mha (Szabolcs, 1989) are affected by soil salinity or sodicity.

The Asian part of the former Soviet Union (Szabolcs, 1989) contains 15% of the world's total salt affected soils. Most of the soils in Central Asia are classified as saline, with only desert soils suffering from a combination of salinity and sodicity. Estimates from 1985 are that 60% of irrigated soils in Uzbekistan are moderately to strongly salt-affected with a resulting 30% decrease in production (Glazovskiy, 1991, as cited in Ghassemi et al., 1995). The region's soils are characterized by the occurrence of gypsiferous soils. The classification convention of soils in the region is based on a description of the dominant salt and a measure termed total toxic salts. It gives a more realistic indicator of salinity that would be detrimental to plant productivity than the standard measure of electrical conductivity of the saturated soil water extract (EC_e) (EC-

IFAS, 1999). However, the method requires fairly sophisticated laboratory analysis, is time intensive and is not easily comparable with international standards and conventions. Efforts to convert to the use of EC_e, advocated by the FAO (Rhoades et al., 1999), are discussed in Shirokova et al. (2000). They found good agreement between using a conversion factor of 3.6 to convert $EC_{1:1}$ mixture, readily measured in the field with a portable meter, to the standard EC_e, which is the international standard requiring laboratory determination.

2.4.1. Effect of deficit irrigation on soil salinity

The effect of deficit irrigation on soil salinity is an important issue that has been addressed in a number of modeling studies. In an instance with subsurface drainage at a depth of 2 m, Prathapar and Qureshi (1999) used SWAM93 to determine that a moderate level of deficit irrigation (irrigating to 80% of ET) could maintain crop yields and not increase soil salinity in semi-arid areas. However, when irrigation was reduced to 65% of ET, soil salinity increased due to capillary rise and the fact that monsoon rains were consumed by the crop rather than used for leaching.

Where no subsurface drainage exists in arid areas with shallow water tables, deficit irrigation maintains the water table deeper than for larger irrigations. However, Prathapar and Qureshi (1999), using SWAM93, found that by irrigating to only 65% of crop ET, significant capillary rise occurred and salinity increased relative to larger irrigations. Irrigating to 80% of the crop water requirement maintained salinity at the same level as full irrigations by keeping the profile wet enough so that rains were used for leaching, but did keep the water table at levels intermediate to the full irrigation and the drier deficit irrigation strategy. The simulations were run for only one year. Longer simulation times may have shown that the deficit irrigated land remained productive longer by avoiding waterlogging. Further, other methods of deficit irrigation (Doorenbos and Pruitt, 1977) return the soil profile to field capacity after a large soil water depletion has been achieved. These systems afford greater leaching using less water, though the crop will have suffered a reduction in transpiration if capillary rise has not been too great.

2.5 CROP RESPONSE TO WATER DEFICIT AND SALT STRESS

2.5.1. Water stress

Water limiting conditions, if serious enough, can affect almost all aspects of plant physiology (Hsiao, 1973). The following discussion focuses on mild water stress, as encountered in agricultural settings, where available soil water is inadequate to meet the climatic demand and where water stress is gradually imposed as in the case of soil drying. One of the most widely debated issues is whether root signals or leaf water status regulate growth (Hsiao et al., 1998; Davies and Zhang, 1991). Munns et al. (2000) suggests that much of the current misunderstanding and confusion is centered on difference in time scales and environments in which experiments are conducted.

Plants grow only at night when turgor pressure in cells is a maximum. The internal water pressure of cells causes stretching and is required for growth (Volkmar and Woodbury, 1994). When the vapour pressure deficit between leaves and air is great, as is the case in full sunlight, stomata open, transpiration increases, and leaves begin to loose turgor. The loss in turgor is thought to induce abscisic acid (ABA) synthesis in chloroplasts, which is subsequently transported to guard cells. The ABA acts to inhibit the influx of K^+ ions into the guard cells, which in turn reduces the entrance of water, causing stomata to close partially (Srivastava and Arvind, 1995). Therefore, the presence of ABA in leaves is associated with closing of stomata, not necessarily in response to a soil water deficit, but rather as part of an internal check on stomatal functioning. In this case, water stress is a transient condition that occurs in well watered plants during times of high solar radiation and vapour pressure deficit (VPD).

As soil water is depleted by plant consumptive use and the soil dries, the water potential difference between the soil and the plant is reduced. At this point, the first change observed is a reduction in cell growth, and slow cell wall and protein synthesis (Hsiao, 1973). The classical view held that decreases in leaf water potential and turgor caused reduced leaf elongation rates. Indeed, Hsiao et al. (1998) have shown that, under conditions of low water status (during transpiration), increased turgor via pressurization can increase growth rates in maize leaves. However, when plant water status was high (non-transpiring state) pressurization and increase in turgor had no effect on leaf elongation rates. This suggests a cause other than lowered leaf water status in causing reduced growth rates.

In some cases, stomatal conductance was decreased by mild soil water deficit before any reduction had occurred in leaf water potential (Jones, 1985). This realization led to experiments in which apple tree roots were split between two pots, with one half maintained at a high water content and the other half subjected to drying (Davies and Zhang, 1991). Leaf area expansion, leaf initiation and stomatal conductance were reduced though leaf water potential was not affected. The role of a root sourced chemical signal mediating stomatal conductance was confirmed when the dry roots were re-watered or excised and growth rates were restored. ABA had been shown to control stomatal opening (Jones, 1985; Cowan et al., 1982; Zhang and Davies, 1989) and the split root experiments of Davies and Zhang (1991) provided evidence that ABA originating in the roots, under conditions of soil drying, was mediating stomatal closure.

Subsequently, much work investigated this hypothesis and, while the general concept has been supported by a substantial amount of data, the regulation of stomata is now seen as a very complex process. When leaf water status is not excessively low, ABA is required to close stomata. Stomata on excised ABA-mutant leaves immersed in osmotic solutions of up to -1.5 MPa did not close. However, in regular leaves containing ABA, stomata were more sensitive to ABA when leaf water potential was lower (Tardieu and Davies, 1992). This mechanism is thought to mitigate stomatal opening throughout the day (open in morning when leaf water potential is high and closed at midday when leaf water potential is low due to transpiration), as ABA present in the xylem flow from roots would be fairly constant over a day. Reviews by Sharp (2002) and Wilkinson and Davies (2002) highlight the many interactions between different sources of ABA, mobilization of ABA from different regions, ethylene, pH and CO_2 in what is understood to be a highly complex regulatory process. Lowered leaf water potentials are now seen as a consequence of lower rates of stomatal conductance (Davies and Zhang, 1991).

Reduced leaf water potential can be mediated in plants in a process termed osmolyte accumulation (OA), which has been proposed as an adaptive response to soil water drying. The process involves cells accumulating solutes to a concentration that causes water flow into cells; turgor and cell function can then be maintained. However, in a review of work on OA, Serraj and Sinclair (2002) find little evidence that OA can help to sustain yield levels needed for production agriculture; rather it may be more appropriate as a survival technique in wild conditions. They question the value of lowering the leaf water potential to draw in more water, while maintaining stomata open to assimilate more CO_2, when water is in limited supply. In a systems analysis using 20 years of weather simulations, Sinclair and Muchow (2001) found that in no case did delaying stomatal closure result in increased yields. Very little water available to plants is held in the soil at the low potentials achieved in OA. On the other hand, sustained root growth due to OA is a good strategy to avoid drought by mining larger soil volumes (Serraj and Sinclair, 2002). Increased rooting depth has been shown to consistently increase yield under conditions of drying soil (Sinclair and Muchnow, 2001) and high osmotically adjusting lines in wheat have been found to be associated with increased root depths (Morgan, 1995).

2.5.2 Salinity stress

Plant response to salinity is now understood to encompass two phenomena: immediate water deficit effects on the plant and specific ion toxicity effects that are noticeable weeks to months later, after thresholds of specific ions are surpassed in leaf tissue (Munns et al., 2000). Water deficit effects are caused by the osmotic potential as perceived by the roots and result in reduced cell elongation rates, with greater reductions occurring in the shoot than root cells (Munns and Termaat, 1986). The reductions in growth rates and transpiration rates are proportional to the concentration of external salts, while fluxes of Na^+ and Cl^- in the xylem transpiration stream do not increase at the same rate. Therefore, increased Na^+ and Cl^- concentrations in leaf cells are likely to be a result of inability to compartmentalize the ions in leaf vacuoles and the reduction in leaf expansion (Munns and Termaat, 1986). Additionally, an equivalent reduction in growth is observed in rice when osmotica other than salts are used (Yeo et al., 1991). Munns and colleagues (Munns and Termaat, 1986; Munns, 1988; Munns, 1993) had suggested that water relations and turgor were not important in regulating leaf cell elongation rates, but rather chemical signaling from the roots was responsible for reduced growth. However, Hsiao et al. (1998) showed that turgor did in fact regulate leaf growth in osmotically stressed plants whose leaves had low water potential, as is the case when plants are transpiring. Conversely, when water status was high (i.e. plants were not transpiring at night) increased turgor pressure did not increase the leaf elongation rate in salt stressed plants. To resolve the apparent contradiction, Munns et al. (2000) monitored elongation rates of salt stressed leaves for a period of days and found that in daylight pressure applied to salt stressed plants restored turgor and prevented reductions in expansion. At night, when the plants were not transpiring, they found that turgor maintenance did not prevent a decrease in growth rates and in some cases resulted in lower growth rates than the salt stressed plants without turgor maintenance, in agreement with the result of Hsiao et al (1998). The regulation of plant response to water or salinity stress is complex and probably is controlled by the interaction of cell water status, solute accumulation, cell metabolism and growth regulators (Hsiao et al., 1998; Wilkinson and Davies, 2002). Hormones from the roots are felt to play an important role in mediation of the response of cells to both water and salt stress (Wilkinson and Davies, 2002; Sharp, 2002)

Physiological investigations of the crop response to salinity have typically been conducted using solution cultures and adding NaCl to create saline conditions (Savvas et al., 2006; Khadri et al., 2006; Bayuelo-Jimenez et al., 2003; Brugnoli and Lauteri, 1991). However, this is not realistic of field conditions, particularly in the Fergana Valley where (1) calcium salts dominate and (2) the soils are saline and the irrigation water is of good quality. The presence of Ca^{2+} both protects the physical integrity of the soil, by preventing dispersion, and protects the membranes in roots, of which calcium is a key component (Hall, 2001). Calcium is required for root membrane integrity and proper function of ion transport systems in the plant (Lauchli and Epstein, 1970). Salinity inhibits Ca^{2+} uptake, such that many studies investigating NaCl salinity observe calcium deficiency symptoms when the Na^{+}/Ca^{2+} ratio is high (Greenway and Munns, 1980; Lynch and Lauchli, 1985; Maas and Grieve, 1987). Lynch and Lauchli (1985) found that salinity reduced Ca^{2+} concentrations in roots and shoots of barley. They hypothesize that external NaCl decreases the Ca^{2+} radial movement from the soil solution into the root xylem, based on both field and controlled chamber experiments. In their field experiments, soil Ca^{2+} content was 22.2 meq L^{-1}, (saturation). Mass and Grieve (1987) found that the ratio of Na^{+}/Ca^{2+} produced changes in biomass accumulation in maize seedlings, when the relative amounts of Na^{+} and Ca^{2+} were varied while maintaining a constant osmotic potential of -0.4 MPa. They suggest many studies confuse effects of increasing Na^{+} with high Na^{+}/Ca^{2+} ratios. Greenway and Munns (1980) grew beans in solution cultures containing 50 mM NaCl and between 0 and 10 mM Ca^{2+} and reported no growth reduction or increased Na^{+} concentration in the leaves of plants grown on 3 to 10 mM Ca^{2+} compared to control plants grown without NaCl. Above a Na^{+}/Ca^{2+} ratio of 17 (3 mM Ca^{2+}), growth was greatly reduced and Na^{+} leaf concentrations elevated. However, common bean is very sensitive to total salt amounts even when the Na^{+}/Ca^{2+} ratio is low (Eaton, 1942).

2.5.3. Nutrient stress

Soil fertility and organic matter content can affect crop water consumption in a variety of direct and indirect ways, and the interaction of these effects may be very complicated. Furthermore, a deficiency of a particular nutrient is frequently associated with water or salinity stress in depleted soils. Nonetheless, the following discussion will outline the direct (stomatal regulation, osmotic adjustment) and indirect (amount of biomass produced or root development) effects of individual plant nutrients or soil organic matter on crop water use. Increased biomass production and root development affect the amount of water used by or available to the plant and are influenced by the presence or absence of particular nutrients.

Potassium maintains photosynthesis at low water potentials. Water stress causes greater reductions in photosynthesis rates under conditions of potassium deficiency than when adequate potassium is available, though supra-optimal potassium levels do not totally mitigate reductions in photosynthesis (Ashraf et al., 2001; Sen Gupta et al., 1989). The effect is thought to be due to potassium's role in osmotic adjustment, as high solute concentrations in leaves result in higher relative leaf water contents (RWC). A high RWC maintains cell turgor which is needed for various cell functions. The effects of higher leaf potassium levels on maintaining photosynthesis was found to be independent of stomatal control, as stomatal resistance did not change with increasing potassium levels in wheat and barley (Ashraf et al., 2001; Sen Gupta et al., 1989). This result is somewhat surprising as stomatal regulation is mediated by pumping potassium into (opening) and out of (closing) the guard cells of the stomata. However, with an adequate supply of nutrients, potassium accounts for about 1% of a plant's dry weight and in such large quantities the osmotic effects would be apparent before deficiencies would be severe enough to effect stomatal control. On the other hand, other studies (Losch et al, 1992) found increased stomatal resistance (decreased transpiration) with increasing levels of potassium fertilization for sunflower and barley. As explained above, they do not attribute this to changes in the physiological control of the stomata, but rather to morphological changes, such as lower density of stomata and changes in pore size. They postulate that the higher level of potassium nutrition creates a lower osmotic potential (more negative due to higher solute concentration) and results in increased turgor and as a result increased growth and leaf area index (LAI). The change in stomatal density is thought to be related to the increased LAI and growth rate at higher rates of potassium fertilization.

The role of nitrogen on stomatal control is more ambiguous and Ripullone et al. (2004) suggest the mechanism of stomatal response to nitrogen availability is not understood, which is reflected by the contradictory results of different studies in different species. Increases in water use efficiency with increased nitrogen are generally attributed to increases in photosynthesis, as nitrogen is essential for the enzymes (Raven et al., 2004). However, Welander and Ottosson (2000) and Livingston et al. (1999) both found stomatal conductance increased with enhanced nitrogen leaf levels, though not as much as photosynthesis (carbon assimilation) rates. Given the increase in photosynthesis, which has been directly linked to elevated nitrogen levels, the increase in stomatal conductance could be simply a response allowing plants to maintain the CO_2 concentration inside the leaf. Bowmann and Contant (1994) found evidence in alpine willow that higher soil nitrogen levels resulted in higher stomatal conductance, irrespective of leaf nitrogen levels, leading them to postulate the nitrogen may be involved in a root-to-shoot signaling process. Finally, many studies (e.g. Grassi et al.,

2002) found no effect of nitrogen level on stomatal conductance. Clearly, nitrogen will have an important influence on the crop water use as it promotes canopy development, but its direct impact on leaf transpiration remains unclear.

While insufficient phosphorus levels are associated with lowered water use efficiency in plants (Payne et al., 1995; Bruck et al., 2000), the cause is attributed to the reduced photosynthetic rates in leaves grown with insufficient phosphorous. Phosphorus is an essential component of membrane lipids, nucleic acids and energy transfer molecules. These studies show that plants deficient in phosphorus used less water, but again this is associated with lower biomasses and leaf area indices, not reductions in stomatal conduction.

The role of calcium in stomatal control has been investigated (Atkinson, 1991; Atkinson et al., 1990) as before stomatal closure due to ABA signaling, calcium levels increase in the cytosol of guard cells. While calcium deficiency in soils is fairly uncommon (Salisbury and Ross, 1992), experiments have not found a relationship between high soil calcium levels and stomatal regulation (Atkinson, 1991).

Finally, magnesium, sulfur and chlorine function in osmotic adjustment under conditions of severe water stress and/or saline soils. The soil organic matter influences the bio-availability of nutrients thereby affecting transpiration.

Transpiration can be affected by nutrient deficiency that affects either lateral or primary root development. Both Pandey et al. (2000) and Eghball and Maranville (1993) report reduced water extraction deeper in the soil profile, under water limiting conditions, with deficient nitrogen as compared to adequate fertilizer levels. However, this effect may be a result of a reduced transpiration rate in nitrogen stressed plants due to reduced biomass production, as discussed in the next section. In fact, in the review of Lopez-Bucio et al. (2003) on the role of nutrients in regulating root structure, increased soil nitrate was found to decrease primary root elongation, while lateral root density stayed relatively constant at different nitrate availabilities. However, under conditions of very low nitrate availability, if one section of the roots is exposed to high nitrate levels, that section responds by increasing growth, whereas growth is inhibited in sections grown in regions of low nitrate availability. Lopez-Bucio et al. (2003) postulate this phenomenon suggests the global effect of nitrogen sufficiency. Plants grown in soils with low phosphorus tend to grow long and dense root hairs which increase their ability to absorb limited phosphorus sources (Lopez-Bucio et al. 2003); this is not generally thought to be a response to water availability. High soil phosphorous levels increase primary root elongation, increasing the soil water reservoir accessible to the root system (Lopez-Bucio et al. 2003). Finally, other elements (sulfur and iron) also affect root growth and development.

Lower LAI reduces transpiration water loss. The relationship between inadequate nitrogen and reduced LAI or biomass production is well documented (e.g. Pandey et al., 2000). Thus, in conditions of water shortage, lower levels of nitrogen fertilization (40 kg ha^{-1} as opposed to 120 kg ha^{-1} or 160 kg ha^{-1}) produced better yields as the reduced transpiration rate associated with a lower LAI enabled the crop to use the small amount of water available more slowly, avoiding or delaying severe dehydration (Pandey et al., 2000).

2.6 WATER SAVING IRRIGATION: CONCEPTS AND TECHNOLOGIES

2.6.1 Water use efficiency

Water use efficiency (WUE), often referred to as water productivity (Pereira et al., 2002), is the amount of plant material produced per unit of water used. Increasing WUE is a way for arid and semi-arid areas to increase their agricultural production when there is little or no prospect for expansion of water resources. WUE can be decomposed into many individual components such as conveyance, farm distribution and storage, irrigation application, transpiration, photosynthesis, biomass conversion and yield formation water use efficiencies (Hsiao et al., 2007). An improvement to any one of the efficiencies results in an equivalent fractional increase in the overall WUE. Analytically, Hsiao et al. (2007) have shown that for the same fractional increase in WUE, relatively greater improvements are needed in the high efficiency elements, as compared to smaller improvements in elements with low efficiencies. A systems approach with careful identification of the social, economic and technical constraints and costs for improvements illuminates the best way to increase WUE for a given situation.

In this review, WUE will be defined as the biomass produced per unit of water evapotranspired. As such, Wallace (2000) indicates that there are two approaches to increasing crop WUE. The first is by adopting technologies that increase the proportion of water that is evapotranspired by the crop, as opposed to that lost to drainage, runoff or seepage, corresponding to conveyance, farm distribution and storage, irrigation application and transpiration efficiencies above.

The second approach is to increase the crop's capacity to produce biomass (assimilate CO_2) and yield per unit of water transpired. In this second approach, which is the focus of much of the literature on crop response to irrigation (Impa et al., 2005; Yu et al., 2004; Tsukaguchi et al., 2005), WUE as the biomass produced per unit of water transpired. This corresponds to the photosynthesis and biomass conversion water use efficiencies above. Efforts to improve this quantity focus on manipulations of the plant environment to elicit a crop response to regulate stomatal openings to minimize transpiration in relation to carbon assimilation. Theoretically, for a given cultivar, these quantities are believed to be fairly conservative under conditions of constant atmospheric vapour pressure deficit and CO_2 concentration (Steduto et al., 2007; Fereres and Soriano, 2007). These authors suggest that little opportunity exists to improve these quantities outside of major genetic breakthroughs, and efforts would be better directed at improving the engineering and management issues of irrigation to improve WUE. Passioura (2004) adds that, from a farmer's perspective, increasing the harvest index (ratio of seed yield to total biomass) is a practical third approach to increasing WUE.

2.6.2 Regulated deficit irrigation

Regulated deficit irrigation (RDI) is a relatively inexpensive and easy to implement water saving irrigation technology. The strategy involves manipulating the soil water to induce the crop's inherent response to drought conditions (Davies et al., 2002). In water scarce environments, the goal is generally to increase the WUE. RDI is used in other environments, but with different objectives. For instance, in vineyards the objective is typically to retard vegetative growth and influence fruit quality (Loveys et al., 2004). In RDI, the irrigation water requirement is not completely fulfilled, allowing the soil water to be depleted beyond a threshold, such that the crop experiences water stress. The crop response, which may or may not include a reduction in the rate of water use and/or yield reductions, depends on the degree of soil drying, the crop characteristics and the timing of the water deficit. It is generally thought that withholding water during the vegetative period, as opposed to the flowering or fruit forming stages, has less impact on final yields (Loveys et al., 2004). The water savings associated with RDI are attributed to reductions in stomatal conductance, which occurs as a result of the plant roots encountering drying soil, and precedes any change in leaf water potential. Stomatal regulation is thought to be mediated by chemical signals originating in the roots and traveling to the guard cells via the xylem. Further, these signals are now thought to involve both abscisic acid (ABA) and the alkalization of the xylem flow, associated with soil drying (Loveys et al., 2004; Wilkinson, 2004). While the stomata control both the rates of transpiration and CO_2 entry into the cell, some evidence suggests that initially the reduction in stomatal conductance is greater than the concurrent reduction in carbon assimilation. This results in increased instantaneous WUE values (Chaves and Oliveira, 2004). While some studies show that RDI improves WUE on a seasonal basis (Oweis et al., 2000; Zhang et al., 2000), other investigators have not found consistent evidence that WUE increases with deficit irrigation (Garside et al., 1992; Kang et al., 2000c; Lawn, 1982). Hsiao et al. (2007) state that the increase in WUE with RDI is due to increases in application efficiency.

The timing of water stress in RDI and selection of appropriate crop varieties with phenologies to match the times of water stress is proposed by many authors as a way to optimize production under conditions limited water (Hsiao et al., 2007; Doorenbos and Pruitt, 1977; Allen et al., 1998). One approach is to allow larger soil water depletions at the times when the crop is least likely to experience yield reductions and adequate water at more sensitive times, typically the vegetative and flowering/pod-filling stages, respectively. Another approach suggested is to select crops with phenologies to match the timing of water stress, by choosing crops with early flowering or quick pod-filling. Further to this, mild water stress in early stages can accelerate flowering and pod-filling stages and result in shorter growing seasons with reduced ET water demand. To take advantage of these techniques requires a good knowledge of the particular variety's phenology and response to water limited conditions.

2.6.3 Alternate furrow irrigation

Alternate furrow irrigation is the field application of partial root drying (PRD). PRD is a variation of RDI that generally improves the WUE of crops, for example pot grown tomatoes (Davies et al., 2000) and pot grown common bean (Wakrim et al., 2005). In many cases, the strategy circumvents the yield losses frequently associated with RDI, as in grape (Loveys et al., 2000), soybean (Graterol et al., 1993) and pot and field grown maize (Kang et al., 1998; Kang et al., 2000a; Kang et al., 2000b). PRD involves exposing part of the root system to drying soil while maintaining other sections in well watered soil, and is most effective when the two sections of roots are alternately exposed to wet and dry soil (Kang et al., 1998). The method is thought to work via a reduction in stomatal conductance mediated by a chemical signal generated in the roots when they are exposed to drying soil, as in RDI. This physiological response of the plant, due to exposure of some of its roots to drying soil while the plant is kept well hydrated by other roots in moist soil, is hypothesized to cause the benefits associated with PRD.

For furrow irrigation systems, PRD is practiced as alternate furrow irrigation. The water savings associated with the technique are reduction in water use when drying soil is detected, reduced evaporation due to fewer irrigated furrows and reductions in the applied water as the volume under the dry furrow does not receive water. Wakrim et al. (2005) found the WUE of common bean increased, though with significant yield decreases for both RDI and PRD, in a pot experiment, and that there were no differences in yield or WUE between the two strategies.

2.7 CROPS

Grain legume crops provide valuable protein for human consumption while improving land productivity by their ability to fix nitrogen in association with soil bacteria. They flower and produce seeds in a relatively short time and could be grown after winter wheat harvest in Uzbekistan. This offers farmers the opportunity to grow food or raise income while still conforming to the state order system. Further, being short season crops, they require relatively little water, though many are considered sensitive to drought (Allen and Allen, 1981).

2.7.1 Common bean

Common bean (*Phaseolus vulgaris*) is one of the most important legume crops worldwide, has over 500 varieties and is a key component of human diets in many parts of the world (Allen and Allen, 1981). Extensive accounts of the crop are found in the literature and a review of the crop is not provided in this thesis. References to common bean's salinity and water stress sensitivity are provided in those respective sections.

2.7.2 Green gram

Green gram (*Vigna radiata* (L.) Wilczek) is an important food legume in India, Burma, the Philippines, Pakistan, Iran and neighbouring countries and is receiving increasing attention in Australia. Also referred to as mung bean, it is consumed in a variety of forms including seeds, paste, flour, noodles or sprouted as in North America and China. The high protein content (25 %) of the seed, as well as its easy digestibility, make it an important food crop in regions where animal consumption is limited by cultural or economic factors (Poehlman, 1991).

Green gram is a warm season, short day plant that is sensitive to cold temperatures and excessive rainfall or soil moisture levels (Poehlman, 1991). Development rates to flowering and maturity are both hastened by increasing temperature (Lawn, 1979) with the rate to flowering increasing as temperatures increase to between 23 and 28°C, depending on the cultivar (Aggarwal and Poehlman, 1977). Conversely, the development rates to both flowering and maturity were negatively correlated to photoperiod by roughly the same factor as the positive correlation to temperature (Lawn, 1979). Both the photoperiod and temperature effects are widely documented in the literature and green gram's sensitivity to both factors largely restricts its production to latitudes below 40° (Poehlman, 1991). However, it is their combined effect which occurs in the field as determined by sowing date and latitude (increasing photoperiod and temperature as spring progresses, particularly at temperate latitudes). The interaction is not well understood and is dependent on cultivar (Aggarwal and Poehlman, 1977). Muchow et al. (1993) found the time from seeding to pod-set was always 42 days for the cultivar King, grown at 14° S, when the sowing date changed by as much as 6 weeks. Minimum temperatures were between 19.7 and 22.3°C and maximum temperatures ranged from 32.1 to 33.5°C. However, at 27° S latitude, the time to the onset of pod-filling increased to 50 days. This region had lower minimum (18.8°C) and maximum (28.6°C) temperatures.

In a study varying sowing dates and latitudes, Muchow et al. (1993) found that, while the yields and final above-ground biomass of the cultivar King varied with environmental conditions, the relationship between the two was constant. For the cultivar King, at the onset of flowering between 0.47 and 0.53 of the non–pod biomass is allocated to leaf tissue, whereas 0.75 to 0.81 of the non–pod nitrogen is located in the leaves (as opposed to the stem) (Muchow et al., 1993). Seed nitrogen content is 4.57 % (Muchow et al., 1993).

During the progression from pod–filling to maturity, leaf biomass and nitrogen levels decreased as they were mobilized for use in pod and seed development. The decrease in both is associated more with reduced LAI than with a decrease in specific leaf nitrogen content. Little mobilization of nitrogen, and no carbon mobilization, is observed from stems (Muchow et al., 1993).

2.8 CROP MODELS

The past 30 years have seen an explosion in the development and number of crop models, as well as papers on crop modeling in the scientific literature. The earliest models were focused on explaining processes such as respiration and photosynthesis (de Wit, 1970). Subsequently, two main approaches to crop models evolved (Brisson et al., 2006); the Dutch group models (van Ittersum et al., 2003) were largely heuristic and focused on crop ecophysiology, whereas the American family of models (CERES, Ritchie and Otter, 1985; Ritchie et al., 1998; CROPGRO, Boote et al., 1998a) had a strong emphasis on agronomy and production agriculture. Finally, CropSyst (Stöckle et al., 2003) arose from EPIC (Williams et al., 1984) which simulates environmental conditions, including erosion and soil productivity in agroecological ecosystems. The most often cited goals of the models are: to make agronomic research more accessible to producers and decisions makers (Jones et al., 2003; van Ittersum et al., 2003), to facilitate a systems approach in agricultural research (Jones et al., 2003; Stöckle et al., 2003; van Ittersum et al., 2003), to promote cooperation and data sharing between different researchers (Jones et al., 2003) and to illuminate areas where current understanding of crop physiology is inadequate to describe crop processes (Brisson et al., 2003; van Ittersum et al., 2003; Sinclair and Seligman, 1996).

2.8.1 Types, uses and limitations

Crop models exist along a spectrum, being static statistical models at one extreme, and dynamic, mechanistic models at the other. The former predict an output of interest, such as yield, in response to an input environmental variable such as water, radiation or nutrient availability. When based on sufficient data, these models provide useful guides to the consequence of a particular management decision, while providing no insight into the mechanisms or processes involved (Sinclair and Seligman, 2000). A common example of a static model is the crop yield response to water of Doorenbos and Kassam (1979). The review presented here considers dynamic or process-oriented models; combinations of mechanistic and semi - empirical models defined by mathematics based on physical, biological and chemical laws applicable under a wide range of environments and conditions (Poluektov and Topaj, 2001). These models are very complex and require model developers to be specialists in each field encompassed by the model (Poluektov and Topaj, 2001).

2.8.2 Model evaluation and measures of agreement

The most basic way to assess the performance of a model is by comparing measured observations to the values simulated by the model. A number of criteria or measures exist to quantify how well the observations agree with model predictions. Four commonly implemented measures of agreement are: the root mean squared error (RMSE),

$$\text{RMSE} = \left((1/N) \sum_{i=1}^{N}(Y_i - \hat{Y})^2\right)^{1/2}$$

where Y_i is the observed value for situation i, and $\hat{Y}$ is the value predicted by the model, and N is the total number of situations; mean absolute error (MAE),

$$\text{MAE} = \left(\frac{1}{N}\right)^{N} \sum_{i=1} \left|Y_i - \hat{Y}\right|;$$

modeling efficiency (EF),

$$\text{EF} = 1 - \frac{\sum_{i=1}^{N}\left(Y_i - \hat{Y}\right)^2}{\sum_{i=1}^{N}\left(Y_i - Y'\right)^2}$$

where Y' is the average of all Y_i; and the Willmott (1981) agreement index (index),

$$\text{index} = 1 - \frac{\sum_{i=1}^{N}\left(Y_i - \hat{Y}\right)^2}{\sum_{i=1}^{N}\left(\left|Y_i - Y'\right| + \left|\hat{Y}_i - Y'\right|\right)^2}$$

RMSE is a classical measure, in the same units as the variable of interest, that provides a good estimate of the distance between observed and simulated values, as it does not compensate for over and under estimation as is the case with simply summing differences. The sum of differences indicates the bias of the model without giving any indication of the error present. MAE, like RMSE, is a good measure of error that does not compensate for under and over prediction. Further, it avoids giving too much significance to one large error, like RMSE does, as the differences are not squared. The advantage of the use of RMSE over MAE is that the former can be decomposed into different components that help locate the model errors (Wallach, 2006). For example, the square of RMSE can be decomposed into a bias, a term related to the differences in standard deviations of the measured and simulated values and a term related to the correlation between the two (Kobayashi and Salam, 2000). Likewise, Willmott (1981) proposes that the square of RMSE be separated into a systematic component and an unsystematic component. EF and index are both normalized measures that enable the comparison of different model outputs or datasets (Wallach, 2006). Both measures take a value of 1 when there is perfect agreement between models and reality, while a value of 0 indicates the model performs only as well as predicting the average of measured values (Willmott, 1981; Wallach, 2006).

Clearly, each measure provides different information about the performance of a given model and, when used in combination, can provide sound criteria for evaluating and improving model performance. Finally, the use of graphical representations of simulated versus measured values, and plots of the residuals as a function of explanatory variables, are useful diagnostic tools for modelers and is to be encouraged in scientific publications to aid in the readability of modeling papers (Willmott, 1981; Wallach, 2006).

2.8.3 Available crop models

This section presents an overview of some of the most commonly used dynamic, generic models that predict crop growth in response to a range of agronomic inputs. Specifically, CropSyst (Stöckle et al., 2003), STICS (Brisson et al., 2003) CROPGRO (Boote et al., 1998a; Jones et al., 2003) and APSIM (Keating et al., 2003) are reviewed. Other models that are in wide use like AZODYN (Jeuffroy and Recous, 1999); CERES (Ritchie and Otter, 1985); SUCROS (van Ittersum et al., 2003); and GOSSYM (McKinion et al., 1988), model only winter wheat; cereals; sugar, potato and sunflower; and cotton, respectively, and are not included in this review. The review is organized by presenting each model individually; a brief introduction will highlight what makes the model unique or especially noteworthy, followed by a discussion of their main modules and relevant testing results related to water deficit.

2.8.3.1 CropSyst

CropSyst (Stöckle et al., 2003) was originally developed to add a process–oriented crop growth component to EPIC, which predicts the impact of soil erosion on land productivity (Williams et al., 1984). As such, CropSyst has a strong focus on environmental aspects such as prediction of erosion and soil structure, nitrogen and water dynamics, and simulates a number of management practices while being much more process oriented than EPIC. CropSyst is one of only two crop models (the other being APSIM) to consider groundwater contribution by simulating capillary rise of groundwater into the root zone by solving Richard's equation in two dimensions. With this approach, a salt balance is coupled to the water balance, to assess the effect of salinity on crop growth. Further, the model is responsive to atmospheric CO_2 levels, making investigations of all aspects of climate change on crop growth feasible. Finally, the authors claim that it has a strong emphasis on good software design and engineering, written in C++ to ensure true modularity and runtime efficiency. If its sensitivity to the environment is its strong point, the simplicity of some of the growth processes modeled is its weakness, detracting from its potential to enrich the current understanding of crop physiology (Brisson et al., 2006).

Crop development is based on thermal time accumulation and does not consider the effects of photoperiod. This limits its usefulness in comparing the effects of different locations and sowing dates. Development is accelerated by water stress (Stöckle et al., 2003).

To compute leaf area, CropSyst uses the concept of specific leaf area (SLA), defined as leaf area per leaf mass. In this model SLA is assumed constant across all crop ages and stresses, which is a simplification. Through the use of SLA, leaf area is treated as a function of biomass production. Water stress then acts to change the predicted daily leaf area production and leaf duration before senescence. Leaf area is not responsive to planting density or nitrogen stress. Senescence depends on leaf age (Stöckle et al., 2003).

Daily potential biomass accumulation is determined as the minimum of two predictions (Stöckle et al., 2003); the first is based on radiation use efficiency (RUE) and the quantity of photosynthically active radiation (PAR) intercepted (Monteith, 1977), while the second is based on the concept of WUE, similar to the approach of Tanner and Sinclair (1983). The use of RUE results in a coupling of photosynthesis and respiration, and assumes a constant value of RUE; in reality RUE values exhibit great variability (Stöckle et al., 2003). The RUE method allows the effect of CO_2 levels to limit biomass production. The WUE approach also takes into account the direct effect of radiation through its role in transpiration, which controls stomatal opening. The WUE approach is appropriate for water limiting conditions, but less so for humid environments where transpiration would probably not be affected because of low vapour pressure deficits (Stöckle et al., 2003). The WUE approach is also problematic since it is hard to validate, given the high degree of measurement error associated with field level transpiration, as opposed to evapotranspiration (ET), estimates (Brisson et al., 2006). After the daily potential biomass estimate is selected, it is further reduced by temperature, water and nitrogen stresses. An error may be introduced when the WUE – based approach is used, due to the double role played by nitrogen stress on transpiration (canopy resistance is increased, which indirectly reduces photosynthesis) and directly reducing biomass accumulation, through a nitrogen stress factor (Stöckle et al., 2003).

Final yield is a function of total biomass accumulation and harvest index (HI); the latter determines the amount of biomass allocated to yield. HI is a constant that is modified by conditions of stress (water and nitrogen) by differing degrees depending on the timing of the stress (Stöckle et al., 2003). CropSyst does not directly simulate carbon or nitrogen partitioning to different plant components.

CropSyst solves Richard's equation in determining the soil moisture content of the soil. The lower boundary conditions can be set as either free drainage or saturated (water table) and upper boundary condition can be flux, to represent ET, or saturated, in the case of surface irrigation. The water balance calculations are dependent on the specified root zone depth, measurement of which is prone to error. The progression of the rooting depth is tied to leaf area growth and reaches a user specified maximum unless water or nitrogen limits growth (Stöckle et al., 2003).

Potential ET is determined using either the FAO-56 (Allen et al., 1998) or Priestly-Taylor methods together with a crop coefficient based on crop growth stage, height and roughness. Partitioning of potential ET to transpiration and evaporation is performed using an optical analogy and application of Beer's law (Stöckle et al., 2003); this performs somewhat poorly for row crops (Brisson et al., 2006). Root water uptake determines the amount of water actually transpired and depends on the potential difference between soil and canopy, root density and climatic demands. Root water uptake is calculated per soil layer to account for capillary rise. CropSyst accounts for soil salinity by adding an osmotic potential (caused by presence of salts in the soil solution) to the matric potential which together sum to the total soil water potential used to solve Richard's equation and a the salinity reduction function of van Genuchten (1987) (Ferrer-Alegre and Stockle, 1999). Actual transpiration is used to determine the water stress coefficients which reduce both photosynthesis (RUE) and leaf expansion.

Soil mineral nitrogen is represented in both nitrate and ammonium forms. Mineralization, nitrification, denitrification, ammonium sorption, symbotic fixation and crop uptake processes are all considered. Water and nitrogen balance communicate to model nitrogen transport and leaching (Stöckle et al., 2003).

Stöckle et al. (1994, 1997) and Pala et al. (1996) achieved good agreement with CROPSYST and observed values of yield and biomass for wheat (Utah, Syria), maize (Colorado and France), sorghum (France) and soybean (France) under different levels of water availability.

2.8.3.2 STICS

STICS (Brisson et al., 2003) is the most generic of the crop models, simulating the greatest number and range of crops. The complexity of the model, if estimated on the basis of parameters describing species and cultivars, is less than that of CROPGO. This makes it somewhat less suitable as a crop physiology heuristic tool, while very appropriate as a planning tool as many management approaches and environmental conditions can be considered for a wide range of crops.

STICS is the only model to use leaf temperature as a predictor of development. Leaf temperature is used in calculating water deficit effects. Development is determined on two scales; one for vegetative growth, including leaf area and roots and another for reproductive organs, which occur independently (Brisson et al., 2003). The model does not consider plant death between germination and emergence.

Leaf area growth is independent of biomass and is driven only by temperature, plant density and crop parameters. Photosynthesis can be simulated for closed canopies using the Beer's law analogy, or using hedgerow level photosynthesis. This latter method is appropriate for row crops and conditions of incomplete cover. Crop geometry, row spacing and leaf area index (LAI) are all used to estimate the amounts of diffuse and direct radiation arriving at the crop (Brisson et al., 2003). Leaf senescence depends on crop age.

As in CropSyst, biomass is calculated as a function of RUE (Brisson et al., 2003), a concept that results in the coupling of respiration to photosynthesis and determines the partitioning of carbon between roots and above ground biomass. This approach is a simplification of reality that rarely holds true, although it is very economical for coding parameters (Brisson et al., 2006). RUE varies with growth stage, temperature and water and nitrogen stresses. CO_2 limits RUE allowing climate change simulations.

STICS handles the production of yield differently for determinate and indeterminate crops. For determinate crops, the process is straightforward and similar to that used in CropSyst. The concept of HI is used to determine carbon and nitrogen content of grains, with cultivar specific limits on the maximum number of units and unit weight as thresholds (Brisson et al., 2003). This approach is economical in the number of parameters required. The number of grains produced is determined by the growth during seed/pod formation stages (legumes) and depends on the cultivar. For indeterminate plants, the growth of harvested parts begins between the onset of filling and end of fruit setting. Fruits set per day are proportional to a potential rate, the effective temperature, and the source sink ratio (Brisson et al., 2003). Many aspects of the growth of indeterminate plants depend on source - sink ratio. The source is new assimilates as well as reserves. Reserves are not localized in STICS, but determined from the difference of total biomass, and biomass of fruits, LAI, etc. The fruit sink size is the product of number of fruits and growth potential, summed for all compartments of growth, based on phenological stage (Brisson et al., 2003). Fruit number, as opposed to leaf or fruit growth, is the first aspect of growth affected by limited photosynthesis, in what the model developers refer to as trophic stress.

Unlike CropSyst, which solves Richard's equation to simulate water and nutrient dynamics in the soil profile, the tipping bucket approach used in STICS can only approximate the water content of each soil layer (Brisson et al, 2006). The root zone, which is generally hard to measure experimentally, limits the soil depth considered in the water balance. The soil is characterized by texture, structure, fissures independent of horizons, and stones. For each soil horizon, a maximum infiltration is defined, such that macropores get filled when the soil is above field capacity. When macropores in a given horizon are filled, water will move upwards to fill the micropores in higher horizons approximating upward flux (Brisson, 1998). Drainage depths are calculated using Hooghoudt's equation and a surface runoff factor determines runoff amounts.

Potential ET is determined using either the FAO 24 or Priestly-Taylor methods together with a crop coefficient based on LAI, height and roughness. Allen et al. (1998) concluded that neither of these methods produces ET estimates as accurately as the FAO 56 Penman – Monteith equation. The model can calculate the partitioning of ET to soil evaporation and plant transpiration based on LAI (or percent ground cover) using either the Beer's law optical analogy or an energy balance. Partitioning of potential ET to transpiration and evaporation using an optical analogy and application of Beer's law performs somewhat poorly for row crops and was the motivation for incorporating the energy balance method in both STICS and CROPGRO (Brisson et al., 2006). Use of the energy balance method to determine ET alleviates the error in calculating convection that occurs under row canopies. The method considers minimal plant resistance, in terms of LAI, radiation and air saturation deficit, and CO_2 content and the crop height to estimate roughness (Brisson et al., 2003).

Root growth is responsible for water and nitrogen uptake for the entire root zone (Brisson et al., 2003). Root depth exploration depends on soil temperature and is impeded by excessively wet or dry moisture conditions and restrictive soil layers. The end of root growth coincides with that of leaf growth (Brisson et al., 2003). There are two options for determining root density. With the standard option, root density is set such that effective absorption is achieved and is a maximum at the soil surface. The second option is for the case of a low density- profile. In this situation, growth with respect to length is similar to leaf growth and is distributed to each layer according to the proportion of roots present in each layer and any restrictive soil conditions. A root density of 0.5 cm cm^{-3} is the maximum that water or nitrogen uptake can distinguish (Brisson et al., 2003).

As root growth is governs the ability for roots to uptake water, actual transpiration is set equal to root water uptake and can be less than potential transpiration when low soil water conditions beyond the threshold for maximal stomatal functioning are encountered.

Reduced transpiration results in the calculation of two water stress coefficients, which reduce both photosynthesis (RUE) and leaf expansion. The stomatal stress index equals the relative transpiration (actual/potential) and affects RUE. The leaf expansion stress index equals the ratio of actual to potential transpiration and drops from a value of one when the soil is moist when the actual transpiration drops below the critical potential for cell expansion (Brisson, 1998; Brisson et al., 2003).

Three stress factors affect different aspects of growth in response to soil nitrogen levels: a nutrition factor reduces RUE, a leaf growth factor and a factor that influences senescence (Brisson et al., 2006; Brisson et al., 2003). The model accounts for mineral and organic nitrogen sources with mineral nitrogen present as both nitrate and ammonium. While only nitrate is leached, plant uptake does not discriminate between the two forms. Nitrogen absorption is the minimum of demand, as determined by dilution curves and supply (Brisson et al., 2003). Mineralization of humus depends on soil texture, temperature, moisture, amount of humified nitrogen and organic matter. Nitrogen leaching is determined using the concept of nitrogen diffusivity calculated at each soil layer by determining the nitrogen concentration in soil water solution. STICS does not consider phosphorus or potassium dynamics or their effect on crop growth. Finally, nitrogen fixation for legume crops is set to meet crop demands but limited by water stress, presence of nitrate, temperature and water logging (Brisson et al., 2003).

2.8.3.3. CROPGRO

CROPGRO (Jones et al., 2003) is considered the most physiologically based agronomic model currently available. CROPGRO began as a legume based crop growth model that originated as earlier versions of SOYGRO, PNUTGRO and BEANGRO (Hoogenboom et al., 1992). It is now one of the two primary crop models, the other being CERES, in the Decision Support System for Agrotechnology Transfer (DSSAT) software package. DSSAT manages soil, weather, and management and crop databases to simulate various agricultural and climatic scenarios over multiple years. DSSAT can simulate 27 different crops and includes the CERES and CROPGRO families of crop models, is over 15 years old and has been applied in over 100 countries. The crop models contained in DSSAT are in modular form and comprised of one code for simulating soil water, nitrogen and carbon dynamics. Crop growth and development are simulated with CERES (maize, wheat, rice, barley, sorghum, millet), CROPGRO (soybean, peanut, dry bean, chickpea, cowpea, faba bean, velvet bean, tomato), CROPSIM and SUBSTOR (potato). By maintaining separate crop modules within DSSAT, the individual crop models can capture more of the species specific physiological differences while considering the same soil, climate and management scenarios (Jones et al., 2001; Jones et al., 2003). As such, it can not be considered as generic, like CropSyst or STICS, and the following discussion is limited to the CROPGRO model.

CROPGRO can simulate closed canopies, in which photosynthesis depends on LAI and potential ET and is calculated daily, or hedgerow canopies, in which light interception for photosynthesis depends on LAI, row orientation and spacing, percent shading, crop dimensions and density, and is calculated hourly at the leaf level (Jones et al., 2003). Specific leaf area (SLA) sets the ratio between leaf area and biomass and varies with age, water deficit, radiation, temperature and cultivar. In early development stages, until the plant has its first five leaves, the upper limit to leaf area is set by temperature. In later stages, leaf area is sensitive to planting density. Senescence depends on nitrogen status and dynamics in the plant. This reflects LAI greater sensitivity to water and nitrogen stresses than biomass (Jones et al., 2003).

While the option to use RUE exists, the approach to biomass accumulation, in which respiration and leaf level photosynthesis are determined independently, is in general much more complex and process oriented than in the models presented previously. The disadvantage of this complexity being the high degree of parameterization required and its associated error due to increased model bias (Wallach, 2006).

New daily growth is a function of available assimilated carbon, how it is partitioned to different trophic levels, and the respiration energy requirement for different tissues (Jones et al., 2003). During the vegetative stages, carbon resources are allocated between leaf, stem and roots, dependent on stress and species. At the onset of the reproductive stages, each day different cohorts of flowers, pods and seeds are added and compete with vegetative tissues for carbon and nitrogen resources, depending on species, water and nitrogen status, and temperature. For determinate crops, all assimilate is partitioned to reproductive organs, whereas in indeterminate crops, a fraction will still be allocated to vegetative growth. Nitrogen, protein and carbon may all be mobilized from leaf tissues and allocated to seeds, causing a decline in photosynthesis due to nitrogen stress. Respiration is a function of photosynthesis, though computed independently, and as a function of species parameters (Jones et al., 2003; Boote et al., 1998a; Boote et al., 1998b).

CROPGRO employs source-sink relationships to determine the carbon and nitrogen content of grains, though many of these relationships are not perfectly understood. Total biomass accumulation during reproductive organ formation determines the number of seeds, dependent on cultivar traits.

A tipping bucket approach is used in CROPGRO and the DSSAT suite of crop models to determine water infiltration and soil moisture in successive soil layers. Water drains to the next layer when the soil moisture is above the drained upper limit (equivalent to field capacity) or can be simulated as upward flow when the soil is saturated in layers below, depending on the soil's hydraulic conductivity (Ritchie, 1998). Many soil – water parameters can be estimated by DSSAT based on soil texture (Ritchie, 1998). All water balance calculations are constrained to the user specified root zone depth, which is generally error prone due to measurement uncertainties. The CENTURY (Parton et al., 1988) model is included with the DSSAT models to simulate the effects of organic surface residues.

Potential ET is calculated using one of the FAO 24, FAO 56, Priestly-Taylor, or hourly energy balance methods in combination with a LAI based crop coefficient, incorporating effects of roughness and crop height. Partitioning of potential ET to transpiration and evaporation using an optical analogy and application of Beer's law is generally unsatisfactory for row crops and is improved when the energy balance approach is implemented (Brisson et al., 2006).

Root water uptake is determined per soil layer and depends on root length density, soil water content, soil hydraulic conductivity, root diameter and water potential difference between soil and roots in an approximation of radial flow to roots (Jones et al., 2003; Ritchie, 1998). Actual crop evapotranspiration is determined as the minimum of potential crop evapotranspiration and root water uptake. If root water uptake is less than potential evapotranspiration, stomatal closure is simulated; though experimental evidence of (Bourgault, 2008) suggests that the extent of this phenomenon is dependent on species. Three water stress factors are computed when the actual transpiration changes in relation to potential evapotranspiration. The water stress factor for reducing photosynthesis acts when potential root water uptake is less than potential transpiration (Jones et al., 2003; Ritchie, 1998). A second water stress factor for reducing expansive growth, associated with plant turgor, is reduced when potential root water uptake is less than 1.5 times the potential transpiration (Jones et al., 2003; Ritchie, 1998). The third water stress factor acts to increase biomass partitioning to the roots when the ratio of actual transpiration to potential transpiration is less than 1 (Hoogenboom et al., 1992). The water stress factors affecting above ground growth are similar in CROPGRO and STICS, but only CROPGRO simulates root growth response to soil water status.

CROPGRO has been successfully tested in a number of systems and environments (Boote et al., 1997; Mavromatis et al., 2001; Singh et al., 1999), but with relatively few evaluations of its water balance or ability to simulate water stress. Heinemann et al. (2000) obtained good agreement between measured and simulated results with CROPGRO investigating the effects of irrigation schedule and duration for dry beans irrigated by a centre pivot system in Brazil. Nielsen et al. (2002) determined that both RQZWM and CROPGRO adequately predicted soybean yield, biomass and LAI in response to water deficit in a series of sprinkler, rain-out and drip irrigation experiments. However, the degree of water stress imposed in the experiments is not clear and some results seem confounding. For example, in the sprinkler line source experiments, water stress was not imposed until late in the reproductive phase, though CROPGRO predicted large reductions in LAI, causing the reductions in ET. The authors point out that stomatal regulation or plant water status would be the reason for reductions in ET, though this response was not captured by the model.

In a comparison of the water uptake algorithms in CropSyst and CERES, in which the latter uses the same water balance as CROPGRO, both models performed comparably well at predicting water uptake of maize and soil water content under conditions of wet and dry soil (Jara and Stöckle, 1999). While CropSyst is more process oriented, the improvement in simulation of water use and soil water content only occurred in the driest conditions and then the relative improvement was very small. To limit the comparison to the water simulation algorithms, field measurements of maximal evapotranspiration, using the latent heat flux over a well watered treatment from the Bowen ratio energy balance method, leaf area and root fraction in a particular layer (CropSyst) and root length density (CERES) were used as inputs to the models. In actual simulations these would also be predicted and the errors in these quantities would propagate to the water use simulations (Jara and Stöckle, 1999).

2.8.3.4. APSIM

Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003) is a modeling framework designed to simulate yield in response to a number of management variables. APSIM has been developed in Australia and has tried to combine together cropping models with environmental models, using a modular, systems approach to make predictions about crop and land productivity in the short and long terms. Much like DSSAT, APSIM is the interface for soil, climate and crop models. Currently, each species, or group of species, is simulated in its own model, so that the processes captured for different species are not consistent. Efforts had been made to consolidate models into one process based model (Wang et al., 2002), though no literature or public versions are available. None the less, while APSIM is not generic, it is included in this review as it models green gram (Robertson et al., 2002), treats an adequate level of physiological processes (Keating et al., 2003) and includes a response to soil salinity (Rodriguez et al., 2006). The following description is based on APSIM – Legume (Robertson et al., 2002).

Development in APSIM – Legume is based on thermal time, time within a temperature threshold range, with temperature thresholds taken form literature values. Development is divided into a number of phenological stages, whose duration is based on photothermal time, time with a temperature and photoperiod threshold range, accumulation (Robertson et al., 2002). Initial soil moisture levels affect the time between sowing and emergence. Water, nitrogen and vernalization stresses are considered in calculations of development rate, but Robertson et al. (2002) note that the lack of literature on evaluating the model with these stresses limits accurate parameterization.

Potential leaf area expansion is a function of the rate of leaf appearance, determined by node appearance due to photothermal days, and maximum leaf size. Leaf area production is reduced if inadequate carbon supplies are available to meet the daily increase in LA, in an approach similar to that found in CROPGRO. Carbon supply is generally limiting at high plant densities (Robertson et al., 2002).

Potential daily above-ground biomass production depends on LAI, radiation interception and a crop specific RUE. While photosynthesis is not computed using a leaf level energy balance, radiation interception is reduced to account for row spacing. RUE is further limited by temperatures of the current and previous days. Actual daily biomass can be limited based on RUE, nitrogen and water stresses. Biomass is partitioned to six different plant parts, depending on the growth stage. Plant height is used in intercrop systems to determine the radiation that arrives at the canopy (Robertson et al., 2002).

Daily increases in HI are used to determine amount of carbon allocated to grains. If carbon reserves are inadequate to meet grain requirements, carbon can be translocated from leaves and stems, dependent on crop specific limits (Robertson et al., 2002).

Crop nitrogen demand is set to maintain plant parts at the critical nitrogen level, which is crop specific, for the current day's biomass production, as well as total biomass. Crop uptake is by mass flow due to nitrogen in the soil solution, active transport or nitrogen fixation. A parameter sets the amount of nitrogen that will be fixed in the presence of mineral nitrogen in the soil. Nodule growth and nitrogen fixation are limited by low soil water conditions (Robertson et al., 2002).

APSIM simulates the water balance using either a tipping bucket approach or a numerical solution of Richard's equation (Keating et al., 2003). In the tipping bucket approach water infiltration and soil moisture in successive soil layers are calculated based on soil properties such as the drained upper limit (equivalent to field capacity), the lower limit (analogous to permanent wilting point), hydraulic conductivity and soil texture. Water drains to the next layer when the soil moisture is above the drained upper limit or can be simulated as upward flow when the soil is saturated in layers below, depending on the soil's hydraulic conductivity (Keating et al., 2003). Nitrogen or solute movement is determined using a mixing algorithm and water flow into adjacent layers (Keating et al., 2003). Infiltration and runoff procedures are responsive to soil cover. All water balance calculations are constrained to the user specified root zone depth, which is generally error prone due to measurement uncertainties. An alternative to the simplified tipping bucket approach is found in the APSIM - SWIM (Connolly et al., 2001). This module uses the SWIM model to numerically solve Richard's equation and the convection dispersion equation to determine infiltration, runoff, soil moisture content and solute transport (Keating et al., 2003).

Daily root growth is proportional to the above ground biomass growth, depending on the growth stage. Root depth exploration can be limited by compaction and pH (Robertson et al., 2002). A specific root length parameter converts root biomass to length, which is then used to determine water uptake in the SWIM module. When water supply is less than potential transpiration, determined using the Penman – Monteith or Priestly – Taylor approaches, transpiration is reduced to equal the potential root water uptake, simulating stomatal closing (Robertson et al., 2002). Under this condition, a water stress factor acts to reduce the rate of leaf area expansion. Likewise, under water limiting conditions, photosynthesis is limited by using WUE and the actual transpiration (Robertson et al., 2002).

2.8.4 Modeling crop response to salinity

Many models which determine water and solute flow in the soil from numerical solutions of Richard's equation and the convection–dispersion equation, account for salinity effects in the way in which root water uptake (RWU) is handled. In these models, two general approaches are used to simulate RWU. The model type first formulated by Gardener (1964) is referred to as the microscopic approach, and considers the physics of water flow through soil micropores in response to soil conductivity, water potential gradient between the root and soil, and the rooting density distribution with depth. This type of model was modified by Nimah and Hanks (1973) to include both soil matric and osmotic potentials in the potential gradient term. The macroscopic approach is based on empirical reduction functions, $\alpha(h,h_o)$, which reduce water uptake from a maximum (usually potential plant transpiration) in response to lowered water potential (matric, h, and osmotic, h_o). This type of model, modified to include salinity effects, is found in Feddes et al. (1976), van Genuchten (1987) and Homaee et al. (2002b) among others. Excellent reviews of different model forms are found in the literature (Homaee et al., 2002a; Green et al., 2006; Skaggs et al., 2006a).

The macroscopic model was judged to be much more representative of actual root water uptake in response to salinity stress in a comparison of the microscopic model of Nimah and Hanks (1973) and the macroscopic model of van Genuchten (1987) (Cardon and Letey, 1992a),. The microscopic model of root water uptake was unresponsive to salinity when the soil was moist, and dropped sharply to zero as the soil dried. Cardon and Letey (1992a).

Within the macroscopic models of root water uptake, different methods exist for accounting for the relative effects of water and salinity effects including additive (van Genuchten, 1987; Cardon and Letey, 1992b), multiplicative (van Genuchten, 1987; Skaggs et al., 2006b) as well as hybrids or combinations of these types (Homaee et al., 2002b). In a comparison of six types of macroscopic uptake terms, Homeaa et al. (2002a) determined the additive term (van Genuchten, 1987) performed the worst in all cases. Shalhevet and Hsiao (1986) found the effect of water stress to be twice that of salinity stress with equivalent water potential This raises doubts about the theoretical validity of an additive approach. Homaee et al. (2002a) found their own multiplicative combination reduction model (Homaee, 2002b) performed best under almost all circumstances.

The two terms in the Homaee et al. (2002b) reduction function coincide with the water stress reduction factor of Feddes et al. (1976) and the salinity reduction factor of Maas and Hoffman (1977). Their model is essentially the same as that proposed by van Dam et al. (1997) except Homaee et al. (2002b) increased the water potential corresponding to the permanent wilting point, to increase with increasing salinity by adding the osmotic potential to the potential corresponding to the wilting point. One caution is that the Maas and Hoffman (1977) reduction function was formulated to relate soil salinity to relative yield, not ET or root water uptake. However, the general form of the model should be valid if reductions in yield roughly parallel reductions in water uptake with the appropriate yield response factor (Doorenbos and Kassam, 1979) and appropriate choices of the constants a and h^*_o (Green et al., 2006). Homaee et al. (2002b) appear to apply directly the coefficients from Maas and Hoffman (1977) and cite the availability of these coefficients for a wide variety of crops as the main reason they chose this particular salinity reduction function over others (van Genuchten, 1987; Dirksen and Augustijn, 1988) with harder to obtain parameters.

From the literature cited above, it is clear that approaches exist to model root water uptake in response to salinity. However, most of the hydrological models include only very elementary crop model routines that ignore climate, management and genetic factors that govern crop growth. While the current version of CROPGRO does not consider the effects of soil salinity or groundwater contribution on crop growth, other crop models have attempted to incorporate a salinity response. CROPSYST uses the macroscopic empirical reduction function of van Genuchten (1987) and adds osmotic potential to the matric potential in calculating the soil-root water potential gradient (Ferrer-Alegre and Stöckle, 1999). Ferrer-Alegre and Stöckle (1999) found the approach was very successful in predicting transpiration and biomass production for experiments growing barley and sweet corn, and provided reasonable predictions of yield (Ferrer-Alegre and Stockle, 1999). It is not clear how osmotic potential is estimated from the field collected data and their model requires significant parameterization.

A second approach to modeling crop response to salinity is found in Castrignano et al. (1998) using CERES (DSSAT family of models) with maize. Castrignano et al. (1998) reduced photosynthesis as a function of the pre-dawn leaf water potential. Pre-dawn leaf water potential was calibrated to the total water content of two soils at three salinity levels to the leaf water potential. The agreement of their model to observed data was very good for LAI, yield and biomass and good for transpiration on a silt loam, and less satisfactory for a clay soil.

Rodriguez and Nuttall (2003) investigated the factors that would best describe a salinity response in APSIM-Wheat. Their approach was to determine if the effect of salinity, sodicity and/or boron toxicity in soils on (i) the water availability at -1500 kPa (permanent wilting point) or (ii) the ability of roots to explore a particular soil layer could lead to prediction improvements of APSIM-Wheat in the marginal soils. The greatest improvements were realized when salinity (note that the EC of the soil studied was not specified) was used to reduce the water availability, followed by using salinity to reduce root exploration. However, the authors concluded that their results indicate that more work needs be conducted to improve the model's performance under conditions of substantial soil salinity. Thirteen percent of their residuals in yield were attributed to soil salinity, indicating important, if not major, effects of salinity unrelated to water availability. Previous work with APSIM-Wheat had simply proposed that soil constraints (salinity, sodicity, or boron toxicity) act to raise the water content near the permanent wilting point (Sadras et al., 2003).

2.9 CONCLUSIONS

In light of climate change and increasing water scarcity and insecurity, the need for improved water management in agriculture and irrigation becomes ever more important. This is particularly so in Uzbekistan where the economy is heavily dependent on irrigated agriculture and environmental degradation due to irrigation has numerous consequences. The science of evapotranspiration under standard conditions is well understood and established, and has been so since the pioneering work on Penman (1948) and later refinements of Monteith (1965). However, when water, salinity or nutrients limit evapotranspiration, understanding of the crop physiology and engineering application limits one's ability to adapt to a changing climate and water regimes. With improved knowledge of the fundamental processes, applications can be developed to manipulate the natural crop response to water stress, as is the case in partial root zone drying and deficit irrigation. Finally, there is a huge potential for synthesis between the fields of salt stress physiology, water stress physiology, evapotranspiration science, irrigation engineering and agronomy in what could lead to significant steps forward in adapting to climate change with great environmental and, ultimately, societal impacts.

Crop modeling offers the potential to integrate the many fields and highlight knowledge gaps for researchers. More importantly, well tested models give farmers, technicians and those who make policy using agriculture tools to develop their management decisions. This is believed to be especially valuable in developing countries where the ability to take risks may be very low for all levels of stakeholders. The choice of crop model is determined by the intended use of the outputs, whether it be a farm-level decision weighing the economics of trying a different management technique or conservation practice, policy analysis of allocation of irrigation water or irrigation water pricing, as an educational aid in teaching crop physiology to undergraduate and graduate students, or in conducting physiology experiments to highlight areas where current understanding of crop processes are not sufficiently well understood. From the literature review CROPGRO was judged the most able to respond reasonably well to all of these factors based on its detailed account of crop physiology, ability to differentiate growth responses in similar crops, transferability to other vegetable crops, flexibility in defining agronomic management scenarios and history of testing and validation in many locations and climates. However, it is not without its shortcomings, many of which are addressed in other models, specifically not considering soil salinity. It is hypothesized that CROPGRO can be improved by incorporating a salinity response function based on the most successful approaches reviewed.

CONNECTING TEXT TO CHAPTER 3

The purpose of this chapter is to identify water saving irrigation strategies appropriate for food legumes production following the winter wheat harvest in the Fergana Valley, Uzbekistan. Water use efficiency and feasibility of adaptation are key criteria for evaluating the irrigation and cropping strategies.

This chapter was published in 2006 as an original research manuscript in Agricultural Water Management, volume 86 (Webber et al., 2006). The content of this chapter is identical to that found in the manuscript, though the formatting has been changed to be consistent with this thesis.

CHAPTER 3: WATER USE EFFICIENCY OF COMMON BEAN AND GREEN GRAM GROWN USING ALTERNATE FURROW AND DEFICIT IRRIGATION

ABSTRACT

The pressure on water resources in the Fergana Valley of Central Asia is expected to increase, as population and industrial activity grow. Increasing water use efficiency (WUE) associated with crop production is a way for arid and semi-arid areas to increase their agricultural production where there is little or no prospect for expansion of water resources. The WUE of two water saving irrigation technologies were evaluated for two legumes, grown as a second crop, in the Fergana Valley of Uzbekistan. Conventional and alternate furrow irrigation and three irrigation schedules were used to irrigate food legumes in a field experiment conducted over two growing seasons (2003 and 2004) after winter wheat harvest. The treatments consisted of factorial combinations of three factors, organized following a split-plot randomized complete block design with four blocks: three irrigation schedules (recommended, moderate and severe depletions) as the main plot factor and combinations of the two irrigation strategies (conventional and alternate furrow irrigation) and two crops (*vigna radiata* (L.) Wilczek and *phaseolus vulgaris*) as the two sub-plot treatment. The WUE was quantified for commercial yield, above ground biomass and root biomass per unit of irrigation water applied and per unit of water evapotranspired. The results of this study indicate that the WUE for both commercial yield and biomass were approximately twice as high for green gram as for common bean. Conversely, the water use efficiency for root biomass in common bean (0.15 kg m^{-3}) was slightly higher than green gram (0.13 kg m^{-3}). WUE increased in green gram when deficit irrigation or alternate furrow irrigation were practiced, whereas it remained constant in common bean for all treatment combinations. These results suggest that common bean is not as well suited to water scarce conditions as green gram. Alternate furrow irrigation and deficit irrigation are appropriate methods to increase WUE, allowing application of less irrigation water, particularly for green gram production.

Keywords: alternate furrow irrigation; common bean (*Phaseolus vulgaris*); green gram (*Vigna radiata* (L.) Wilczek); irrigation scheduling; regulated deficit irrigation; water use efficiency; Fergana Valley of Uzbekistan

3.1 INTRODUCTION

Extensive environmental degradation of the Aral Sea basin has been the price of Uzbekistan's irrigated agriculture (cotton and wheat) dependent economy. The pressure on water resources is expected to increase as the requirements for increased food production and industrial needs increase in parallel with the country's rapidly growing population (Micklin, 2000). The improvement of on-farm irrigation systems and the introduction of low cost water saving irrigation technologies have been identified as key components of reducing agricultural water demand (Horst et al., 2005). Increasing water use efficiency (WUE), defined in this paper as the amount of plant material produced per unit of water transpired, is a way for arid and semi-arid areas to increase their agricultural production where there is little or no prospect for expansion of water resources. Wallace (2000) indicates that there are two approaches to increasing crop WUE. The first is by adopting technologies that increase the proportion of water that is transpired by the crop, as opposed to that lost to drainage, runoff or seepage. The second approach is to increase the crop's capacity to produce biomass (assimilate CO_2) and yield per unit of water transpired. Passioura (2004) adds that, from a farmer's perspective, increasing the harvest index (ratio of seed yield to total biomass) is a practical third approach to increasing WUE.

Regulated deficit irrigation (RDI) and alternate furrow irrigation (AFI) are two water saving technologies that are relatively inexpensive and easy to implement. Both strategies involve manipulating the soil water to induce the crop's inherent response to drought conditions (Davies et al., 2002). In water scarce environments, the goal is generally to increase the WUE. The same strategies may be used in the production of other crops, but with different objectives. For instance, in vineyards the objective is typically to retard vegetative growth and influence fruit quality (Loveys et al., 2004). In RDI, the irrigation water requirement is not completely fulfilled, allowing the soil water to be depleted beyond a threshold, such that the crop experiences water stress. The crop response, which may or may not include a reduction in the rate of water use and/or yield reductions, depends on the degree of soil drying, the crop characteristics and the timing of the water deficit. It is generally thought that withholding water during the vegetative period, as opposed to the flowering or fruit forming stages, has less impact on final yields (Loveys et al., 2004). The water savings associated with RDI are attributed to reductions in stomatal conductance, which occurs as a result of the plant roots encountering drying soil, and precedes any change in leaf water potential. Stomatal regulation is thought to be mediated by chemical signals originating in the roots and traveling to the guard cells via the xylem. Further, these signals are now thought to involve both abscisic acid (ABA) and the alkalization of the xylem flow, associated with soil drying (Loveys et al., 2004; Wilkinson, 2004). While the stomata control both the rates of transpiration and CO_2 entry into the cell, some evidence suggests that initially the reduction in stomatal conductance is greater than the concurrent reduction in carbon assimilation. This results in increased instantaneous WUE values (Chaves and Oliveira, 2004). While some studies show that RDI improves WUE on a seasonal basis (Oweis et al., 2000; Zhang et al., 2000), other investigators have not found consistent evidence that WUE increases with deficit irrigation (Garside et al., 1992; Kang et al., 2000c; Lawn, 1982).

Partial root drying (PRD) is a variation of RDI that generally improves the WUE of crops, for example pot grown tomatoes (Davies et al., 2000) and pot grown common bean (Wakrim et al., 2005). In many cases, the strategy circumvents the yield losses frequently associated with RDI, as in grape (Loveys et al., 2000), soybean (Graterol et al., 1993) and pot and field grown maize (Kang et al., 1998; Kang et al*.,* 2000a; Kang et al., 2000b). PRD involves exposing part of the root system to drying soil while maintaining other sections in well watered soil, and is most effective when the two sections of roots are alternately exposed to wet and dry soil (Kang et al., 1998). The method is thought to work via a reduction in stomatal conductance mediated by a chemical signal generated in the roots when they are exposed to drying soil, as in RDI. This physiological response of the plant, due to exposure of some of its roots to drying soil while the plant is kept well hydrated by other roots in moist soil, is hypothesized to cause the benefits associated with PRD.

For furrow irrigation systems, PRD is practiced as alternate furrow irrigation. Wakrim et al. (2005) found the WUE of common bean increased, though with significant yield decreases, for both RDI and PRD in a pot experiment, and that there were no differences in yield or WUE between the two strategies.

The objectives of this study were (i) to quantify the effects of alternate furrow irrigation and RDI on the WUE (for each of commercial seed yield, above ground biomass, and root biomass per unit of water transpired, WUE_{seed}, $WUE_{biomass}$ and WUE_{root}, respectively) of common bean and green gram and (ii) to determine the optimal irrigation schedule and irrigation water requirement for each crop, in order to maximize their WUE.

3.2 MATERIALS AND METHODS

3.2.1 Site description, experimental design and crop varieties

Two seasons of field data were collected during 2003 and 2004 on two different adjacent fields on the private farm, ”Azizbek-1”, in the Fergana Valley of Uzbekistan (40°23´N, 71°45´E). Despite the close proximity of the fields, the soil characteristics and groundwater depths differed between site-years. For the 2003 site, the soil in the top 60 cm was classified as a silt loam. with a coarser texture at depths greater than 1 m that prevented a groundwater contribution from the water table, which was at an average depth of 2.2 m. The available water content in 2003 was 96 mm in the top 60 cm of the soil. There was more variability in the field used in 2004, with the soil type ranging from a sandy loam to a silt loam over the field and an available water content of 75 mm in the top 60 cm. The groundwater table was also considerably higher and varied along the length of the field, with an average depth of 1.45 m. At the start of August, the groundwater table rose to within 40 cm of the soil surface in some locations and contributed significantly to the soil water in the root zone for a period of less than one week, due to excessively heavy irrigations in an adjacent field.

The experimental layout was a randomized complete block (four blocks), split-plot design. The treatments were comprised of factorial combinations of three factors: irrigation schedule (main-plot factor - recommended rate, moderate and severe soil water depletion), irrigation strategy (conventional furrow or alternate-furrow irrigation) and crop (common bean or green gram). The combinations of furrow irrigation strategy and crop made up the split-plot treatments. Each plot measured 15 by 15 m and contained 23 furrows 12 m in length. All sampling was conducted within a central 5 by 5 m quadrat. The average field slopes were 0.0024 and 0.0023 m/m in 2003 and 2004, respectively. Due to variations in slope across and along the field, and the relatively short length of the experiments furrows, there was variability in slopes between and within individual plots.

Local varieties of common bean (*Phaseolus vulgaris*) and green gram (*Vigna radiata*) were planted half way between the top of the bed and the furrow bottom. Beds were 60 cm apart. In 2003, planting was carried out on July 13 and local practices were followed for planting density, resulting in a fairly sparse plant stand, 70,000 and 105,000 plants/ha for green gram and common bean, respectively. In 2004, the seeding date was July 11 and the plant density for both crops was increased to 333,000 plants/ha, to be comparable with densities found in similar studies at locations elsewhere in the world (Haqqani and Pandey, 1994). In both years the cropping history consisted of cotton the previous year followed by winter wheat, which was harvested in early July. Pest and weed control were conducted as required.

3.2.2 Irrigation scheduling and management

In both years, a pre-irrigation of approximately 800 m^3 ha^{-1} was applied to every furrow in each plot, at 2 days before seeding. The purpose of this irrigation was to bring the soil in the 60 cm root zone to field capacity and to create a good seedbed. At the time of emergence, a second irrigation of 600 m^3 ha^{-1} was applied, also to every furrow, to encourage a full and even plant stand.

Subsequent irrigation scheduling was determined using daily water balances, which were determined for each of the twelve treatments. Each water balance calculated excess or deficit water in the crop root zone relative to field capacity. Inputs to the system considered were irrigation water requirement, precipitation and groundwater contribution. The only water output considered was crop evapotranspiration (ET), as deep percolation and runoff were assumed to be negligible.

Crop ET was determined from the water balance as the sum of precipitation, ground water contribution, irrigation water and the soil water use over the growing season. Additionally, crop ET was predicted, to use in irrigation scheduling, with the FAO Penman-Monteith equation using weather data collected at the experimental site and crop coefficients for standard and stress conditions, as appropriate (Allen et al., 1998). The method assumes that water stress occurs when the root zone water deficit is greater than recommended depletion of the available soil water, which is 45% of the readily available soil water for both green gram and common bean. In response to water stress, the crop reduces ET from a maximum value, ET_{max}, under non-stressed conditions to a value ET_{actual}, given by:

$$ET_{actual} = k_s ET_{\max} \quad [1]$$

where k_s is the water stress coefficient. The water stress coefficient varies linearly between 1 (no water stress) and 0 (permanent wilting point, or 100% depletion).

The groundwater table depth was measured every three days at three and five locations across the field, respectively in 2003 and 2004. As stated above, there was no ground water contribution to the root zone in 2003. In 2004, the groundwater contribution was estimated using an empirical model (Ayars et al., 2006) that takes into account the distance between the root zone and groundwater table, soil type, ET, and the soil moisture content. The model was validated using field data using the water balances for the recommended irrigation schedules for common bean and green gram, where the non-stressed ET was estimated using the FAO Penman-Monteith equation.

Irrigations were applied when the root zone water deficit equaled the maximum allowable depletion of the available soil water (Table 3.1). For the FAO recommended irrigation schedule, or no stress condition, the plots were irrigated when 45% of the available water was depleted. The depletion factors, $p_{nominal}$, for the moderate stress treatments were 60% for common bean and 65% for green gram. For the treatments receiving the largest water stress, the depletion factors were 70% for common bean and 80% for green gram. The depletion factors, p, are not constant and vary as a function of their nominal value, $p_{nominal}$, and ET_{actual}, as given in the following relationship (Allen et al., 1998):

$$p = p_{nominal} + 0.04(5 - ET_{actual}) . \quad [2]$$

Soil moisture measurements, made two days before and two days after each irrigation and every five days between irrigations, were used to check the water balance, particularly the effect of the water stress coefficient and the predicted groundwater contributions. Soil moisture was measured gravimetrically at 0, 10 and 20 cm depth and with a neutron probe at 40 and 60 cm, in the centre of 2 furrows in the conventional furrow treatment plots and in the centre of 4 furrows in the alternate furrow treatments. The gravimetric soil moisture measurements were converted to volumetric values by multiplying by the soil bulk density.

Table 3.1. Amount of irrigation water applied, number of irrigation events and the groundwater contribution to the crop root zone as a fraction of crop evapotranspiration for each treatment during the two growing seasons.

Year	**Crop**	**Irrigation schedule (nominal depletion factor)**	**Total irrigation (m^3 ha^{-1}) (number of irrigations)**		**Estimated groundwater contribution to crop ET (%)**	
			Conventional furrow	**Alternate furrow**	**Conventional furrow**	**Alternate furrow**
2003	Common bean	Recommended (0.45)	3100 (5)	3100 (6)	0	0
		Moderate stress (0.60)	3100 (4)	3050 (5)	0	0
		Severe stress (0.70)	3150 (4)	2450 (4)	0	0
	Green gram	Recommended (0.45)	3600 (6)	3050 (6)	0	0
		Moderate stress (0.65)	2800 (4)	2350 (4)	0	0
		Severe stress (0.80)	2000 (3)	1900 (3)	0	0
2004	Common bean	Recommended (0.45)	3000 (7)	2500 (7)	8	10
		Moderate stress (0.60)	2650 (5)	2200 (5)	8	11
		Severe stress (0.70)	2300 (4)	1950 (4)	10	12
	Green gram	Recommended (0.45)	3550 (7)	2850 (7)	7	8
		Moderate stress (0.65)	3000 (5)	2500 (5)	8	10
		Severe stress (0.80)	1700 (3)	1500 (3)	12	15

Plots were irrigated using either conventional or alternate furrow irrigation. In conventional furrow irrigation water is introduced into every furrow in the plot. In alternate furrow irrigation water is introduced into only every second furrow. In this study, the furrow receiving water is alternated between successive irrigations.

The literature contains very little on irrigation scheduling for alternate furrow irrigation systems. As a result, there was a change in the scheduling methodology for alternate furrow irrigation to ensure the water savings possible with this strategy. In 2003, separate irrigation schedules were used for the conventional and alternate furrow treatments within the same crop and depletion factor. In the alternate furrow treatments, the average of a wet and dry furrow's soil moisture was used in the water balance. As a result, the alternate furrow treatments had lower soil water contents and two of the alternate furrow irrigation treatments received one irrigation event more than their corresponding conventional furrow irrigation treatments. In 2004, the methodology was modified slightly to ensure equal numbers of irrigations for the alternate and conventional furrow corresponding treatments and significant water savings for the alternate furrow irrigation treatments. Irrigations for the alternate furrow treatments were applied on the same day as the corresponding conventional furrow treatment, with the result that only 75% of the water was applied.

In both years, initial inflow rates were selected using the SIRMOD software package (ISED, 1989). Within each experimental plot, the lower ends of the furrows were blocked, so there was no outflow. Inflows to each plot were measured with small portable flumes and from there distributed by field staff as evenly as possible to each of the furrows. Due to the high variability of slopes between plots, inflow rates were often adjusted to ensure the advance time (the time for the water front to reach to the end of a furrow) was approximately equal to one half of the total irrigation time. Small inflow rates were used for high efficiency and uniformity, as required with short furrows. As a result, it was not possible to measure the inflow into individual furrows. However, micromanagement of flow rates to individual furrows prevented ponding. The choice to use shorter furrows than commonly found in other irrigation studies was justified as the simultaneous collection of data on irrigation scheduling and crop response to drought required very high distribution uniformity to ensure all along a furrow received the same depth of irrigation water.

3.2.3 Biomass and yield measurements

Seed and biomass yields were used to compute the respective WUE values. In 2003, common bean was harvested four times between October 3 and November 1 and green gram was harvested eight times starting September 21 with the final harvest on November 2. In 2004, harvest dates were September 20 and October 3 for common bean and green gram was harvested four times between September 21 and October 9. All plants within a central 5 m quadrat were harvested. One day before harvest, a 50 cm section of row was sampled to determine the above ground biomass and, in 2004 only, the root biomass.

3.2.4 Statistical analysis

Statistical significance for detection of differences between various means was determined using the general linear model (GLM) procedure of the Statistical Analysis System (SAS, Cary, N.C., U.S.A.). Differences between specific least-square means were determined using t-test at $P \leq 0.05$. Data were analyzed separately in 2003 and 2004 as the fields used in the respective years differed in soil type, water holding capacity, groundwater depth, plant density and the irrigation scheduling for alternate furrow irrigation was slightly modified in 2004.

3.3 RESULTS AND DISCUSSION

3.3.1 Seed, above ground and root biomass yields

The seed, above ground and root biomass yields are given in Table 3.2. (Bourgault, 2008). For common bean, RDI at the moderate depletion level produced the same seed yields as the recommended irrigation schedule, whereas seed yields decreased with the large depletion factor. In green gram, RDI produced the highest yields, though the level at which the highest yields occurred changed between years. In 2003, RDI at the moderate depletion level produced the same seed yields as the recommended irrigation schedule, whereas seed yields decreased with the large depletion factor. In 2004, green gram yields increased with the use of the large depletion factor. For root biomass production, there was a strong interaction between crop and RDI. At the level of the large depletion factor, common bean increased root biomass yields while in green gram root biomass decreased at this level.

The irrigation strategy did not have an effect on common bean or green gram seed yields in 2003. In 2004, there was a strong interaction between the irrigation strategy and crop. Common bean yielded slightly less when alternate furrow irrigation was implemented compared to conventional furrow irrigation. Green gram yielded higher with alternate furrow irrigation. The irrigation strategy had no effect on the above ground biomass in 2003 and caused a decrease of 9% in 2004 when alternate furrow irrigation was used. It had no impact on root biomass yields.

Table 3.2. Seed, above ground biomass and root biomass of common bean and green gram grown with three irrigation schedules (recommended, moderate and large depletions) and two irrigation strategies (conventional and alternate furrow) in 2003 and 2004 (from Bourgault, 2008). Within each year and measure, value associations with the same letters are not different ($P \leq 0.05$) as determined using t-tests on least square means.

Year	*Crop*	*Depletion for irrigation scheduling*	*Seed Yield (kg ha $^{-1}$)*		*Above ground Biomass at Harvest (kg ha $^{-1}$)*		*Root Biomass at Harvest (kg ha $^{-1}$)*	
			Conv. furrow	Alt. furrow	Conv. furrow	Alt. furrow	Conv. furrow	Alt. furrow
2003	Common bean	Rec. (0.45)	765 ^{ABC}	674 ^{BCDE}	2530 ^{BC}	3010 ^{BC}		
		Moderate (0.60)	620 ^{BCDE}	623 ^{BCDE}	2225 ^{C}	2297 ^{C}		
		Large (0.70)	552 ^{DE}	500 ^{E}	2162 ^{C}	2631 ^{C}		
	Green gram	Rec. (0.45)	793 ^{AB}	718 ^{ABCD}	2892 ^{C}	4267 ^{B}		
		Moderate (0.65)	870 ^{A}	806 ^{AB}	5571 ^{A}	4322 ^{AB}		
		Large (0.80)	554 ^{CDE}	612 ^{CDE}	2127 ^{C}	2962 ^{C}		
2004	Common bean	Rec. (0.45)	729 ^{CD}	687 ^{DE}	2264 ^{EF}	1978 ^{EF}	353 ^{BC}	293 ^{DE}
		Moderate (0.60)	782 ^{CD}	571 ^{E}	1957 ^{EF}	1604 ^{F}	327 ^{BCD}	322 ^{BCD}
		Large (0.70)	572 ^{E}	552 ^{E}	2421 ^{E}	1654 ^{F}	374 ^{B}	435 ^{A}
	Green gram	Rec. (0.45)	849 ^{C}	1047 ^{AB}	4916 ^{AB}	4241 ^{BC}	354 ^{BC}	319 ^{BCD}
		Moderate (0.65)	975 ^{BC}	970 ^{BC}	4817 ^{AB}	5068 ^{A}	305 ^{CDE}	334 ^{BCD}
		Large (0.80)	1045 ^{AB}	1163 ^{A}	3520 ^{CD}	3457 ^{D}	256 ^{E}	297 ^{CDE}

3.3.2. Water use efficiency (WUE)

Crop effects

In both 2003 (Fig. 3.1) and 2004 (Fig. 3.2), the mean WUE_{seed} was approximately twice as large for green gram (0.45 and 0.54 kg m^{-3}) compared to common bean (0.26 and 0.34 kg m^{-3}). The differences between years were probably due to the different planting densities and, possibly, ground water contributions. $WUE_{biomass}$ was also over twice as large for green gram as for common bean in both 2003 (Fig. 3.3) and 2004 (Fig. 3.4). Averaged across all treatments, the ratio of WUE_{seed} to $WUE_{biomass}$, or the harvest index (HI), was smaller in green gram than for common bean in both 2003 (0.21 to 0.27) and 2004 (0.21 to 0.28), though this effect is considered minor relative to the larger magnitudes of the WUEs of green gram. WUE_{roots} (Fig. 3.5) was less, across all treatment combinations, for green gram, with an average value of 0.16 kg m^{-3} compared to 0.19 kg m^{-3} for common bean. Green gram invested proportionally more of its photosynthetic resources into yield and biomass production per unit of water transpired, whereas common bean invested more heavily in root production.

Irrigation schedule effect

When RDI was practiced, the response of the two crops was very different. For common bean, WUE_{seed} remained constant across all treatment combinations at 0.26 kg m^{-3} (2003) and 0.34 kg m^{-3} (2004). Likewise, $WUE_{biomass}$ was constant across all stress levels. While WUE_{seed} and $WUE_{biomass}$ did not change when subjected to soil drying, the HI decreased at the severe stress level. WUE_{roots} increased to 0.23 kg m^{-3} with the large depletion factor, from 0.16 kg m^{-3} for the well watered treatment. This indicates that common bean sensed the water deficit in the soil and responded by investing more photosynthetic resources in root production per unit of water use in an attempt to extract more water. However, this strategy was not able to translate into increased values of WUE_{seed} or $WUE_{biomass}$. Green gram responded to RDI by increasing its WUE_{seed} by 48% (moderate depletion) in 2003 and 95% (large depletion) in 2004. With the use of RDI, $WUE_{biomass}$ also increased compared to the recommended depletion. Like common bean, green gram responded to the severe water stress by increasing its WUE_{roots}. However, while common bean increased its root biomass under severe stress; green gram actually reduced its root biomass (Table 3.2). The increase in WUE_{roots} for green gram is therefore explained by the greatly reduced water use at the high stress level (data presented in Chapter 4). This suggests that the two crops use very different mechanisms to respond to soil drying; common bean produced more roots whereas green gram reduced its rate of water use.

The difference in the two crops' responses is further illustrated by looking at the HI. In 2004, at the recommended and moderate depletion levels, the HI was lower in green gram (0.21) than common bean (0.37). At the severe stress level, the ratio was reversed; HI was greater for green gram (0.34) than common bean (0.28), with the probability of significance taken as P < = 0.10. Common bean's decrease in HI with water stress was also evident in 2003 (18% decrease), though only statistically significant at the P <= 0.11 level and the HI in green gram was the same at all levels of RDI. It seems clear that the two crops react oppositely under severe water stress; in common bean, the HI decreases, whereas it remains the same or increases for green gram. It appears that under stress common bean partitions less of its resources to seed production and more to root production. The strategy to extract more water by developing more root biomass comes at the expense of seed production.

<u>Irrigation strategy effects</u>

The effect of alternate furrow irrigation on WUE_{seed} differed between the crops. Alternate furrow irrigation had no effect on the WUE_{seed} in common bean across all levels of water stress, contrary to the findings of Wakrim et al. (2005). In green gram, WUE_{seed} increased by 10% in 2003 (P <= 0.10) and by 31% in 2004 compared to the conventional furrow irrigation treatments. The larger difference in 2004 is expected due to the modifications in irrigation scheduling as detailed in the Materials and Methods section. There was no evidence of interaction between using alternate furrow irrigation and the level of water stress imposed on the WUE_{seed}. $WUE_{biomass}$ was unchanged in common bean by alternate furrow irrigation, and in green gram it was unchanged in 2003 and increased by 16% in 2004. WUE_{roots} increased in both crops when the strategy was used in combination with RDI.

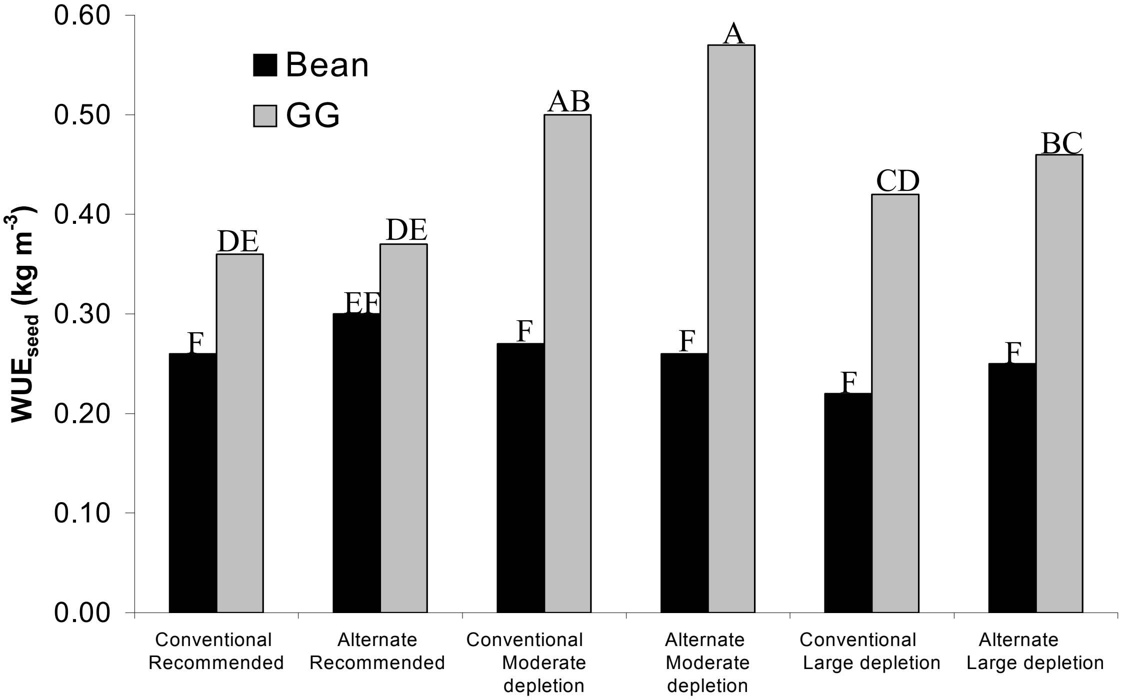

Figure 3.1. Commercial yield water use efficiency (WUE$_{seed}$) in 2003 for all treatments. Bar associations with the same letters are not different ($P \leq 0.05$) as determined using t-tests on least square means.

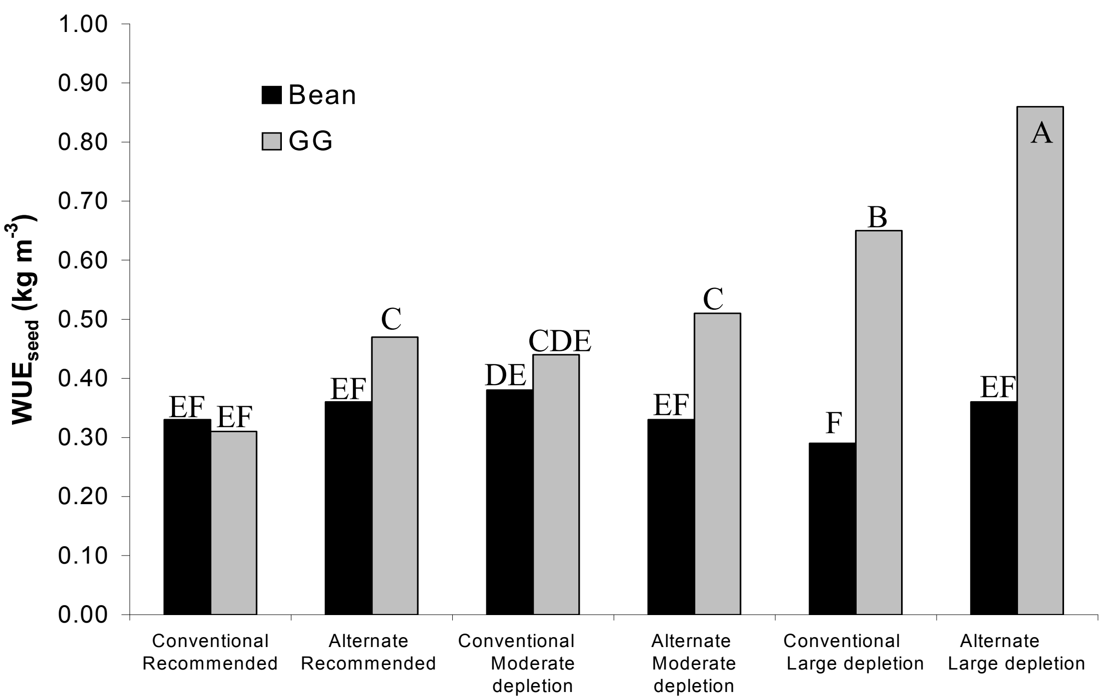

Figure 3.2. Commercial yield water use efficiency (WUE$_{seed}$) in 2004 for all treatments. Bar associations with the same letters are not different ($P \leq 0.05$) as determined using t-tests on least square means.

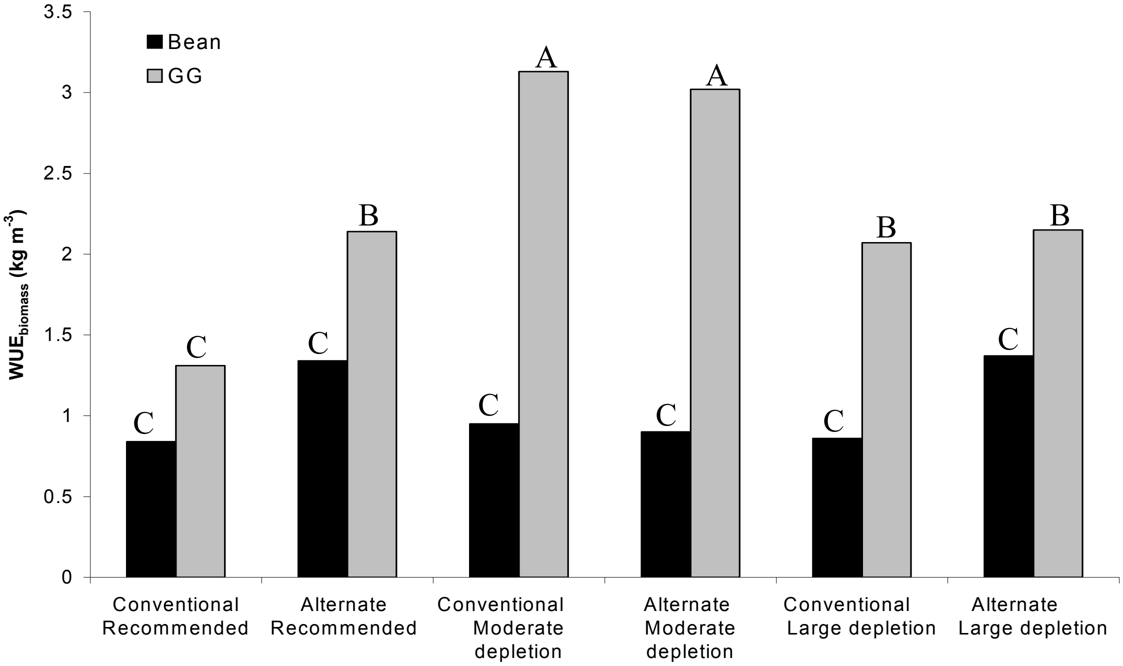

Figure 3.3. Total above ground biomass water use efficiency ($WUE_{biomass}$) in 2003 for all treatments. Bar associations with the same letters are not different ($P \leq 0.05$) as determined using t- tests on least square means.

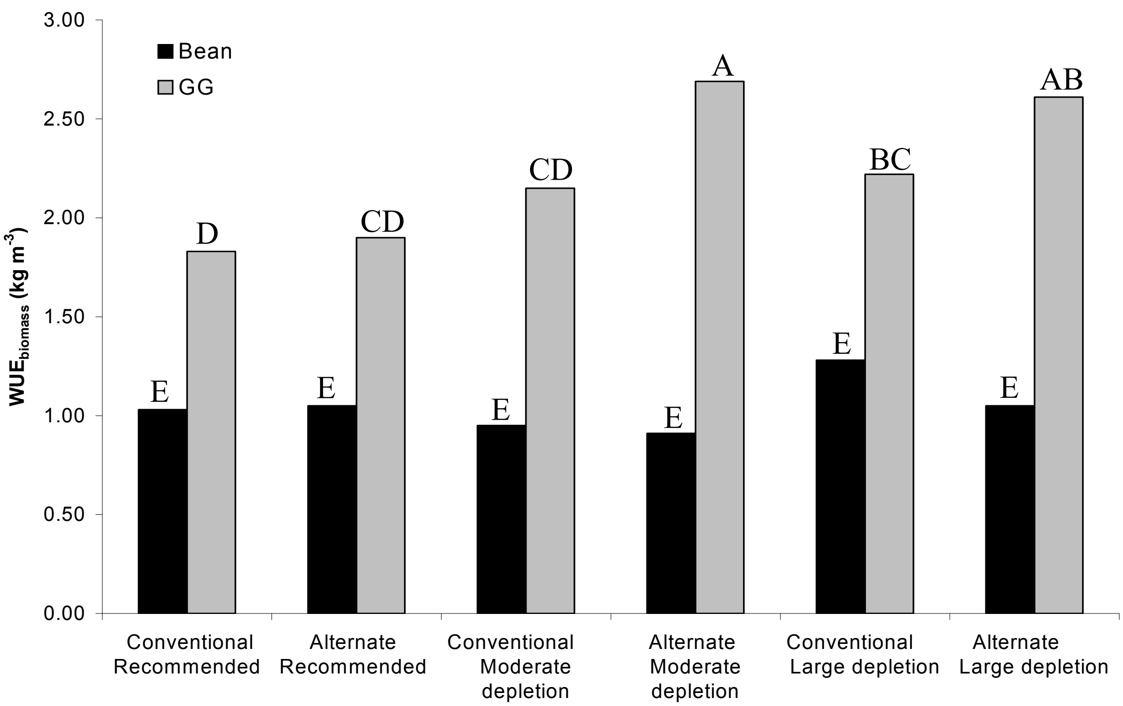

Figure 3.4. Total above ground biomass water use efficiency ($WUE_{biomass}$) in 2004 for all treatments. Bar associations with the same letters are not different ($P \leq 0.05$) as determined using t- tests on least square means.

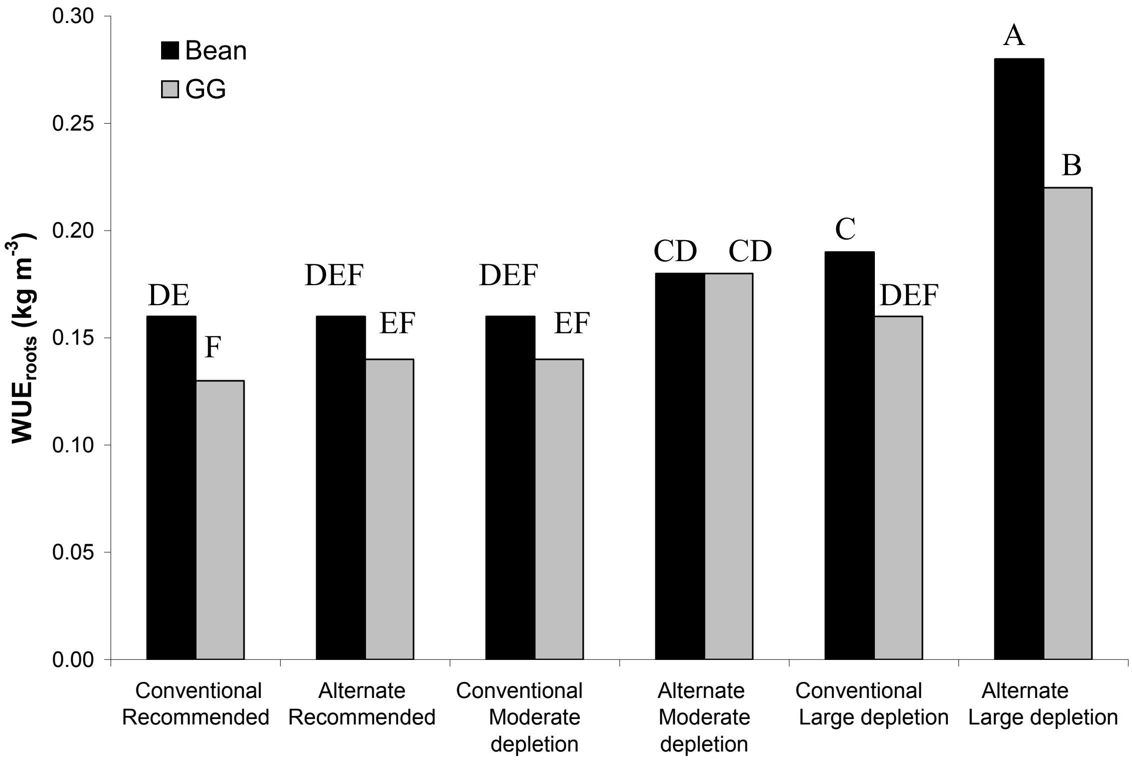

Figure 3.5. Root biomass water use efficiency (WUE_{roots}) in 2004 for all treatments. Bar associations with the same letters are not different ($P \leq 0.05$) as determined using t- tests on least square means.

3.3.3 Optimal irrigation schedule and irrigation water requirements

The volume of applied irrigation water given in Table 3.1 is the sum of the pre-irrigation, a small irrigation at the time of emergence and all subsequent irrigations. The climatic conditions were similar for both years, with little variation in reference crop evapotranspiration (ET_o) between years (Fig. 3.6). Rainfall amounted to only 17 and 5 mm in 2003 and 2004, respectively.

Alternate furrow irrigation produced water savings of 25% for both crops at all irrigation levels in 2004. In the first attempt, in 2003, to find an optimal irrigation schedule using alternate furrow irrigation, average soil moisture values from both the wet and dry furrows were used for irrigation scheduling in the alternate furrow plots. As a consequence of this, the soil moisture values were always drier in the alternate furrow treatments. As a result, the alternate furrow plots were irrigated more frequently and, in 2003, no consistent pattern of water saving was realized compared to the corresponding conventional furrow irrigated plots. It was decided that in extending the FAO-56 methodology for irrigation scheduling to alternate furrow irrigation systems, only the soil moisture in the wetted furrows should be considered to ensure water savings.

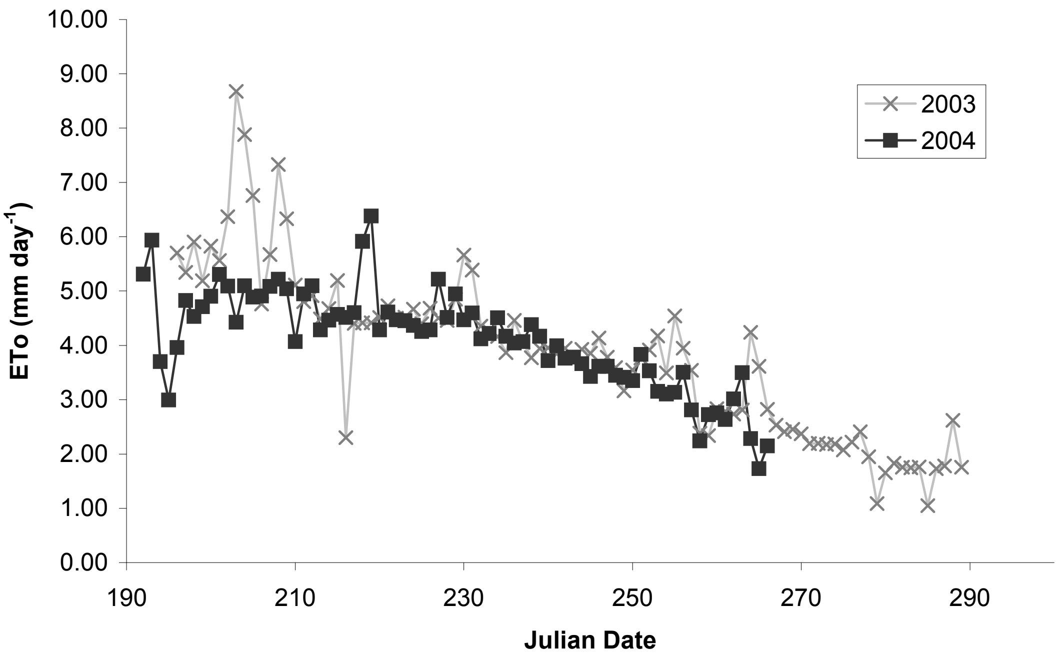

Figure 3.6. Comparison of the FAO Penman-Monteith reference crop evapotranspiration (ET_o) between years as determined at the experimental sites.

Based on the results of the two seasons of field work, it is possible to make irrigation recommendations to maximize the WUE_{seed} of green gram grown as a second crop in the Fergana Valley, and probably in a wider area of central Asia. Implementing RDI and irrigating in alternate furrows produced the highest WUE_{seed}, yield and the greatest seasonal water savings. In 2003, there was no groundwater contribution and the moderate depletion factor produced the highest WUE_{seed} with no yield losses. This involved a pre-seeding irrigation, a second small irrigation a few days after seedling emergence and two vegetative irrigations applied when the soil water depletion was 65%. In 2004, with a groundwater contribution (Table 3.1), the large depletion factor gave the highest WUE_{seed} and yields. This strategy included a pre-seeding irrigation, a second small irrigation at seedling emergence and one full irrigation when the soil water depletion reached 80%, coinciding with the time of flowering. Based on the findings for green gram's WUE and yield (Bourgault, 2008), it can be concluded that the FAO irrigation recommendations for this crop (Allen et al., 1998) led to over irrigation and reduced yields.

Based on the results of this experiment, no irrigation recommendations can be suggested to maximize WUE for common bean. As WUE was constant for all levels of water stress and alternate furrow irrigation, any reduction in water use resulted in a corresponding reduction in yield. In deciding on an irrigation schedule, farmers would need to weigh the relative cost of yield losses with water savings in choosing an appropriate soil water depletion factor.

The differences in WUE between the two crops when subjected to soil water deficits clearly indicate that the crops employ very different mechanisms in response to drought conditions and require different approaches for irrigation. When subjected to RDI at the large depletion level, the average irrigation requirement for green gram was reduced by 43% (2003) and 50% (2004) whereas the irrigation requirement for common bean was reduced by only 15% (2003) and 22% (2004). Green gram's physiological response makes it an excellent crop to irrigate with alternate furrow and deficit irrigation techniques, both to save water and increase WUE. When subjected to soil drying, it has a mechanism that enables it to reduce its water consumption while maintaining yields. Common bean's physiological response to drought does not lend itself to either of the two water saving technologies. Unlike green gram, which appears to closely regulate its water use, common bean did not reduce its irrigation requirement, but invested in root development. Common bean's strategy was not successful at improving its WUE_{seed} and any reduction in applied water resulted in yield reductions.

3.4 CONCLUSIONS

Both alternate furrow irrigation and deficit irrigation practices can reduce irrigation water requirements and increase water use efficiency, important considerations for arid and semi-arid climates. Consistent water savings, of close to 25%, are realised with alternate furrow irrigation over conventional furrow irrigation and, when used in combination with deficit irrigation scheduling, water savings can be as large as 50% with no yield reductions, as compared to the recommended irrigation volumes. However, this study indicated that the success of these technologies depends largely on the ability of the crop to withstand and/or adapt to water stress. Green gram's WUE was twice that of common bean. When less water was applied to green gram, WUE doubled as compared to the recommended irrigation amounts. On the other hand, the commercial seed and above ground biomass WUEs of common bean were constant for all combinations of deficit irrigation and alternate furrow irrigation, suggesting it is not as well adapted to water-scarce conditions.

3.5 ACKNOWLEDGEMENTS

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CONNECTING TEXT TO CHAPTER 4

The previous chapter identified alternate furrow and deficit irrigation as two irrigation strategies capable of increasing water use efficiency for legume crops grown as second crops in the Fergana Valley, Uzbekistan. However, of the two crops evaluated, green gram showed much greater potential to improve water use efficiency than common bean. This chapter investigates seasonal water use, patterns of water extraction and transpiration rates to describe and compare the differential responses of the two crops to water deficit imposed by these technologies. The results of this chapter will inform the modeling work in a following chapter and serve as guides in selecting crops with similar responses to water deficit.

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CHAPTER 4: PLANT - SOIL WATER DYNAMICS OF ALTERNATE FURROW AND REGULATED DEFICIT IRRIGATION FOR TWO LEGUME CROPS

ABSTRACT

Water scarcity and severe environmental degradation are causing water managers in Central Asia to reevaluate irrigation water use. In this area, the goal of any intervention must include water conservation without reducing crop productivity. The objective of this study was to evaluate the impact of two irrigation technologies, regulated deficit irrigation and alternate furrow irrigation, on components of the plant-soil water system for common bean and green gram. The use of both deficit irrigation and alternate furrow irrigation resulted in water savings and reduced crop evaporative consumption. The reduction was greater in green gram than common bean when both technologies were used. The pattern of water extraction from the soil profile, when under stress, was different between the crops. Severely stressed common bean extracted more water at 60 cm than non-stressed plants, whereas severely stressed green gram used less water at all depths. Transpiration rates were generally lower for green gram than for common bean and decreased in both crops as soil water deficit increased. However, when the soil water was returned to field capacity by irrigation, common bean's water use was higher than the non-stressed condition while green gram's transpiration rate only increased slightly from the before irrigation value. Collectively, these results indicate distinct crop-dependent responses to soil drying. Use of the FAO's water stress coefficient in predicting evapotranspiration under water limiting conditions appears to over predict water use for green gram and could lead to over-irrigation; considerable water savings are available for this crop.

Keywords: alternate furrow irrigation; regulated deficit irrigation; soil water balance; evapotranspiration; common bean (*Phaseolus vulgaris*); green gram (*Vigna radiata*)

4.1 INTRODUCTION

As in most arid and semi-arid regions, drought and water scarcity influence many aspects of life in Uzbekistan. Irrigation is required for almost all crop production, and agriculture forms the backbone of the country's economy. When Uzbekistan was a part of the Soviet Union, intensive land and infrastructure development during the 1960's resulted in the rapid doubling of its irrigated area and Uzbekistan gained the status of the world's 4th largest cotton producer, with 8 million acres of irrigated land. This same time period saw water withdrawals from the Syr Darya and Amu Darya rivers increase from 60.6 km^3 to 105.0 km^3 and the population of the five countries in the Aral Sea basin increase from 14.1 to 41.5 million (UN/SPECA, 2001). The result of this development was greatly reduced flows in the basin's rivers and the drying of the Aral Sea. This is considered one of the most serious anthropogenic environmental disasters in history. Since the early 1980's, when water withdrawals for irrigation left virtually no water for the Aral Sea, progress has been made to address the region's water scarcity (Micklin, 2000). However, the pressure on water resources is expected to increase as the population grows and water management is transferred to farmers in a state controlled system requiring them to produce cotton and wheat to gain access to water, other agricultural inputs and machinery. The improvement of on-farm irrigation systems and the introduction of low cost, water saving irrigation technologies are identified as key and attainable components for reducing agriculture's water demand (Horst et al., 2005). Furthermore, growing legumes as a second crop, after winter wheat, offers farmers a way to increase their income and improve both their food security and land productivity, while still fulfilling their commitment to produce cotton and wheat.

Regulated deficit irrigation (RDI) and alternate furrow irrigation (AFI) are two water saving technologies that are relatively inexpensive and easy to implement. Both strategies involve manipulating the soil water to induce the crop's inherent response to drought conditions, usually in order to improve their water use efficiency (Hsiao et al., 2007; Webber et al., 2006; Davies et al., 2002). In RDI, the soil water is allowed to be depleted beyond a threshold value at which the crop experiences water stress. Water savings generally result with the use of RDI and are attributed to reductions in stomatal conductance which occur as a result of the plant roots encountering drying soil. This is thought to be mediated by abscisic acid (ABA) and the alkalization of the xylem flow (Loveys et al., 2004; Wilkinson, 2004). While the stomata control both the rates of transpiration and CO_2 entry into the cell, some evidence suggests that, initially, the reduction in stomatal conductance is greater than the concurrent reduction in carbon assimilation. Whether this always results in increased WUE remains unclear as evidence exists to show that it can cause both increased and decreased WUE (Garside et al., 1992; Kang et al., 2000b; Lawn, 1982; Webber et al., 2006). Partial root drying (PRD), practiced as alternate furrow irrigation (AFI) in surface irrigation systems, is a variation of RDI that generally improves the WUE of crops (Davies et al., 2000; Wakrim et al., 2005). In many cases, the strategy circumvents the yield losses frequently associated with RDI, as in grape (Loveys et al., 2000), soybean (Graterol et al., 1993) and controlled environment and field grown maize (Kang et al., 1998; Kang et al., 2000a). PRD involves exposing part of the root system to drying soil while maintaining other sections in well watered soil, and is most effective when the two sections of roots are alternately exposed to wet and dry soil (Kang, 1998). The method is thought to operate in the same manner as RDI, with the benefit of keeping the plant well hydrated through roots still in moist soil.

In a previous study, it was demonstrated that the water use efficiency of green gram could increase substantially if water savings irrigation technologies were used whereas the water use efficiency of common was constant under all irrigation strategies (Webber et al., 2006). In this study, different aspects of water use were studied to distinguish the responses of these two crops. Particularly, root water extraction with depth in the soil profile and the plant transpiration rate were examined.

The methodology suggested in the (Allen et al., 1998) to compute the rate of evapotranspiration (ET_{actual}) when water conditions are limited, involves multiplying the maximum value of evapotranspiration, ET_{max}, achieved under optimal conditions by the water stress coefficient, k_s

$$ET_{actual} = k_s ET_{\max} . \qquad [1]$$

The water stress coefficient varies between 1, when the crop does not experience water stress, and 0, when the soil is at the permanent wilting point. In their model, a crop is expected to experience water stress when the actual root zone depletion of total available soil water, D_r, exceeds a threshold value, the readily available water, RAW. When the depletion exceeds the readily available water ($D_r > RAW$), k_s will decrease linearly from 1. In the case that the actual depletion has not yet exceeded the readily available water ($D_r > RAW$), $k_s = 1$ and the crop is not expected to experience water stress. This condition holds for crops that have previously experienced water stress and are subsequently irrigated, irrespective of the length or severity of the preceding soil water deficit. This method does not explicitly account for conditions of variable soil drying, as is the case of AFI.

In an attempt to contribute to the understanding of irrigated food crop production systems when water is limited, this study looks the water use response and extraction of two legume crops as affected by the use of RDI and AFI. The specific research objectives were: (1) to evaluate the effect of using regulated deficit and alternate furrow irrigation, alone or together, on patterns of water extraction from the soil profile, and (2) to assess the ability of the FAO Penman-Monteith equation to predict ET under water limiting conditions by comparing to the ET estimate obtained from the water balance.

4.2 MATERIALS AND METHODS

4.2.1 Experimental design, site description and cropping systems

A field experiment was conducted in the Fergana Valley of Uzbekistan (40°23´N, 71°45´E) during the summers of 2003 and 2004. A randomized complete block split-plot design, with four blocks was used where the treatments were comprised of factorial combinations of RDI level, as the main plot factor (recommended, moderate and large depletion factors), and furrow irrigation strategy (alternate furrow (AFI) and conventional furrow (CFI)) plus crop (common bean and green gram), comprised the sub-treatments. Each plot measured 15 m by 15 m and contained on average 23 furrows of 12 m length. The furrow spacing was 60 cm.

Adjacent fields were used in the two years in order to have the same cropping rotation in both experimental years. Cotton was grown in the year previous to the experiment, followed by a crop of winter wheat which was harvested early in the following summer. The legume crops were planted following winter wheat harvest. The soil textures in the rooting zones were similar in both years (Table 4.1). In 2003, the surface silt loam was 54 cm in depth and the available water content was 96 mm in the 60 cm rooting zone. In 2004, the thickness of the surface silt loam layer averaged 34 cm and the available water content in the rooting zone was 77 mm. Average groundwater depth was 2.2 m in 2003 and 1.5 m in 2004. In the field used in 2003, a coarse layer of soil at depths of greater than 1 m effectively prevented a groundwater contribution to the root zone.

Table 4.1. Soil physical and hydraulic properties in 2003 and 2004.

Year	Horizon	Field Capacity		Wilting point		Available water content		Bulk density	Porosity
	(cm)	(% vol)	(mm)	(% vol)	(mm)	(% vol)	(mm)	(g cm^{-3})	(% vol)
2003	**0-30**	31	94	13	38	18	56	1.1	59
	30-54	33	79	18	43	15	36	1.3	52
	54-65	35	39	19	21	16	18	1.1	58
	65-81	23	38	9	14	14	23	1.3	52
2004	**0 - 22**	29	64	17	37	12	26	1.2	53
	22 – 35	30	39	20	26	10	13	1.3	49
	35 – 50	22	33	10	15	12	18	1.2	53
	50 - 82	34	109	18	58	16	51	1.4	44

Local varieties of common bean (*Phaseolus vulgaris*) and green gram (*Vigna radiata*) were sown, following winter wheat, in mid-July. Local varieties were used as they are adapted to the conditions prevalent in the region. The same seed stock was used in both years. Cotton was grown on both fields in the year preceding the experiment, so that subsequent production of a legume constitutes a double cropping system. The fields were planted on July 13 in 2003 and July 11 in 2004. In 2003, local practices were followed for seeding resulting in planting densities of 70,000 and 105,000 plants/ha for green gram and common bean, respectively. In 2004, the plant density was increased to 333,000 plants/ha for both crops, to be comparable with densities found in similar studies (Haqqani and Pandey, 1994). While the changes in density between years is the weak point in the methodology, the water use between years should still be comparable, with the exception of the green gram treatment with the highest depletion level. The leaf area index between years was very similar (Bourgault, 2008) and the crop coefficients used in the FAO 56 methodology are largely a function of percentage ground cover (or leaf area). Further, yields between years were very similar, again with the exception of the driest green gram treatment (see Webber et al., 2006 from Bourgault, 2008) In the field, this was observed nearly complete ground cover in 2003. When the density was lower, individual plants were able to grow larger. Only in the driest green gram treatment was the ground cover judged as less than full. Pests and weeds were controlled as required.

4.2.2 Water balance

Daily water balances were used for subsequent irrigation scheduling. The approach used in this study for the water balances deviates from the water balances used in typical irrigation studies, much as the method of imposing water stress deviates substantially from that typical of controlled experiments in plant stress physiology. Rather, this study is attempting to chart a middle ground between these two approaches and integrate knowledge from both fields.

The root zone was treated as a constant at 60 cm throughout the growing season. Although, this is a simplification, it was assumed for two reasons. Firstly, the plant roots are continually growing into wet soil. Secondly, from a practical perspective, the irrigation application efficiencies associated with the small irrigation depths that would result from using a small root zone are prohibitively low.

A separate water balance was used for each of the twelve treatments to account for the amount of available water (relative to field capacity) in the crop root zone. Inputs considered were irrigation requirement (Irr_i), effective precipitation (P_i) and groundwater contribution (GWC_i), where i is the day index. Crop evapotranspiration ($ET_{c,i}$) was the only output considered, as the furrows were blocked at their lower ends, so there was no runoff water. Drainage and deep percolation were not considered, as only the irrigation requirement (and not the actual depth of water applied) was used in the balance. This practice of neglecting the deep percolation is not acceptable for water balance studies, but was implemented for this study, which had the objective of investigating the *crop response* to deficit irrigation and alternate furrow irrigation. The goal was to ensure all plants along the central 5 m of each 12 m long furrow received the full irrigation requirement. A study in an adjacent field on the same farm used a more typical water balance approach and furrows measuring 400 m in length to quantity irrigation efficiencies and savings in irrigation volumes of alternate furrow irrigation, overcoming the limitations of using microplots (Horst et al., 2005; Horst et al., 2007).

All variables for the water balance are expressed in mm as follows:

$$SW_{use,i} = SW_{use,i-1} + ET_{c,i} - Irr_i - P_i - GWC_i \qquad [2]$$

where $SW_{use,i}$ is the soil water use relative to field capacity on day i and $SW_{use,i-1}$ is the soil water use relative to field capacity on the previous day. To gauge the accuracy of the $ET_{c,i} = k_s ET_{max}$ estimates, and to adjust the water balances to reflect actual water consumption of the stressed crops, root zone soil moisture was monitored. Measured volumetric soil moisture ($SM_{\%vol,i}$) values were converted to $SW_{use,i}$ according to:

$$SW_{use,i} = \frac{\left(FC_{\%vol} - SM_{\%vol,i}\right)}{100} d_{rootzone} \qquad [3]$$

where $FC_{\%vol}$ is the soil moisture content at field capacity and $d_{rootzone}$ is the depth of the root zone (mm). The measured estimate of $SW_{use,i}$ was then substituted into the balance [2] replacing the value calculated in [3] each time soil moisture was measured.

Soil moisture values were determined, on average, every five days. Additionally, they were measured two days before and two days after irrigations events. Soil moisture was measured gravimetrically at 0, 10 and 20 cm depth and with a neutron probe at 40 and 60 cm. Ideally, soil moisture would have been measured to greater depths but, due to equipment limitations and the large number of samples, measurements were not taken below 60 cm. However, to test this assumption, soil moisture was monitored to 100 cm depth in the four plots of the green gram moderate depletion treatment. No variations in soil moisture, greater than the regular measurement error, were noted in these plots. In 2003, measurements were taken in triplicate mid-length along one furrow in the conventional furrow treatment plots and in 2 furrows in the alternate furrow treatments. The 0 cm mark was taken half way between the furrow bottom and bed top, at the level plants were seeded. In the alternate furrow treatments, one sample was taken from a furrow that had been irrigated and the other from a furrow that had not been irrigated in the previous round of water application. In 2004, the number of spatial samples was doubled to address the variability in soil properties (two samples from conventional furrow treatments and four samples from the alternate furrow treatments), but the number of replicates was reduced to two due to oven space limitations.

Precipitation was measured with a Vantage Pro Meteorological Station (Davis Instruments Corp., Hayward, USA) located in a neighboring field. Effective precipitation was taken as 75% of the actual rainfall (Allen et al., 1998).

To estimate the daily groundwater contribution (GWC_i) the following empirical model was used (Ayars et al., 2006):

$$GWC_i = \frac{a}{e^{b(Z_R/Z_{\max})}\left(1+e^{C/(x+0.01)}\right)} ET_{c,i} \qquad [4]$$

where a, b, c are regression coefficients, Z_{max} is the depth of the groundwater table would beto result in a GWC of less than 1 mm day^{-1} (m), Z_R (m) is given by:

$$Z_R = \left| d_{GWT} - \frac{1}{3} d_{rootzone} \right| \qquad [5]$$

and x is the relative water deficit defined in terms of $SM_{\%vol}$, and the volumetric soil moisture at saturation ($SAT_{\%vol}$) and permanent wilting point ($PWP_{\%vol}$):

$$x = \frac{SAT_{\%vol} - SM_{\%vol}}{SAT_{\%vol} - PWP_{\%vol}} \qquad [6]$$

The regression coefficients are reported as a = 3.9, b = 3.8 and c = 0.5 (Wu et al., 1999). Z_{max} (m) is a function of soil type. Both the groundwater table depth (d_{GWT}) and $d_{rootzone}$ in [5] are expressed in m. The groundwater table depth was measured every three days at three (2003) and five (2004) locations across the field. To calibrate Z_{max} for this set of data, the water balances for the recommended irrigation schedules of common bean and green gram were used. The non-stressed $ET_{c,i}$, estimated using the FAO Penman–Monteith equation, was assumed accurate for fitting the GWC_i to the measured soil moisture values.

ET_c was calculated as the product of the FAO Penman-Monteith reference equation for reference crop ET (ET_o) and crop and stress coefficients, as appropriate (Allen et al*.,* 1998). The climate data used to determine ET_o included minimum and maximum daily temperatures (T_{min} and T_{max}), minimum and maximum daily relative humidity (RH_{min} and RH_{max}), wind speed measured 2 m above ground (u_2) and sunshine hours (N). With the exception of N, all weather observations were measured with a Vantage Pro Meteorological Station (Davis Instruments Corp., Hayward, USA) located in a neighboring field. Sunshine hours were obtained from a neighbouring weather station located approximately 20 km from the field. The climatic conditions were very similar between years as demonstrated in a plot of daily ET in Webber et al. (2006).

4.2.3 Irrigation scheduling

To prepare the seedbed and bring the soil water to field capacity, a pre-irrigation of approximately 56 mm (net) was applied to every furrow in every plot, 2 days before seeding. Note that the exact amount applied was a function of the soil moisture at the time of harvest of the preceding wheat crop. Following seeding, at the time of emergence, a second irrigation of 42 mm (net) was applied, also to every furrow, to encourage a full and even plant stand.

All subsequent irrigation scheduling was based on the average soil water content in each treatment. For a given treatment j, an irrigation was applied when $SW_{use,i,j}$ equaled that treatment's maximum depletion of the available soil water (MD_j) was reached or exceeded:

$$MD_j = \left(p_j + 0.04ET_{c,i}\right)\left[\frac{FC_{\%vol} - PWP_{\%vol}}{100} d_{rootzone}\right] \quad [7]$$

where p_j is the nominal depletion factor for the treatment shown in Table 4.2. This is the methodology recommended in Allen et al. (1998).

Table 4.2. Depletion factor, representing the proportion of the available soil water that is depleted before irrigation water is applied

Irrigation schedule	Crop	Depletion factor
Recommended	Common bean	0.45
	Green gram	0.45
Moderate deficit	Common bean	0.60
	Green gram	0.65
Severe deficit	Common bean	0.70
	Green gram	0.80

In 2003 this methodology was used for all twelve treatments, resulting in twelve irrigation schedules. As a result, some of the alternate furrow irrigation treatments received an extra irrigation because these treatments reached the specified depletion more quickly, having received less irrigation water. In 2004, the methodology was changed to ensure significant savings in applied water for the alternate furrow irrigation treatments, to allow the crop response to reduced water application to be evaluated. The number of irrigation schedules was reduced to six; alternate furrow treatments were irrigated on the same day as the corresponding conventional furrow treatment, applying only 75% of the water. The 25% reduction is based on an estimate of the percentage of volume under the dry furrow that does not contain a significant number of plant roots.

4.2.4 Irrigation Applications

Irrigation volumes to be applied were determined by dividing the irrigation requirement from the water balances by an irrigation efficiency of 70%. This value was later shown to be a conservative estimate of the irrigation efficiency (data not shown) but was used to ensure a high distribution uniformity so that all of the plants received the full irrigation requirement, to accurately access the stress associated with each depletion level. Initial inflow rates were selected using the software package SIRMOD (ISED, 1989). The model uses a modified Kostiakov infiltration equation. The parameters of this model governing the initial water infiltration were determined with a ‘‘two-point’’ method (Walker and Skogerboe, 1987) using inputs of the advance times at the middle (6 m) of representative furrows and the end (12 m) of the same furrows. The parameter governing the steady infiltration rate, f_o, was determined from the inflow–outflow balance after the outflow rate was stable, following the methodology outlined in Horst et al. (2007).

The down-slope ends of each furrow, within each experimental plot, were blocked, so there was no outflow. Inflows to each plot were measured with small portable flumes. The water entered a distribution ditch at the top of each plot. From the distribution ditch, water was distributed by field staff as evenly as possible to each of the 23 to 24 (conventional furrow) or 11 to 12 (alternate furrow) furrows. Due to the variability of slopes between plots (land leveling is generally needed throughout the Fergana Valley), inflow rates were often adjusted to ensure that advance time across the plot was approximately equal to one half of the total irrigation time.

4.2.5 Transpiration measurements

Instantaneous transpiration rates were measured from ten plants per plots every two days before and two days after irrigation events using a LICOR-1600M diffusion porometer (Li-Cor, Lincoln, Nebraska USA) between 10:00 am and 4:00 pm.

4.2.6. Statistical analysis

The statistical significance of applied treatments was tested using the general linear model (GLM) of the Statistical Analysis System (SAS, Cary, N.C., U.S.A..). Differences between specific pairs of means were tested with a t-test. Unless otherwise specified, differences were only considered significant when they were detected at a probability of $P \leq 0.05$. Data were analyzed separately in 2003 and 2004 as the fields used in the respective years differed in groundwater contribution and the plant densities were also different between years.

4.3. RESULTS

4.3.1. Water balance components

The water balance components are summarized in Table 4.3. These values were used to calculate the crop consumptive use of water ($ET_{balance}$). The use of the deficit irrigation schedules resulted in fewer irrigation events for both crops, as compared to the recommended schedule.

In 2004, the water applied to the alternate furrow treatments was 75% of the water applied to the corresponding conventional furrow treatments leading to consistent savings in applied water. The same magnitude of savings in applied water was not realized in 2003 for reasons indicated above. However, the seasonal changes in soil water were lower in 2003 (Table 4.3) which enabled reductions in crop water use (results presented in the following section) and soil water storage for AFI.

Table 4.3. Number of irrigations, net irrigation water application, groundwater contribution, precipitation, and the change in soil water content for all levels of deficit irrigation (depletion levels) and alternate furrow (AFI) and conventional furrow (CFI) irrigation.

Year	Crop	Depletion factor	Number of irrigations*		Net irrigation application* (mm)		Ground water contribution (mm)		Rainfall (mm)		Change in soil water (mm)	
			CF	*AF*	*CF*	*AF*	*CF*	*AF*	*CF*	*AF*	*CF*	*AF*
2003	Common bean	0.45	4	5	176	177	0	0	17	17	39	27
		0.60	3	4	176	170	0	0	17	17	33	37
		0.70	3	3	179	129	0	0	17	17	34	30
	Green gram	0.45	5	5	210	171	0	0	17	17	10	17
		0.65	3	3	152	122	0	0	17	17	16	12
		0.80	2	2	96	93	0	0	17	17	34	38
2004	Common bean	0.45	6	6	169	132	19	20	5	5	28	34
		0.60	4	4	142	111	20	19	5	5	40	43
		0.70	3	3	120	95	23	20	5	5	43	39
	Green gram	0.45	6	6	206	159	19	20	5	5	38	39
		0.65	4	4	169	131	18	18	5	5	31	35
		0.80	2	2	78	63	20	20	5	5	58	45

*The net irrigation application depth and number of irrigations includes the irrigation at the time of seedling emergence (applied to every furrow for all treatments) and all subsequent irrigation events.

4.3.2 Crop consumptive water use: water balance

RDI reduced the crop consumptive water use ($ET_{balance}$). Averaged across both crops and irrigation strategies, use of the large depletion factor resulted in reductions in water use of 19% (2003) and 28% (2004) compared to the recommended irrigation schedule. However, RDI produced greater water savings for green gram than for common bean, as indicated by the crop by depletion factor interaction present in both years (Table 4.4). In green gram, the moderate depletion factor saved 20% (2003) and 16% (2004) of the water used and the large depletion factor 26% (2003) and 40% (2004), compared to the recommended irrigation schedule. Note that the water savings for the moderate and large depletion factor are not different in 2003, a point that will be discussed later in the paper. For common bean, the magnitude of water savings was much smaller. Use of the moderate depletion factor reduced water use by 6% in 2004 and not at all in 2003 while the large depletion factor used 14% (2003) and 10% (2004) less water than the recommended depletion factor.

Table 4.4. Evapotranspiration determined from the soil water balance ($ET_{balance}$) and estimated using FAO Penman – Monteith equation (ET_{FAO}) and the relative over prediction of ET_{FAO} (ET_{FAO}/ $ET_{balance}$) for common bean and green gram under various levels of regulated deficit irrigation.

		ET_{FAO} (mm)		**$ET_{balance}$ (mm)**		**ET_{FAO}/ $ET_{balance}$**	
Crop	**Depletion factor**	**2003**	**2004**	**2003**	**2004**	**2003**	**2004**
Common Bean	**Recommended**	257a	233a	239a	204b	1.07	1.15
	Moderate stress	228b	216c	244ab	192c	-1.07	1.13
	Severe stress	208c	206d	211c	175d	-1.01	1.19
Green Gram	**Recommended**	208c	233a	225bc	246a	-1.07	-1.04
	Moderate stress	191d	223b	180d	207b	1.07	1.19
	Severe stress	158e	164e	166d	147e	-1.05	1.18
Crop by depletion factor interaction significance		0.3457	<0.0001	0.0009	<0.0001		

Use of AFI as the irrigation strategy resulted in water savings of 9% (2003) and 15% (2004) compared to conventional furrow irrigation (Table 4.5). No interactions were observed between irrigation strategy and crop or RDI schedule in either year.

Table 4.5. Alternate furrow irrigation (AFI) as compared to conventional furrow irrigation (CFI) for ET_{FAO}, $ET_{balance}$ and soil water use at depth *i* (SW_i)

Parameter of interest	2003			2004		
	AFI	CFI	P value	AFI	CFI	P value
$ET_{balance}$ (mm)	201	221	0.0003	179	210	<0.0001
ET_{FAO} (mm)	207	209	0.4993	205	220	<0.0001
SW_{0cm} (mm)	52	73	<0.0001	50	70	<0.0001
SW_{10cm} (mm)	22	34	<0.0001	21	29	<0.0001
SW_{20cm} (mm)	18	31	<0.0001	16	21	0.0105
SW_{40cm} (mm)	20	23	0.0446	12	15	0.0002
SW_{60cm} (mm)	7	10	0.0361	9	13	0.0018

4.3.3. Crop consumptive water use: FAO Penman – Monteith estimate

Using the FAO Penman – Monteith estimate of evapotranspiration (ET_{FAO}), RDI schedules were predicted to produce water savings. Implementation of the large depletion factor resulted in a 21% reduction, over the recommended irrigation schedule, in water use in both years.

The FAO Penman – Monteith equation predicted the larger water savings for green gram than common bean with RDI (Table 4.4). However, this crop by depletion was only significant in 2004 (p values of 0.3457 and <0.0001 in 2003 and 2004, respectively), when reductions in water consumption with the large depletion factor were 30% in green gram compared to only 12% in common bean, relative to the recommended depletion factor.

For the irrigation strategy, the FAO Penman – Monteith estimate of ET correctly predicted water savings for AFI in 2004 when reductions in water use were estimated as 7% less than those irrigated with CFI (Table 4.5). The reduced crop consumption in 2003, albeit smaller than 2004, was not captured by the FAO Penman – Monteith equation.

4.3.4. Distribution of water use in the soil profile

By design, the soil moisture previous to each irrigation event was lower with RDI. The distribution of soil water use as affected by RDI is evaluated by investigating seasonal soil water changes. Different irrigation schedules resulted in different dates and numbers of irrigation events, making a comparison between individual events problematic. The profile of the soil water extraction was highly biased to the soil surface (0 cm) for both crops, though to a greater extent for common bean, due to soil evaporation (Table 4.6). Water extraction decreased with increasing depth in the profile.

Averaged across both crops and irrigation strategies, RDI produced water savings in the 0 – 40 cm depth of the soil profile, with the exception of the 20 cm depth in 2004 (Table 4.6). At 60 cm, no water savings were associated with RDI. Deeper in the soil profile, the response of the two crops varied with increasing stress under RDI. While a strong crop by depletion interaction only occurred in 2004, the same trend is evident in the 2003 data. Water use by common bean at 0 through 40 cm was greatest at the recommended and moderate stress irrigation levels. At these depths, water use with the large depletion was reduced, though this was often not sufficient to allow statistical significance. At 60 cm, the situation was reversed; common bean treatments with RDI consumed more water than the recommended level. In 2004, the large depletion used more water and in 2003 the moderate depletion level consumed the most water. Green gram did not respond similarly. The severe stress irrigation level used less water at depths 0 to 60 cm (excepting 20 cm depth where all treatments consumed the same quantity of water). At the 60 cm depth, where common bean consumed most water with RDI, green gram had reduced (2004) or equivalent (2003) use.

In AFI treatments, the average soil moistures were lower than the corresponding CFI treatments, as only one of every two furrows received water in an alternate furrow irrigation event. In 2003, the AFI plots reached the set depletion more quickly and were irrigated more often than the corresponding CFI treatment (Table 4.3). The method was modified slightly in 2004; AFI plots were irrigated on the same schedule as their corresponding CFI treatment, to ensure water savings, and equal number and timing of irrigations. For the seasonal water use, AFI produced significant water savings at all depths in the soil profile averaged over both crops (Table 4.5). While the crop

Table 4.6. Seasonal soil water use of common bean and green gram under various levels of regulated deficit irrigation

Year	Crop	Depletion factor	Seasonal soil water extraction (mm)				
			0 cm	10 cm	20 cm	40 cm	60 cm
2003	**Common Bean**	**Recommended**	69b	37a	25ab	27a	8bc
		Moderate stress	81a	34a	31a	25ab	13a
		Severe stress	64bc	26b	23b	21bc	10ab
	Green Gram	**Recommended**	72ab	28b	23b	22b	5c
		Moderate stress	55c	25b	23b	18bc	6bc
		Severe stress	33d	18c	18b	17c	8bc
		Interaction significance	0.0001	0.8619	0.4547	0.5441	0.2794
2004	**Common Bean**	**Recommended**	74a	27ab	19ab	16a	8c
		Moderate stress	69a	29a	23a	12b	9bc
		Severe stress	57b	23bc	18ab	12b	12ab
	Green Gram	**Recommended**	59b	29a	18ab	17a	13a
		Moderate stress	61b	24b	17ab	16a	11abc
		Severe stress	41c	18c	16b	11b	10abc
		Interaction significance	0.1853	0.0870	0.4094	0.0065	0.0416

Table 4.7. Seasonal soil water use of common bean and green gram for conventional furrow (CFI) and alternate furrow (AFI) irrigations strategies

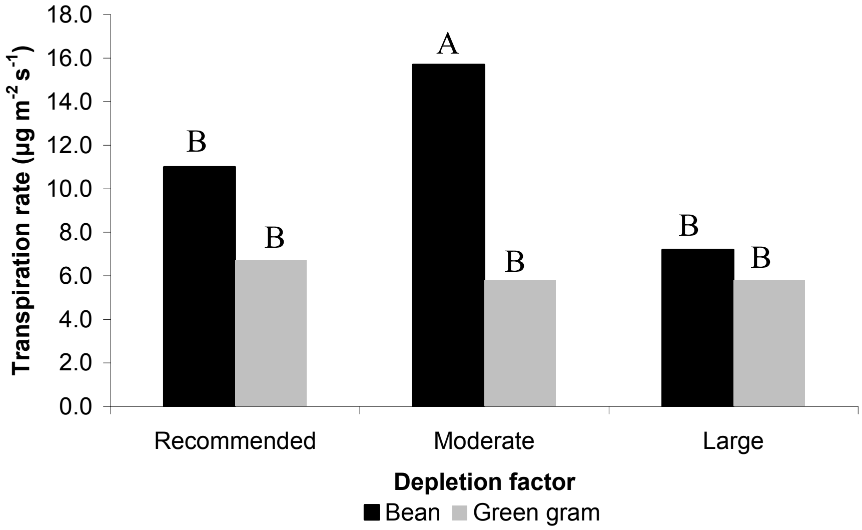
			Seasonal soil water extraction (mm)				
Year	**Crop**	**Irrigation strategy**	**0 cm**	**10 cm**	**20 cm**	**40 cm**	**60 cm**
2003	**Common Bean**	**CFI**	78.8a	36.1a	31.9a	23.7a	12.0a
		AFI	64.3b	28.5b	21.1b	24.1a	9.2a
	Green Gram	**CFI**	67.3b	31.2b	29.3a	21.4a	8.0b
		AFI	40.1c	16.4c	13.9c	15.9b	5.0b
	Interaction significance		0.0452	0.0254	0.3197	0.0214	0.9471
2004	**Common Bean**	**CFI**	75.9a	29.4a	20.0a	13.6b	9.8b
		AFI	56.8c	23.3b	19.8a	12.4b	10.0b
	Green Gram	**CFI**	64.2b	28.8a	22.2a	16.4a	15.4a
		AFI	42.7d	18.5c	12.2b	12.2b	7.3b
	Interaction significance		0.5557	0.1913	0.0140	0.0244	0.0013

by strategy interaction was not significant in all cases, the relative reduction in water use with AFI was at least 1.5 times greater for green gram than common bean for all depths in the profile (Table 4.7).

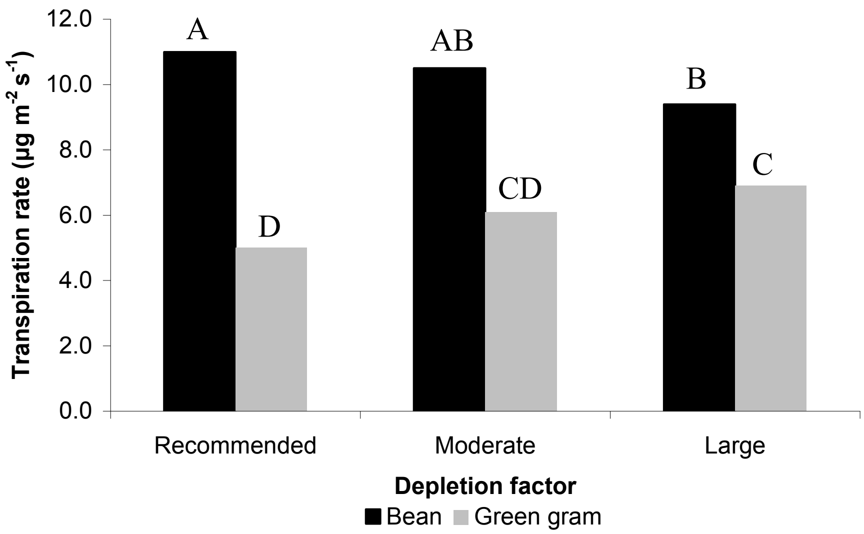
4.3.5. Transpiration rate

Prior to the irrigation at the time of flowering, transpiration rates were higher in common bean than green gram when averaged across all treatment levels (Fig 4.1). The crops responded differently to increasing levels of RDI, as indicated by crop by depletion factor interactions. With increasing levels of water stress under RDI, common bean reduced its transpiration rate in 2004. However, in 2003 the highest rate of transpiration occurred with the moderate depletion factor. Green gram exhibited the opposite behaviour; transpiration remained unchanged (2003) or slightly increased (2004) with the use of RDI. For the irrigation strategies, AFI did not reduce transpiration rates. In 2003 transpiration was the same for AFI and CFI at 8.6 μg m^{-2} s^{-1} (p value of 0.53). In 2004, AFI plots had an average transpiration rate of 8.8 μg m^{-2} s^{-1}, slightly higher than the conventional furrow plots at 7.5 μg m^{-2} s^{-1} ($p = 0.0040$).

After the flowering irrigation, the transpiration rate was still higher in common bean than green gram, when averaged across all treatment levels (Fig 4.2). The effect of RDI on the transpiration rate of common bean seems to be to allow common bean to increase its transpiration rate considerably and transpire at a rate equal to (2003) or greater than (2004) the unstressed treatments. For green gram, the picture was not as consistent across years. In 2003, irrigation caused the plots with the large depletion factor to increase their rate of transpiration, while it stayed the same in 2004. In both years, the transpiration rate remained lower than or equal to that in the plots with the recommended depletion factor. The transpiration rate was slightly greater for the CFI treatment than the AFI treatment. In 2003, transpiration in AFI plots was 9.6 μg m^{-2} s^{-1} and 11.3 μg m^{-2} s^{-1} in CFI ($p = 0.0002$) with green gram having greater reductions in transpiration than common bean (data not shown). In 2004 the rate was 11.3 μg m^{-2} s^{-1} for both AFI and CFI and the crop by depletion interaction present in 2003 was highly non - significant.



(a) 2003

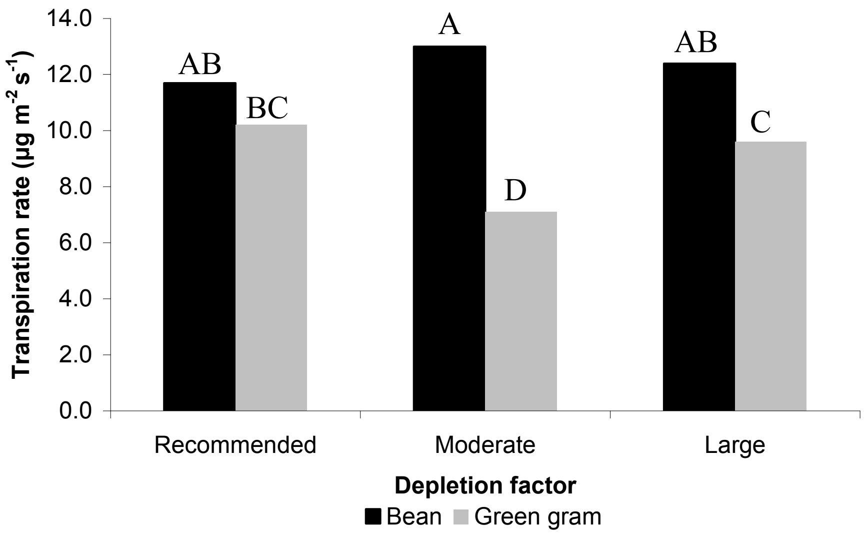


(b) 2004

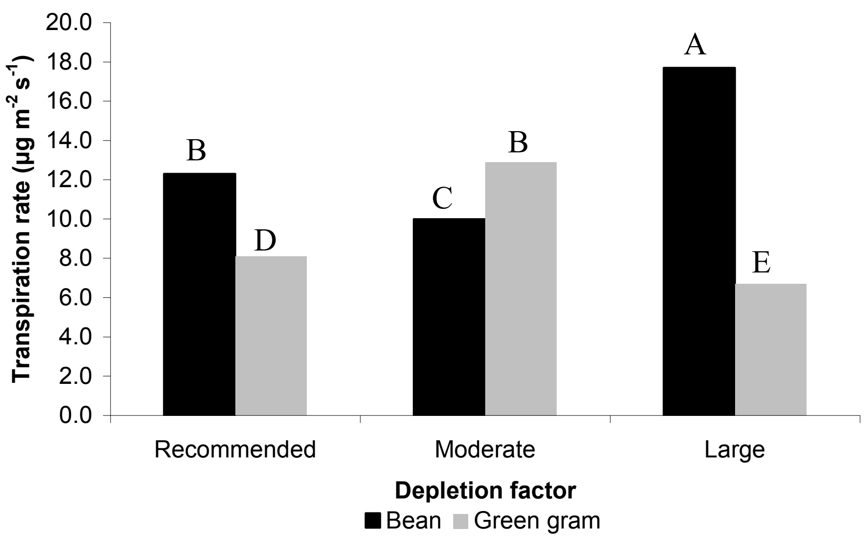
Figure 4.1. Transpiration rate measured two days before the flowering stage irrigation in (a) 2003 and (b) 2004. Bars associations with the same letters are not different ($P \leq 0.05$) as determined using t- tests based on least square means.

4.4 DISCUSSION

Both RDI and AFI reduced the crop consumptive water use for both crops. Green gram has shown greater potential to reduce its water use and maintain yield levels (Bourgault, 2008) and increase water use efficiency (Webber et al., 2006), making it an excellent candidate for irrigation with either of these technologies.



(a) 2003



(b) 2004

Figure 4.2. Transpiration rate measured two days after the flowering stage irrigation in (a) 2003 and (b) 2004. Bars associations with the same letters are not different ($P \leq 0.07$) as determined using t- tests based on least square means.

The responses of the two crops to both technologies show some important differences which may help explain their different degrees of water savings. Water stress due to implementation of RDI caused common bean to reduce its water use by

10% and 14%. This reduction in water use was observed as small reductions in soil water extraction at shallow depths in the profile and little regulation of transpiration. However, at 60 cm depth it caused the beans to extract more water than the unstressed control. To do so, it must use more of its carbon stores to produce roots, possibly at the expense of seed production. This hypothesis is supported by increased root biomass of common bean and decreased seed yields with RDI (Webber et al., 2006; Bourgault, 2008).

The response of green gram to RDI allowed much larger water savings when the technique was implemented. To explain this phenomenon with this field data it was necessary to disregard the large depletion factor in 2003. Factors such as seed placement and the irrigation timing for the large depletion factor resulted in a severely stressed crop, with a leaf area index (LAI) of less than one half that of the recommended and moderate depletion factor treatments (Bourgault, 2008). The unclosed canopy probably created a much greater vapour pressure deficit (VPD) than present at the either the recommended or moderate depletion levels, which would have caused higher transpiration rates independent of any treatment effects. Better early irrigation control and seed placement eliminated this severe reduction in LAI in 2004. Therefore, the proposed response for green gram to RDI is that it appears to reduce its water consumption by decreasing its rate of water extraction and transpiration, as reported by Lawn (1982). Though the severely stressed treatment received only one irrigation in 2004, the yield reductions reported in Lawn (1982) were possibly avoided as the irrigation was applied at flowering. Unlike common bean, which produced greater root biomass to extract more water deep in the profile, green gram root biomass decreased with RDI (Webber et al., 2006). Unlike common bean, after irrigation events the transpiration rate increase for green gram was small and did not reach the levels in the unstressed plants.

The effects of alternate furrow irrigation on water use also seem to depend on the crop, but to a lesser extent than RDI. While the magnitudes of seasonal water savings were greater in green gram than common bean, the difference was not statistically significant. However, examining the patterns of soil water extraction suggest that greater reductions in water use with this strategy exist for green gram. In neither year did common bean reduce water use at 60 cm depth in the profile when AFI was used. However, the increases in root biomass which were observed for common bean with RDI were not found for AFI. With this strategy, green gram had water savings at 60 cm depth in 2004, but not in 2003. The transpiration data collected in this experiment do not provide any useful insights into understanding the water savings achieved by the strategy.

The FAO Penman – Monteith equation was able to correctly predict water savings for both technologies. In 2004, it also correctly captured the larger water savings of green gram when RDI was implemented. However, no consistent pattern of over or under prediction is present in the relative errors of ET_{FAO} to $ET_{balance}$ between years (Table 4.4) and when analyzed statistically, their model was non – significant. However, examination of the relative errors raises some interesting points which are discussed below. Firstly, in 2003, the magnitudes of the relative errors were all less than 10%, quite random and averaging to approximately zero for both crops. However, there was a clear but small bias of over prediction in the case of AFI (data not presented). The random error is consistent with the fact that half as many soil moisture samples were taken in 2003 as in 2004. The calculation of both ET_{FAO} and $ET_{balance}$ are both very sensitive to the final soil moisture measurements, though they respond oppositely. For example, a high soil moisture measurement indicates little soil water use and a low value of $ET_{balance}$. The same high soil moisture measurement would lead to a high prediction of ET_{FAO} as the plant would not be considered to be experiencing water stress. Despite this sensitivity to soil moisture measurements, the FAO Penman – Monteith equation was able to correctly predict the 20% water savings for RDI, while not capturing the larger water savings for green gram than common bean. When the relative errors are examined for 2004 a different, and likely more accurate, picture emerges due to doubling the soil moisture samples. ET_{FAO} was larger than $ET_{balance}$ by approximately the same amount for all treatments of common bean, suggesting a systematic bias unrelated to treatment effects (perhaps low canopy coverage or nitrogen stress as no fixing nodules were found in any of the common bean treatments, commonly reported for common bean (Smith and Hume, 1985)). This constant over prediction suggests that common bean is responding to water stress much as the FAO Penman - Monteith model (Allen et al., 1998) predicts; a linear decrease in ET as the soil progresses from 45% depletion of the available soil water to the permanent wilting point. A different pattern was evident in green gram; the relative error increased with the higher levels of RDI (Table 4.4) and AFI (data not shown). The lack of a systematic error is consistent with the full canopy and apparent lack of nitrogen stress as the presence of some nodules was observed in green gram. The increasing over prediction of water use for green gram with water stress suggests this crop is not responding to drying soil as predicted by the FAO 56 methodology. Evidence for this hypothesis is found in the transpiration rates measured after irrigation applications. The model used in the FAO 56 methodology supposes that after irrigation, a previously stressed crop will transpire at the unstressed rate. This was observed for common bean and not for green gram.

4.5.1 CONCLUSIONS

This research indicates that significant water savings are possible with the adoption of on-farm water saving technologies for irrigation of legumes as a second crop after wheat harvest in the Fergana Valley of Uzbekistan. The benefits to the local population due to growing legumes as a second crop while using water saving irrigation techniques include a protein rich food, increased land productivity with minimal irrigation or fertilizer input (due to legume nitrogen fixation) and improved land fertility and organic matter if the residue is incorporated into the soil.

The results of this study indicate that both alternate furrow irrigation and deficit irrigation produce water savings by reducing the crop evapotranspiration. However, the degree to which water use was reduced and the mechanisms employed by common bean and green gram are different. When RDI was practiced, green gram reduced evapotranspiration by 26 (2003) and 40% (2004), whereas the reduction in common bean was only 14 (2003) and 10% (2004). With alternate furrow irrigation, the differences in water use between crops were much less pronounced; water savings for both crops averaged 9% in 2003 and 15% in 2004 and were constant across all irrigation schedules. With severe stress, green gram reduced soil water extraction at all depths in the profile, apparently through stomatal regulation. Common bean responded by increasing root biomass to extract more water from deeper in the profile.

The FAO Penman-Monteith equation was able to reasonably predict the water savings of both crops when either technology was implemented, though better for common bean than green gram. The discrepancy seems to lie in the method's assumption that following a period of stress, restoring the soil water through irrigation will cause the plant to transpire at its unstressed rate. This phenomenon was observed for common bean under the severely stressed treatment, where common bean transpired at a rate higher than the non-stressed treatment after receiving irrigation. Green gram continued to transpire at a reduced rate even after irrigation water was applied. When alternate furrow irrigation was practiced, the FAO method overestimated ET for both crops at all stress levels. Before the FAO water stress coefficient can be improved, it will be necessary to better quantify both the responses to irrigation of stressed plants and the effect of alternately maintaining different sections of the roots in drying soil.

4.6 ACKNOWLEDGEMENTS

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CONNECTING TEXT TO CHAPTER 5

In addition to the challenge of water shortage in the Fergana Valley, increasing soil salinity limits agricultural production. While rising water tables and soil salinity are problems in many irrigated areas, the gypsiferous soils of the Fergana Valley make transferring the accumulated knowledge on crop response to salinity difficult to the region. For the most part, salinity effects are less severe in soils containing gypsum, though the legumes studied Chapters 3 and 4 are very sensitive to salinity. This chapter presents the results of a greenhouse study investigating the growth response of common bean and green gram to increasing salinity in a gypsiferous soil. Also, the interaction between the use of deficit irrigation and level of soil salinity in a gypsiferous soil is investigated.

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CHAPTER 5: RESPONSE OF TWO LEGUME CROPS TO SOIL SALINITY IN GYPSIFEROUS SOILS

ABSTRACT

Competition for water resources, increasing land salinization and the need to feed a growing population are challenges facing irrigated agriculture in the Fergana Valley of Uzbekistan. Growing short season legumes with water saving irrigation technologies is one strategy for increasing food production and land productivity using relatively little water. However, little information is available to assess how these crops will respond when produced with deficit irrigation on the gypsiferous soils of the region. This greenhouse study evaluated various growth components of common bean and green gram irrigated with deficit irrigation in soils with and without gypsum and at three levels of soil salinity. Results showed that biomass and leaf area were decreased by approximately 20% for both crops, as EC_e increased from 2.8 dS m^{-1} to 7.5 dS m^{-1}. Yields were higher at all salinities for green gram than in common bean. However, relative yield reductions with increasing salinity were greater for green gram (43%) compared to common bean (19 – 31%). The presence of gypsum enabled both crops to maintain reasonable yield at EC_e values which would be lethal in soils dominated by other salts. The effect of increasing salinity was the same at all levels of deficit irrigation.

Keywords: soil salinity, gypsum, *Phaseolus vulgaris, Vigna radiata*, Fergana Valley of Uzbekistan

5.1 INTRODUCTION

Uzbekistan is one of the world's largest cotton producers and exporters. Together with wheat, cotton cultivation occupies the largest share of the land area under arable crops and uses the largest proportion of the county's surface water for irrigation. As the pressure of the region's scarce water resources increase, due to increases in population, growth in industry, land degradation and the growing recognition of the negative impacts of irrigation on the environment in the wake of the Aral Sea crisis, much attention has been given to farm level practices to save water. It was proposed that growing legumes as a second crop after winter wheat harvest as a means of increasing rural food security and improving land fertility (Webber et al., 2006). When grown with water saving irrigation technologies, these crops yield well and use little water.

To assess whether these or other food crops are appropriate, the crops' tolerance to soil salinity must be determined. Secondary soil salinization in the Fergana Valley is widespread and increasing as the water table rises to within 1 to 5 m of the soil surface, due to heavy leaching and old, poorly functioning drainage systems (EC-IFAS, 1999). Cotton and wheat are salt tolerant (Maas, 1985) and by the time these crops show symptoms of salt stress, the land will already be rendered too saline for cultivation of many other crops. However, compiled information of crop tolerance to salinity (Tanji and Kielen, 2002; Maas, 1985) is not easily transferable to the gypsiferous soils of the region (Szabolcs, 1989) because the salt tolerance is based on the electrical conductivity of the saturated soil paste extract (EC_e). The Ca^{2+} in soil solution in gypsum soils ($CaSO_4 \cdot H_2O$) increases its osmotic potential, reflected in higher EC_e while protecting the plant from the negative effects of sodium salinity.

The current theory on how non-halophytes respond to salinity is considered in two distinct phases and has been articulated in a number of papers (Greenway and Munns, 1980; Munns and Termaat, 1986; Munns et al., 2000). The first response is that of water stress, as leaf expansion rates are reduced long before ions accumulate to toxic levels in cells. Work by Hsiao et al. (1998) showed that this initial response is governed by changes in turgor when the plant water status is low, as happens when plants transpire at their maximum potential in the middle of the day. However, when water status did not limit growth, turgor maintenance did not prevent growth reduction due to salinity. Work by Munns et al. (2000) monitoring leaf expansion during the day and night corroborated this. Chemical signaling from the roots, in response to osmotic potentials, is thought to mediate the growth reduction of leaves when leaf water status is not limiting growth. Much recent work points to the key role of ABA produced in the roots in a series of complex interactions that constitute plant responses to low soil water potentials (Wilkinson and Davies, 2002). The second stage of the crop response to salinity is leaf death due to the accumulation of Na^+ and Cl^- to toxic levels in cytoplasm. Salts travel to the leaves in the xylem transpiration stream, with fully expanded leaves being most affected, as they have accumulated larger amounts of salts. If the rate of leaf death outpaces that of leaf growth and expansion, leaf area decreases and plant death ensues (Munns and Termaat, 1986).

What would the outcome be in soils dominated by calcium salts? The initial response is suspected to be lowered soil water potential would be similar as demonstrated by similar reduced growth rates with NaCl and other various osmotica (Yeo et al., 1991). However, calcium can moderate the effects of sodium salinity, reducing growth reductions (Maas and Grieve, 1987; Eaton, 1942). Calcium is required by the plant for root membrane integrity and proper function of ion transport systems (Lauchli and Epstein, 1970). Salinity inhibits Ca^{2+} uptake, such that many studies investigating NaCl salinity observe calcium deficiency symptoms when the Na^+/Ca^{2+} ratio is high (Greenway and Munns, 1980; Maas and Grieve, 1987) or with increasing NaCl levels (Lynch and Lauchli, 1985). As common bean is considered more drought sensitive than green gram (Webber et al., 2006) the growth of common bean is expected to be more affected than that of green gram, at least initially when osmotic effects dominate.

The objectives of this research were (i) to compare the relative growth response at the vegetative stage to increasing EC_e in soils with and without gypsum; (ii) to evaluate the growth, water use and yield formation with soil salinity on a gypsiferous soil; and (iii) to investigate interactions between regulated deficit irrigation and soil salinity. These objectives were tested on *Vigna radiata* (green gram, a drought adapted local crop (Webber et al., 2006)) and *Phaseolus vulgaris* (common bean, a crop introduced from the Americas and less drought adapted – Allen and Allen, 1981).

5.2 MATERIALS AND METHODS

The influence of salinity on crop development and water use by two legume crops grown in simulated gypsiferous soils was evaluated in two greenhouse experiments conducted at the Macdonald Campus, McGill University in Montreal, Quebec during the spring and summer of 2007. Uzbek varieties of common bean (*Phaseolus vulgaris*) and green gram *(Vigna radiata*) were used. The soil type was a Soulonge fine sandy loam (67% sand; 20% silt; and 13% clay). Chemical and physical properties of the soil are shown in Table 5.1. The greenhouse temperature was 32°C during the day and 20°C at night with the photoperiod set at 14 hours per day.

Table 5.1. Soil physical and chemical properties.

Ca	Mg	K	Na	Field Capacity	Wilting point	Available water content	Bulk density
	(mEq/100 g soil)			(% vol)	(% vol)	(mm m^{-1})	(g cm^{-3})
0.20	0.09	0.01	0.23	28	9	190	1.1

In the first experiment, the effects of growing plants in gypsiferous soils on vegetative growth were assessed for different levels of total soil salinity. The experimental layout was a randomized complete block (four blocks), split-plot design. The treatments were comprised of factorial combinations of three factors: crop (main-plot factor—common bean or green gram), with and without gypsum, and three sodium salinity levels (no NaCl, low NaCl and high NaCl). The combination of calcium salts and sodium salinity comprised the split-plot combinations. Plants were grown in 3 L containers and irrigated daily to maintain the soil water content near field capacity. Pest control was conducted as required. Plants were harvested approximately four weeks after planting. Dry leaf and stem biomass and leaf area were measured on all plants. Leaf water potential was measured on two samples per plant with the WP4-T water potential meter (Decagon Devices, Washington, U.S.A.).

Gypsum ($CaSO_4 \cdot 2H_2O$) was added to soil containers at a rate of 233 mEq per kg soil (or 20 g per kg soil). Three NaCl levels were used: no NaCl, low NaCl (8.6 mEq of NaCl added per kg of soil) and high NaCl (17.1 mEq of NaCl added per kg of soil). In soils without gypsum, the resulting EC_e values were 0.3 dS m^{-1} for the no NaCl level, 2.8 dS m^{-1} for the low NaCl level and 5.0 dS m^{-1} for the high NaCl level. In soils with gypsum, the resulting EC_e values were 2.8 dS m^{-1} for the no NaCl level, 5.4 dS m^{-1} for the low NaCl level and 7.5 dS m^{-1} for the high NaCl level.

In the second experiment, the effects of sodium salinity in soils dominated by gypsum salts were evaluated for a number of plant growth parameters. The experimental layout was a randomized complete block (four blocks), split-plot design (Fig. 5.1). The treatments were comprised of factorial combinations of three factors: crop (main-plot factor—common bean or green gram), salinity level (no NaCl, low NaCl and high NaCl) and three levels of deficit irrigation (recommended depletion, moderate depletion, large depletion). The combination of soil salinity and irrigation schedule comprised the split-plot combinations. Within a block and crop, containers were aligned to create a closed canopy. Plants were grown in 160 L containers (50 cm deep by 43 cm wide by 74 cm long). Each container was drained along its length by a piece of 5 mm diameter perforated drainage and was sloped towards the drain opening. Any drainage water was collected and reintroduced to the plant container to maintain a constant salt load.

Gypsum ($CaSO_4 \cdot 2H_2O$) was added to all soil containers at a rate of 233 mEq per kg soil (or 20 g per kg soil). The three NaCl levels were no NaCl, low NaCl (8.6 mEq of NaCl added per kg of soil) and high NaCl (17.1 mEq of NaCl added per kg of soil). This quantity of gypsum resulted in constant levels of dissolved gypsum at the range of soil water values between the permanent wilting point and field capacity, as would be encountered in gypsiferous soils. The combinations of NaCl and gypsum gave EC_e values of 2.8 dS m^{-1} for the no NaCl level, 5.4 dS m^{-1} for the low NaCl level and 7.5 dS m^{-1} for the high NaCl level. Salts were mixed into the soil with a small portable cement mixer. The capacity of the mixer was approximately half of the soil volume for one container, so the salts and soil were mixed in two equal batches.

Prior to planting, seeds were soaked in an innoculant at 10^8 cells per mL for 24 hours. Seeds were sown in two rows per soil container and at an initial plant density of 16 plants box^{-1}. Experiments were started on March 21, 2007 and June 27, 2007. Plants were staked as required. Pest control was carried out as needed.

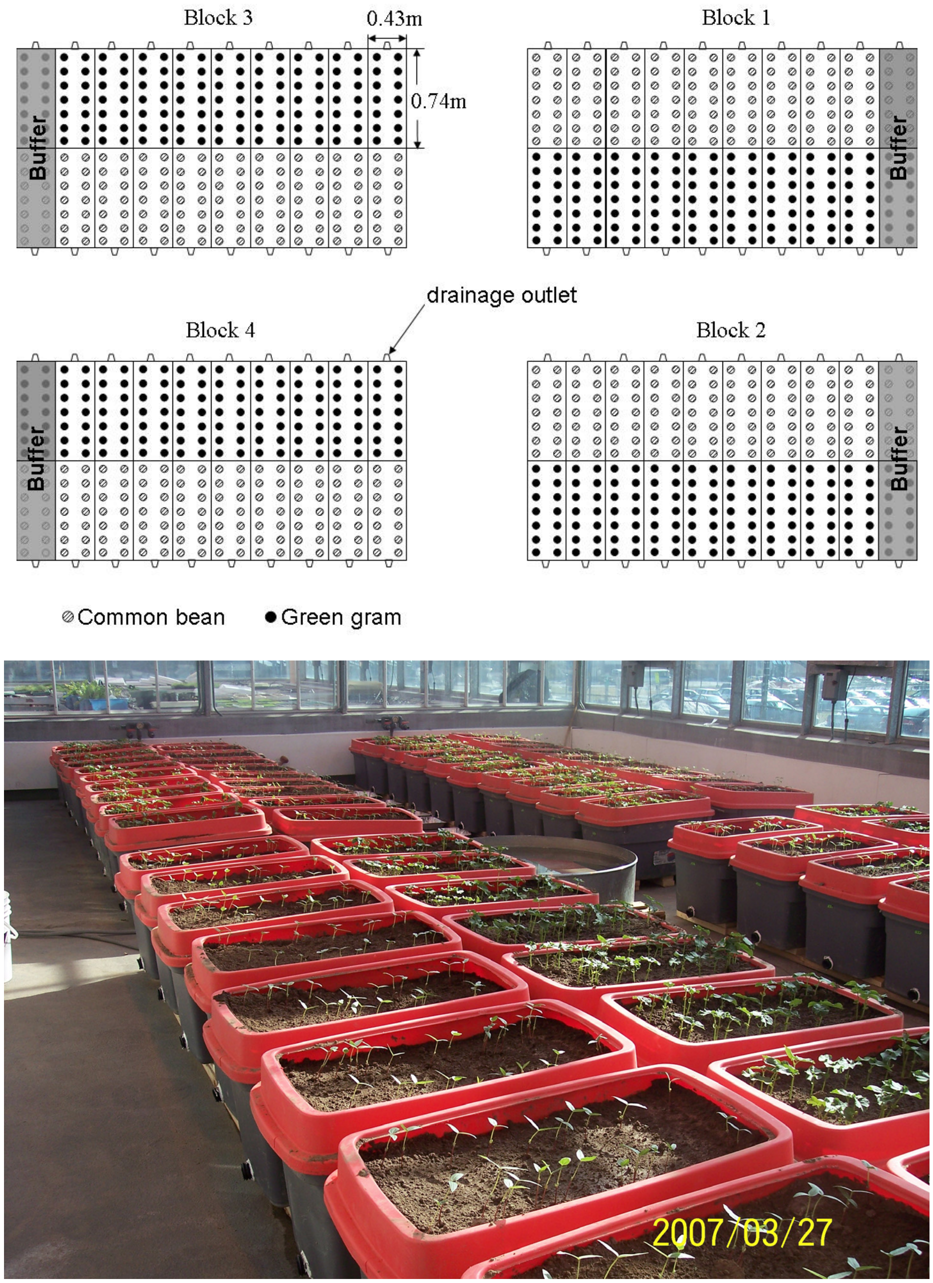


Figure 5.1. Schematic representation and photograph of the experimental layout for experiment 2.

Irrigation water was applied to the soil surface with a watering can. The soil was irrigated to field capacity before planting and a second very small irrigation (about 3 mm) was applied to the soil surface a few days after planting. All subsequent irrigation amounts and dates were determined using daily water balances in a methodology similar to that described by Webber et al. (2006). The three irrigation levels consisted of different depletions of the available soil water (ASW): recommended depletion (45% for both crops), moderate depletion (60% for common bean and 65% for green gram) and substantial depletion (70% for common bean and 80% for green gram). The soil water depletion was determined by gravimetric soil moisture measurements in each container. Measurements were taken in each box at depths of 5, 20 and 40 cm, at least every day before irrigation. Irrigations were sufficient to bring the soil water back to field capacity (0% depletion).

Plant biomass and leaf area index were measured on two randomly selected plants per plot four times at approximately the vegetative, flowering, pod-filling and harvest stages. Final yield was measured by harvesting all dry pods from all plants in the plot 70 days after planting (dap) and 76 dap for common bean and 76 dap and 91 dap for green gram for experiments one and two, respectively. Leaf water potential was measured with a WP4-T water potential meter (Decagon Devices, Washington, U.S.A.) for the central leaflet of two randomly selected trifoliates per plot. In the first experiment, all treatments were assessed on the same day to eliminate any effects of ambient radiation, at both the vegetative and flowering stages. In the second experiment, leaf water potential was measured pre-dawn one to two days after the irrigation at the flowering stage and again one day before the next irrigation. The measurement was made pre-dawn to eliminate any effects of ambient radiation. Stomatal conductance and photosynthetic rate were measured with a LICOR LI-6400 porometer on the central leaflet of two randomly selected fully developed trifoliates per plot. This measurement was made one day before and one to two days after the irrigation event nearest the flowering stage.

Statistical significance for detection of differences between treatments was determined using the general linear model (GLM) procedure of the Statistical Analysis System (SAS, Cary, NC, U.S.A.). Differences between specific least-square means were determined using a t-test at $P \leq 0.05$, unless otherwise stated.

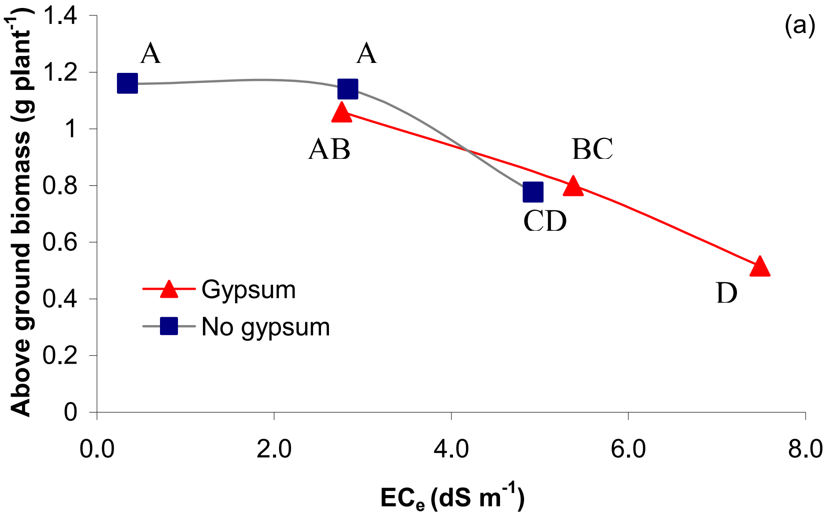
5.3 RESULTS

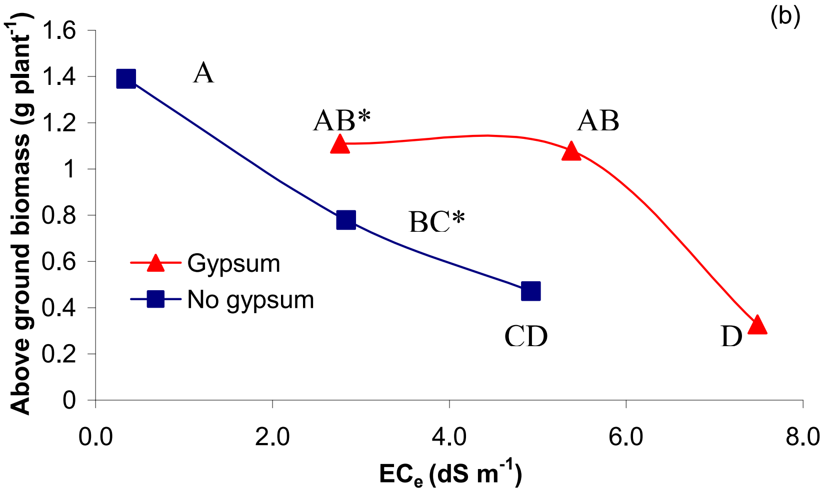
Addition of NaCl to the soil reduced above ground biomass for both crops, though a greater reduction was measured for green gram. Gypsum reduced biomass in common bean and had no effect on green gram's biomass. Neither crop had a salt (NaCl) by gypsum interaction. Common bean biomass decreased as a function of increasing EC_e irrespective of salinity, due to a combination of NaCl and gypsum or NaCl alone (Fig. 5.2). However, green gram biomass was not reduced to the same level in soil containing gypsum as it was in soil without gypsum, as EC_e increased. At an EC_e of 2.8 dSm^{-1}, biomass in the soil with only NaCl was 28% ($p = 0.12$) lower than in the soil containing gypsum, and at an EC_e of 4.9 to 5.4 dS m^{-1} biomass was 56% lower in the soil with only NaCl than in the soil containing both NaCl and gypsum.

Leaf area decreased for both crops with higher levels of NaCl (Fig 5.3). Gypsum reduced leaf area in common bean, but not in green gram. Leaf area for common bean decreased with increasing EC_e with and without gypsum. However, for green gram leaf areas were 29 to 32% higher at a particular EC_e when the soil contained gypsum though without strong statistical significance.

Specific leaf areas are not presented here. For common bean, no consistent pattern was observed as the SLA response varied between the two trials. In green gram SLA was constant for all combinations of salinity.

Leaf number per plant decreased for both crops with increasing levels of NaCl (Fig. 5.4.). The reduction was larger for common bean and occurred at all levels of NaCl. Reduction in leaf number occurred for green gram only at the highest salinity. Leaf number was reduced as a function of EC_e in common bean, whether the soil contained gypsum salts or not. For green gram, soil salinities dominated by gypsum salts did not cause the same reduction in leaf number as soil salinity dominated by sodium chloride at high salinities.

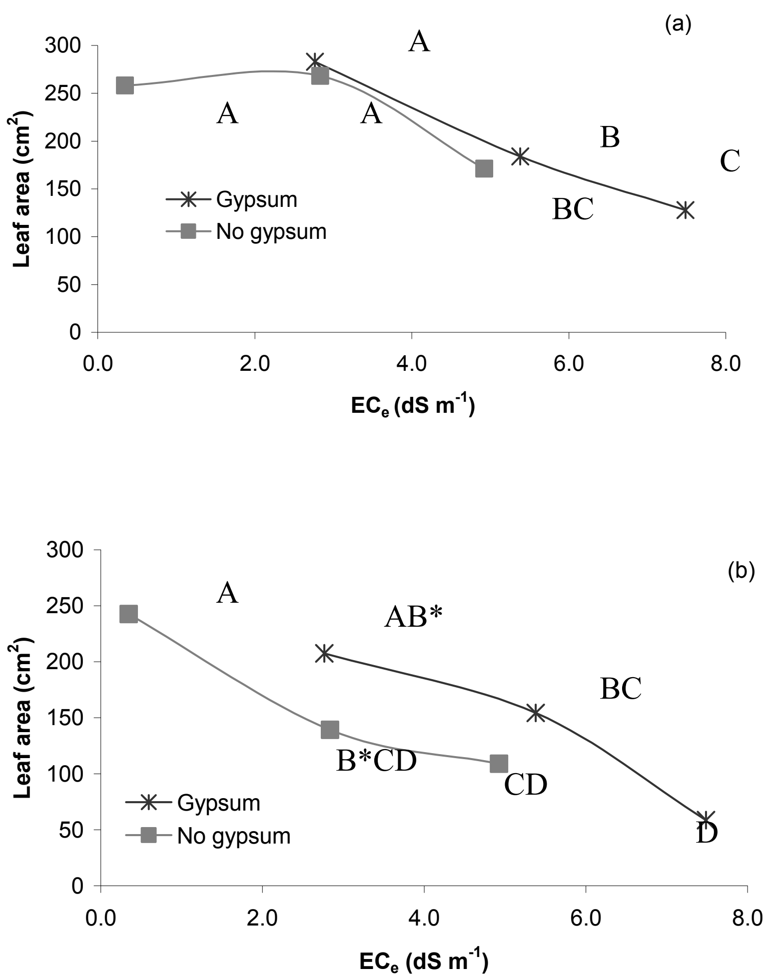




*Statistically different at p = 0.129

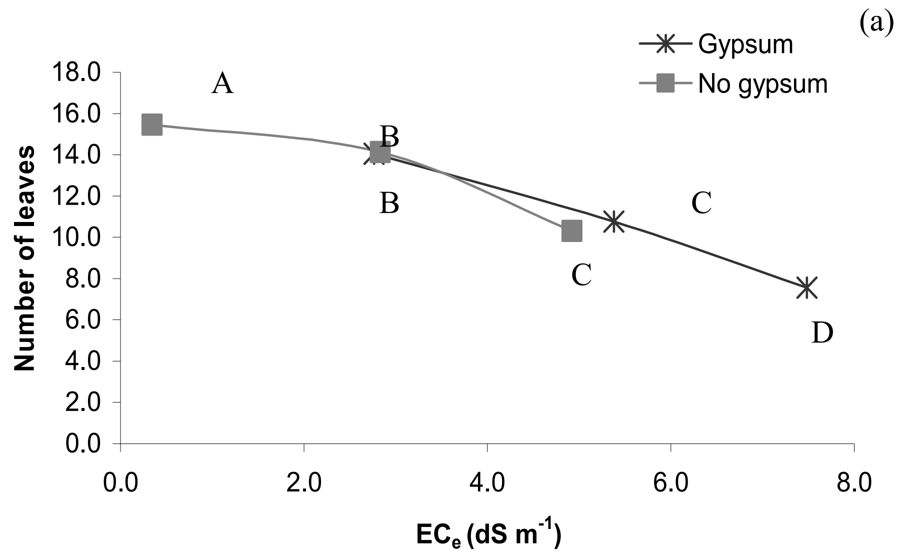
Figure 5.2. Above ground biomass measured at the vegetative stage as a function of increasing EC_e, for (a) common bean and (b) green gram. Data points associated with the same letters are not different ($P \leq 0.05$) as determined using t-tests based on least square means.

Results from the second experiment showing biomass and leaf areas as affected by salt treatment at four stages in crop growth are given in Table 5.2. At the vegetative stage salt reduced growth more for green gram than for common bean. In green gram a reduction in total biomass of between 27 and 31% was noted at the highest level of salinity compared to the control. Likewise, leaf area was reduced by 27 to 30%. In common bean the reduction in biomass was 11 to 16% at the highest soil salinity, though only statistically significant in the second trial. Likewise, at this stage, common bean's leaf area was hardly affected by salt level. Salinity reduced leaf area by 10 to 23%, (again only significant in the second trial) at the highest level of salinity. In neither crop was the reduction in biomass or leaf area due to salt influenced by the level of deficit irrigation.



*these two treatments were statistically different at p = 0.113

Figure 5.3. Leaf area measured at the vegetative stage as a function of increasing EC_e, for (a) common bean and (b) green gram. Data points associated with the same letters are not different ($P \leq 0.05$) as determined using t-tests based on least square means.



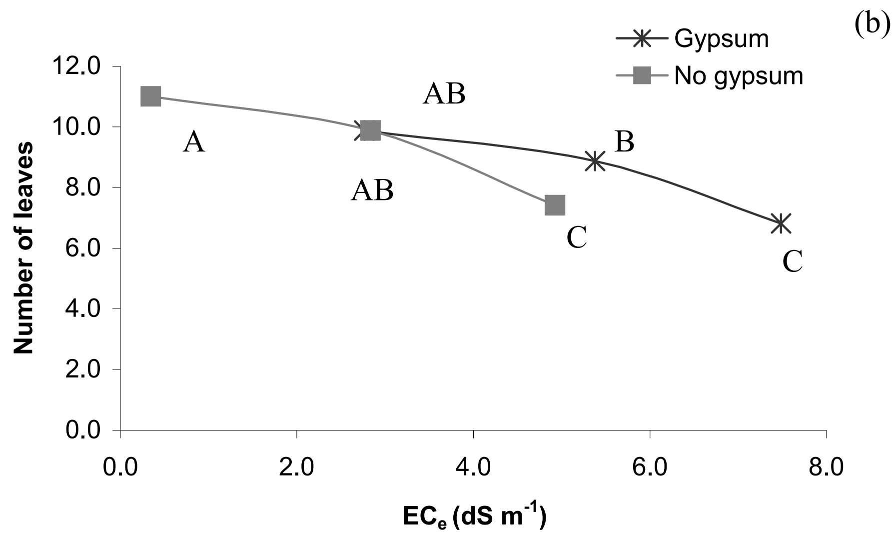


Figure 5.4. Number of leaves measured at the vegetative stage as a function of increasing EC_e, for (a) common bean and (b) green gram. Data points associated with the same letters are not different ($P \leq 0.05$) as determined using t-tests based on least square means.

Table 5.2. Above ground biomass, leaf area and number of leaves of common bean and green gram grown with three levels of soil salinity, averaged over three levels of deficit irrigation.

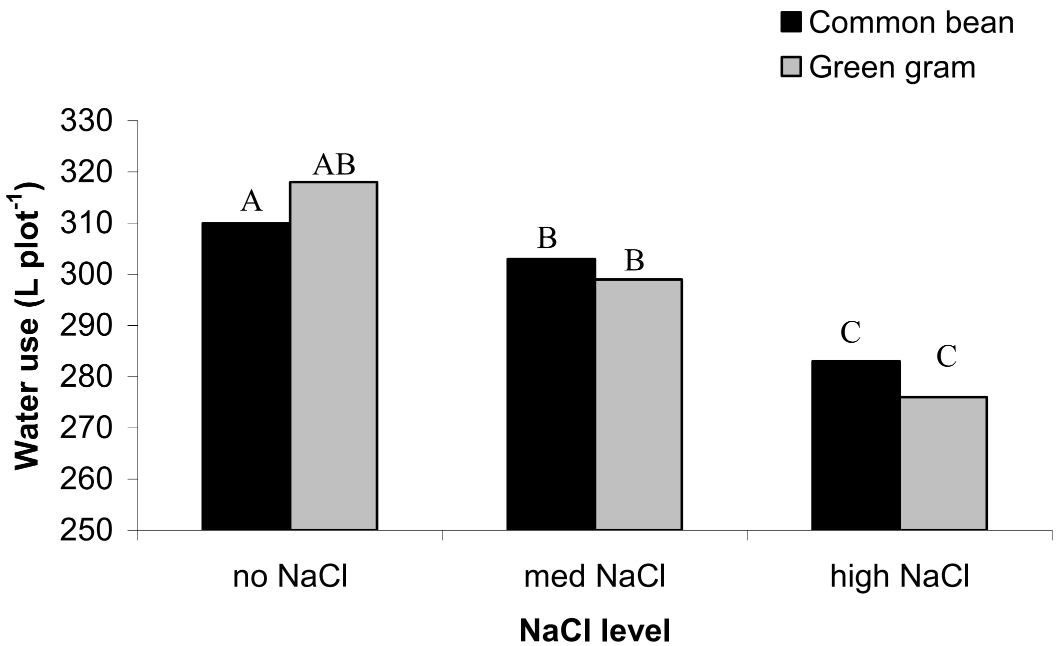
Growth Stage	Crop	Salt	Biomass (g plant^{-1}) Trial 1	Biomass (g plant^{-1}) Trial 2	Leaf area (cm^2 plant^{-1}) Trial 1	Leaf area (cm^2 plant^{-1}) Trial 2	Number of leaves Trial 1	Number of leaves Trial 2
Vegetative	Common bean	No NaCl	1.62 B	0.50 A	490 A	129 A		
		Med NaCl	1.47 BC	0.46 AB	440 A	123 A		
		High NaCl	1.44 BC	0.42 B	458 A	100 B		
	Green gram	No NaCl	1.91 A	0.33 C	324 B	84 B		
		Med NaCl	1.41 BC	0.34 C	240 C	87 B		
		High NaCl	1.31 C	0.24 D	227 C	61 C		
Flowering	Common bean	No NaCl	4.0 AB	4.0 C	905 A	1079 CD	30 A	25 A
		Med NaCl	3.3 BC	3.5 CD	780 A	994 D	26 B	22 C
		High NaCl	3.3 C	2.8 D	788 A	781 E	24 B	17 D
	Green gram	No NaCl	4.1 A	8.2 A	536 B	1516 A	15 C	24 AB
		Med NaCl	3.4 BC	6.3 B	462 B	1339 B	15 C	23 BC
		High NaCl	3.0 BC	6.1 B	429 B	1191 C	14 C	22 C
Podfilling	Common bean	No NaCl	7.4 A	10.8 CD	838 A	2295 A	29 A	51 A
		Med NaCl	5.7 BC	10.9 CD	776 A	2396 A	29 A	49 A
		High NaCl	6.3 AB	9.0 D	838 A	2082 A	25 B	42 B
	Green gram	No NaCl	4.9 CD	16.1 A	505 B	2211 AB	16 C	35 C
		Med NaCl	4.3 D	15.7 AB*	419 B	2162 AB	15 C	35 C
		High NaCl	4.0 D	12.7 BC*	387 B	1858 B	14 C	30 C
Harvest	Common bean	No NaCl	9.5 A	13.7 C	790 AB	294 B	31 B	18 AB
		Med NaCl	9.5 A	14.2 C	943 A	364 B	38 A	19 AB
		High NaCl	6.8 B	9.5 D	699 BC	342 B	26 B	13 AB
	Green gram	No NaCl	9.5 A	22.8 A	552 CD	1246 A	19 C	22 AB
		Med NaCl	8.0 AB	19.4 B	457 D	1167 A	16 C	27 A
		High NaCl	7.3 B	16.3 BC	484 D	1055 A	17 C	22 AB

At flowering, increased soil salinity resulted in lower biomass and leaf area for both crops. The leaf area of both crops decreased by 21% at the highest level of salinity. This decrease in leaf area was the same for all levels of deficit irrigation. For biomass, an interaction existed between crop, irrigation schedule and salinity ($p = 0.0472$). At the recommended irrigation schedule, salt did not reduce flowering biomass in green gram, whereas it reduced biomass by 15% (medium level) and 24% (high level) in common bean. Conversely, with the large depletion factor in deficit irrigation, the level of soil salinity had no impact on common bean biomass.

At pod-filling, there was no clear effect of soil salinity on total above ground biomass for either crop. In general, biomass decreased with increased soil salinity by as much as 20%, but this decrease was statistically significant only for common bean in the first trial and for green gram in the second trial. Likewise, leaf area was unaffected by the salinity level during the pod-filling stage for either culture, though a decreasing trend roughly paralleling that of biomass was present. At this growth stage soil salinity reduced the number of leaves per plant in common bean, but did not affect this variable for green gram.

As mentioned in the methodology, data collected at the fourth sampling period in trial two represents harvest maturity for common bean only. For green gram, the harvest in trial one corresponds to harvest maturity, whereas in the second trial, green gram had not yet reached maturity. This is due to the higher levels of ambient light in the summer months when this trial was conducted (Lawn, 1979). For this reason, the results discussed here do not consider the yield components of green gram for the second trial. Total above ground biomass was reduced by 30% for common bean and 20 to 29% in green gram at the highest level of soil salinity. Dry weights of reproductive organs were likewise reduced in both trials for common bean, and the first trial for green gram. Neither leaf areas nor leaf numbers differed with salt level at the final sampling. Common bean final yield was reduced by 20 to 30% at the highest salinity level (Table 5.3). The yield components (Table 5.3) that explain this reduction are reduced seed weight and the number of pods per plant. The highest level of soil salinity reduced seed weight by 9 to 11% and the number of pods per plant by 17 to 32%. However the reduction in the latter was only significant in the second trial. In both trials, irrigation schedule by salt level interactions existed for seed weight, but was not consistent between trials. The number of seeds per pod was constant across all salt levels. Green gram yield was reduced by roughly twice the amount of common bean yield, at the highest soil salinity (first trial only). Both seeds per pod and pods per plant decreased with increasing salinity, while the seed weight remained constant. Despite the larger reduction in yield of green gram, it maintained much higher absolute yields than common bean at all salinity levels.

Increasing NaCl salinity reduced crop consumptive water use in both crops (Fig. 5.5). The reductions were more pronounced in green gram, with reductions of 6 to 13% at the medium salinity level and 13 to 20% at the highest salinity level. For common bean, water use was not reduced at the medium salinity level, but was reduced by 9 to 17% at the highest level. In both trials a three way crop by deficit irrigation by salinity level existed ($p = 0.11$) (Bourgault, 2008). The data indicated at low evaporative demand, increasing salinity did not decrease water use in common bean when no soil water deficit existed. However, when the evaporative demand was higher (due to longer days), increasing salinity caused a decrease in water use for all deficit irrigation levels. For green gram, water use decreased with increasing salinity at all irrigation levels in both trials. The larger water use, and possibly water use reductions with increasing salinity the second time this experiment was conducted is due to higher ET rates due to greater sunlight intensity and duration in July compared to April.



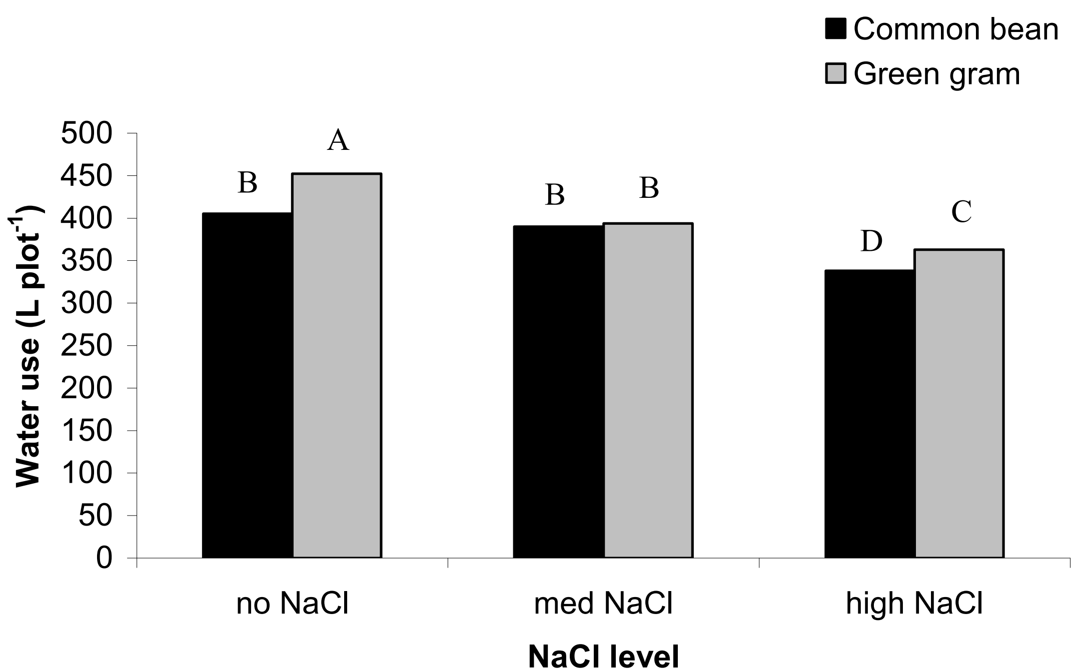


Figure 5.5. Crop consumptive water use determined using the crop water balance. Bars associations with the same letters are not different ($P \leq 0.05$) as determined using t- tests based on least square means.

Table 5.3. Final yield and yield components of common bean and green gram under various levels of soil salinity.

Crop	Salt	Number of seeds per pod		100 - seed weight (g)		Number of pods per plant		Final yield (g plant^{-1})	
		Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
Bean	No NaCl	2.8 C	2.3 C	27.4 A	25.4 A	2.1 D	5.6 A	20.8 C	28.5 A
	Med NaCl	2.7 C	2.9 C	25.8 B	25.0 A	2.2 D	4.7 AB	20.2 CD	26.9 AB
	High NaCl	2.8 C	2.6 C	24.4 C	23.1 B	1.8 D	3.8 B	16.9 D	19.8 C
Green gram	No NaCl	7.6 A		6.2 D		5.9 A		34.7 A	
	Med NaCl	7.3 A		6.2 D		4.8 B		29.1 B	
	High NaCl	6.8 B		6.0 D		3.9 C		19.9 C	

5.4 DISCUSSION

During early vegetative growth, the presence of gypsum in soil did not enable common bean to tolerate higher EC_e values; both common bean biomass and leaf area were reduced as a function of EC_e in both soils with and without gypsum. This is consistent with the idea that initially plant response to salinity is a water deficit effect, as common bean is considered to be more drought sensitive than green gram. While the statistical results indicate the same for green gram, a clear trend in the data shows green gram biomass, and to a lesser degree leaf area, did not decrease as much in soils containing gypsum as they did in soils with only sodium salts.

As for tolerance to absolute salinity level, at the vegetative stage, common bean seems able to withstand an EC_e of 2.8 dS m^{-1} before either leaf area or biomass is decreased. This is roughly the value predicted in Maas and Grieve (1987), as the salinity threshold for common bean is 1 dS m^{-1} and the tolerance should be increased by 1 to 3 dS m^{-1} if the soil contains gypsum. However, the tolerance value estimated by considering the seasonal water use in the second experiment was 4.8 dS m^{-1} and the relative rate of reduction in water use 4.6%/dS m^{-1}(Fig. 5.6). Note, the salinity threshold listed in their work is based on yield potential where as these values are related to water use. For green gram at the vegetative stage, at an EC_e of 2.8 dS m^{-1} a decreasing trend, though not statistically significant, was observed in biomass ($p = 0.13$) and leaf area ($p = 0.11$) when the plants were grown in without gypsum, relative to soil containing gypsum. The cause of this is unclear. It can be speculated that this variety of green gram, which is native to Central Asia, is adapted to growth on the gypsiferous soils of the region. Typically, calcium deficiencies are not expected at the Na^{+}/Ca^{2+} ratios (6 and 9) used in this experiment, though it may have been the case for this variety (Greenway and Munns, 1980). When the seasonal growth and water use values are considered, the salinity tolerance is estimated at 2.6 dS m^{-1} and the relative rate of reduction in water use at 3.5%/dS m^{-1} (Fig. 5.6).

For both crops, biomass and leaf area decreased with increasing salinity as crop development progressed. Generally the decrease in biomass was matched by a relative decrease in leaf area. While biomass and leaf area of both crops decreased with increasing stress, the growth reductions were less than the 19% per dS m^{-1} predicted for common bean (no values are listed for green gram) (Maas, 1985). This suggests that of slope of the relationship presented by Maas (1985) may also differ with gypsiferous soils. The cause may be that the high levels of soil calcium prevented changes to root membranes that favour the entrance and accumulation of sodium and chloride ions in cells, and the effects of salinity were only osmotic effects. It is then hard to comprehend why green gram has been affected to a larger degree as it is more drought tolerant. Green gram suffered larger relative reductions in final yield than common bean did. This is significant, as in a previous study, green gram was better adapted to deficit irrigation techniques (Webber et al., 2006). These results can not determine if this is an indication of this particular variety's sensitivity to salinity or high calcium requirement.

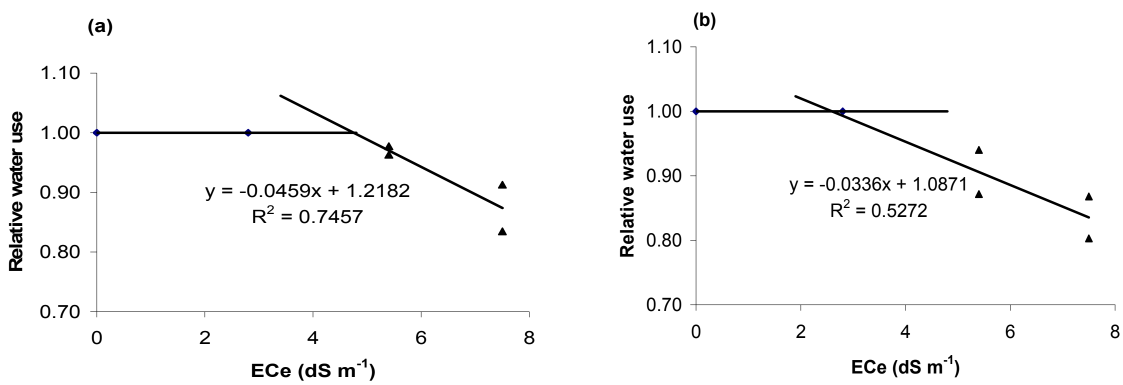


Figure 5.6. Relative seasonal water use with increasing salinity for (a) common bean and (b) green gram

Some reports suggest that salinity problems may be more severe in dry soils as salts concentrations would increase as water was removed from the soil. The lack of an interaction between deficit irrigation and soil salinity indicates that reduced deficit irrigation could safely be implemented in soils suffering from salinity. One explanation may be that the larger application volumes in deficit irrigation result in leaching of salts to the bottom of the root zone.

5.5 CONCLUSIONS

High competition for water resources and increasing land salinization are two challenges facing irrigated agriculture in the Fergana Valley of Uzbekistan. The country's population is also experiencing rapid growth and will require increased food supplies. Strategies to increase food production and reduce agricultural water use must be developed within this context of increasing land degradation due to salinization. The region's soils contain large amounts of gypsum salts, and the vast literature on crop tolerance to salinity is not easily transferable to these soils. For the two legume species tested in this study, common bean and green gram, acceptable yields were attained at the highest level of salinization (ECe of 7.4 dSm^{-1}). Biomass and leaf area accumulation were reduced by approximately 20% as the salinity was increased from 2.8 to 7.4 dSm^{-1}, which is considerably less than expected from the literature. These results indicate that for gypsiferous soils, not only is the yield reduction threshold higher, but the rate of yield decline with increasing salinity is less severe than for soils dominated by sodium and chloride salts. Finally, no interactions were found to exist between the application of reduced deficit irrigation and the degree of land salinization.

5.6 ACKNOWLEDGEMENTS

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CONNECTING TEXT TO CHAPTER 6

Two previous chapters identified and assessed deficit irrigation and alternate furrow irrigation as appropriate water saving irrigation technologies for growing common bean and green gram following winter wheat harvest in the Fergana Valley, Uzbekistan. A third chapter investigated the response of these two crops to soil salinity in a soil dominated by gypsum salts, which are typical of the region.

This chapter addresses the use of a crop model as a planning tool for use of deficit irrigation in the region. The model should be sensitive to crop physiology to detect the different responses to water deficit in legumes and should be responsive to soil salinity. The CROPGRO model is selected as it is considered the most physiologically based agronomic model available. However, the current version of the model does not account for soil salinity. This chapter highlights modifications to CROPGRO to model growth in saline soils and evaluates the new model qualitatively and quantitatively using the experimental results presented in Chapters 3 through 5.

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CHAPTER 6: ADAPTING CROPGRO FOR REGIONS WITH SALINE SOILS

ABSTRACT

Increasing food insecurity, competition for scarce water resources and growing land salinization in the Fergana Valley of Uzbekistan are forcing agricultural water users in the region to reevaluate irrigation practices. Crop models play an important role in helping farmers decide which systems (crops and irrigation technologies) are feasible. The CROPGRO model is physiologically robust, though the current version does not consider the effects of soil salinity on crop water use or growth. While CROPGRO's root water uptake routine considers the physics of micropore radial water flow to roots, this method has been evaluated as largely inferior to empirical reduction functions in simulating root water uptake under conditions of soil salinity in hydrological based models. An iterative process was employed that enabled an approach very similar to the empirical reduction functions. A qualitative analysis of the models indicated that the model performed as expected under a range of atmospheric, irrigation and crop tolerance scenarios. The Willmott agreement index, root mean square error, mean absolute error and relative error were employed to evaluate the model. The modified model performance was excellent for yield and ET when evaluated for a greenhouse study at three levels of each deficit irrigation and salinity in a gypsiferous soil. The modified model was successfully tested with field data, on common bean (*Phaseolus vulgraris*) from an experiment in the Fergana Valley, though the sensitivity of the model to a soil fertility function and relative nodule number made it difficult to assess the model performance.

Keywords: soil salinity, gypsum, CROPGRO, *Phaseolus vulgaris,* Fergana Valley of Uzbekistan, regulated deficit irrigation

6.1 INTRODUCTION

Increasing food insecurity and competition for scarce water resources in the Fergana Valley of Uzbekistan are forcing agricultural water users in the region to reevaluate irrigation practices. Despite high irrigation requirements, cotton and winter wheat are the main crops produced in the country. Farmers are required to produce these crops in a state order system, as cotton exports generate close to one third of the country's gross domestic product. However, the extent and degree of soil salinization increase each year due to rising water tables associated with heavy leaching. As such, efforts to improve food security in the near term should respect farmers' constraints on food crop production: (i) needing to produce cotton and/or winter wheat, (ii) increasing soil salinity and (iii) having little available water (priority of use going to cotton). Inexpensive and easy to implement improvements to the region's predominant surface irrigation systems have been identified and result in water savings (Horst et al., 2005; Horst et al., 2007; Webber et al., 2006). Crop models play an important role in allowing farmers to decide which systems (crops and technologies) are feasible.

CROPGRO is a widely used crop model and considered the most physiologically based agronomic model currently available. Originally developed from individual legume models (Boote et al., 1986; Hoogenboom et al., 1992), CROPGRO now models twelve crops. It is one of two primary crop models (the other being CERES) in the Decision Support System for Agrotechnology Transfer (DSSAT) software package. DSSAT manages soil, weather, and management and crop databases to simulate various agricultural and climatic scenarios over multiple years. DSSAT can simulate twenty seven different crops, is over fifteen years old and has been applied in over one hundred countries. The crop models contained in DSSAT are in modular form and comprised of one code for simulating soil water, nitrogen and carbon dynamics. Crop growth and development are simulated with one of its constituent models. By maintaining separate crop modules within DSSAT, the individual crop models can capture more of the species specific physiological differences while considering the same soil, climate and management scenarios (Jones et al., 2001; Jones et al., 2003). Currently, CROPGRO does not consider the effects of soil salinity on crop growth. This is a serious limitation for its application to regions such as Uzbekistan.

Plant response to salinity is proposed by some authors (Munns and Termaat, 1986; Munns et al., 2000) to encompass two phenomena; water deficit affects the plant immediately, while specific ion toxicity effects are noticeable weeks to months later, after thresholds of specific ions in leaf tissue are surpassed (Munns et al., 2000). Water deficit effects are caused by the osmotic potential, due to salts or other osmotica (Yeo et al., 1991), as perceived by the roots, and result in reduced cell elongation rates, with greater reductions occurring in the shoot than root cells (Munns and Termaat, 1986). Others have determined that Na^+ does induce an immediate reduction in leaf elongation rate, in addition to water deficit effects, before any increase in leaf Na^+ concentrations are detected (Montero et al., 1998). These authors found, at equivalent osmotic potentials, greater reductions in growth rates and increased xylem ABA concentrations with NaCl than concentrated nutrient solutions. However, some work shows that many symptoms of Na^+ toxicity are actually due to Ca^{2+} deficiency as salinity inhibits Ca^{2+} uptake when the Na^+/Ca^{2+} ratio is high (Greenway and Munns, 1980; Maas and Grieve, 1987). This could be the case in the previous study. Calcium can moderate the effects of sodium salinity, attenuating growth reductions (Maas and Grieve, 1987; Eaton, 1942) and is required for root membrane integrity and proper function of ion transport systems (Lauchli and Epstein, 1970). The presence of calcium in gypsiferous soils of the Fergana Valley, Uzbekistan is believed to moderate the toxic effects of sodium salts by protecting membrane functioning and preventing calcium deficiency. Therefore, an approximate salinity response factor, in gypsiferous soils under conditions of low to moderate soil salinity, could act to increase water stress at a given soil moisture, particularly for short season crops.

Various hydrological based models, which determine water and solute flow in the soil from numerical solutions of Richard's equation and the convection–dispersion equation, account for salinity effects in the way in which root water uptake, *RWU*, is handled. A number of good reviews of different model forms are found in the literature (Homaee et al., 2002a; Green et al., 2006; Skaggs et al., 2006b), to which the reader can refer for specific formulations of the various *RWU* functions discussed here. In these models, two general approaches are used to simulate *RWU*. The microscopic approach was first formulated by Gardener (1964), and considers the physics of water flow through soil micropores in the context of soil conductivity, $K(h)$, water potential gradient between the root and soil, $\Delta\Psi$, and the rooting density distribution, $RDF(z)$, with depth, z. This type of model was modified by Nimah and Hanks (1973) to include both soil matric and osmotic potential in the $\Delta\Psi$ term. The macroscopic approach is based on the empirical reduction function, $\alpha(h,h_o)$, which reduces water uptake from a maximum (usually potential plant transpiration) in response to lowered water potential (matric, h, and osmotic, h_o). This type of model, modified to include salinity effects, is described by Feddes et al. (1976), van Genuchten (1987), Cardon and Letey (1992b) and Homaee et al. (2002a, 2002b) among others.

In a comparison of the microscopic model of Nimah and Hanks (1973) and the macroscopic model of van Genuchten (1987), the macroscopic model was judged to be much more representative of actual root water uptake in response to salinity stress (Cardon and Letey, 1992a). The microscopic model of root water uptake was unresponsive to salinity when the soil water content was high, and dropped quickly to zero as the soil dried. Cardon and Letey (1992a) explain this as being due to the large dependence of the term on soil conductivity, $K(h)$ which changes drastically with changes in soil water content, masking the salinity response.

Within the macroscopic models of root water uptake, different methods exist for determining the relative effects of water and salinity, including additive (van Genuchten, 1987; Cardon and Letey, 1992b) and multiplicative (van Genuchten, 1987; Homaee et al., 1999; Skaggs et al., 2006a), as well as hybrids or combinations of these types (Homaee et al., 2002b). In a comparison of six types of macroscopic uptake terms, Homaee et al. (2002a) determined the additive term (van Genuchten, 1987) performed the worst in all cases. Likewise, Shalhevet and Hsiao (1986) concluded that the effect of water stress was twice that of salinity stress with an equivalent water potential, raising questions about the validity of an additive approach. Homaee et al. (2002a) found their own multiplicative combination reduction model (2002b) performed best under almost all circumstances. The combination reduction function proposed by Homaee et al. (2002b) is given by:

$$\alpha(h,h_o) = \frac{h-(h_4-h_o)}{h_3-(h_4-h_o)} \times \left[1-\frac{a}{360}\left(h_o^*-h_o\right)\right] \qquad [1]$$

where h is the soil matric potential (cm), h_o is the soil osmotic potential (cm), h_4 is the matric potential corresponding to the permanent wilting point, h_3 is the soil water pressure head where soil water uptake starts to be reduced, h^*_o is the threshold osmotic head where yields start to decline due to salinity, a is the relative decline in water use per unit of increasing salinity (% / dS m^{-1}), and 360 is a conversion factor, to convert between osmotic head and dS m^{-1} (U.S. Salinity Lab. Staff, 1954).

The two terms in the Homaee et al. (2002b) reduction function coincide with the water stress reduction factor of Feddes et al. (1976) and the salinity reduction factor of Maas and Hoffman (1977). The Homaee et al. (2002b) model is very much like that of van Dam et al. (1997) except that the water potential corresponding to the permanent wilting point, h_4, is increased to increase with increasing salinity by adding h_o to h_4. Note that the Maas and Hoffman (1977) reduction function was formulated to relate soil salinity to relative yield, not ET or root water uptake. However, the general form of the model should be valid if reductions in yield roughly parallel reductions in water uptake with the appropriate yield response factor (Doorenbos and Kassam, 1979) and appropriate choices of the constants a and h^*_o (Green et al., 2006). Homaee et al. (2002b) appear to apply directly the coefficients from Maas and Hoffman (1977) and cite the availability of these coefficients for a wide variety of crops as the main reason they chose this particular salinity reduction function over others (van Genuchten, 1987; Dirksen and Augustijn, 1988) with harder to obtain parameters.

From the literature cited above, it is clear that approaches exist to model root water uptake in response to salinity. However, most of the hydrological models include only very elementary crop model routines that ignore climate, management and genetic factors that govern crop growth. Castrignano et al. (1998) proposed a salinity response factor for the CERES-Maize model. An empirical water/salinity stress factor was calculated using pre-dawn leaf water potential, replacing the standard approach of defining the water stress factor as the ratio of potential root water absorption to potential transpiration found in CERES and CROPGRO. The authors argue that the potential root water absorption calculation is a very weak part of CERES. However, their approach would require calibration of the water available in the soil to the pre-dawn leaf water potential for each crop, soil type and salinity level. This is a difficult measure to take and evidence suggests that crops may regulate stomatal closure and transpiration before any changes in turgor or leaf water status occur (Jones, 1985; Michelena and Boyer, 1982; Davies and Zhang, 1991). A second, more feasible approach is found in CropSyst. The model considers solute transport in the soil water profile with a numerical solution of Richard's equation and a convection equation, enabling the calculation of the soil water osmotic potential (Ferrer-Alegre and Stockle, 1999). The salinity effects in the model are conceptually very similar to that in Homaee et al. (2002b) in that there is an empirical salinity reduction function and osmotic and matric potentials are added together reducing the total water potential gradient between soil water and root (an effect that is similar to changing the permanent wilting point). The main difference is that the salinity reduction function used is the S-shaped curve of van Genuchten (1987) rather than the linear response of Mass and Hoffman (1977). In all of the models reviewed, the assumption is made that salinity effects are limited to water deficit effects and no toxic ion effects are included.

The goal of this research is to assess the potential of using CROPGRO as a planning tool in regions with soil salinity. The specific objectives were: (i) to modify the existing root water uptake routines to account for soil salinity; (ii) to compare the original and modified model in their ability to correctly predict yield and water use under saline conditions; and (iii) to evaluate the modified model for predicting crop growth in Uzbekistan under conditions of water stress by comparing simulations to field data.

6.2 MODEL DESCRIPTION

CROPGRO is well documented (Jones et al., 2003; Boote et al., 1998b). Only aspects related to root water uptake, water stress and the proposed salinity response factor are discussed below.

A tipping bucket approach is used in CROPGRO and the DSSAT suite of crop models to determine water infiltration and soil moisture in successive soil layers. Water drains to the next lower layer when the soil moisture is above the drained upper limit (equivalent to field capacity) or can be simulated as upward flow when the soil is saturated in layers below, depending on the soils hydraulic conductivity (Ritchie, 1998). Many soil – water parameters can be estimated by DSSAT based on soil texture (Ritchie, 1998). All water balance calculations are constrained to the user specified root zone depth, which is generally error prone due to measurement uncertainties. While CROPGRO does not use a process oriented approach to describe soil water flow, the potential root water uptake term, $RWU_p(L)$, for each soil layer L, is very similar to the microscopic uptake term of Gardener (1964) and is given by:

$$RWU_p(L) = \sum_L \left(\min\left(\frac{c_1 e^{\min\left(40, c_2\left(SW(L) - LL(L)\right)\right)}}{c_3 - \ln\left(RLV\left(L\right)\right)}, RWUMAX \right) \times DLAYR(L) \times RLV(L) \right) \quad [2]$$

where $RWU(L)$ is in cm day^{-1}, c_1 is an empirical constant (c_1 = 0.00132), c_2 is an empirical constant ($c_2 = 120 - 250*LL(L)$), $LL(L)$ is the lower limit of plant available water corresponding with the permanent wilting point (cm^3 [water] cm^{-3} [soil]), $SW(L)$ is the actual soil water content (cm^3 [water] cm^{-3} [soil]), c_3 is an empirical constant (c_3 = 7.01), $RLV(L)$ is the root length density for soil layer L (cm [roots] cm^{-3} [soil]), $RWUMAX$ is the maximum daily root water uptake per unit length of root (cm^3 [water] cm^{-1} [root]), and $d(L)$ is the depth of layer L (cm). The total root water uptake, TRWUP, is the sum of all $RWU_p(L)$ for all soil layers, p.

Actual root water uptake, *TRWUP*, is the minimum of potential crop transpiration, E_{op}, and potential root water uptake, $RWU_p(L)$. E_{op} is the product of the reference crop ET_o (this study used the FAO Penman – Monteith equation) and a term representing the fraction of the total incident solar radiation captured by the plant canopy, such that:

$$E_{op} = ET_0 \times \left(1 - e^{-0.7 \times LAI}\right) \quad [3]$$

where LAI is the leaf area index.

The original model calculates three water stress factors when the actual transpiration changes in relation to potential evapotranspiration. A water stress factor, TURFAC, is associated with leaf turgor and reduces expansive growth, when potential root water uptake is less than 1.5 times the potential transpiration (Jones et al., 2003; Ritchie, 1998). TURFAC is computed as:

$$TURFAC = \frac{TRWUP}{1.5E_{op}} = \frac{TRWUP}{1.5ET_0 \times \left(1 - e^{-0.7 \times LAI}\right)}. \qquad [4]$$

The water stress factor for reducing photosynthesis, SWFAC, acts when potential root water uptake is less than potential transpiration (Jones et al., 2003; Ritchie, 1998) and is given by:

$$SWFAC = \frac{TRWUP}{E_{op}} = \frac{TRWUP}{ET_0 \times \left(1 - e^{-0.7 \times LAI}\right)} \qquad [5]$$

The third water stress factor acts to increase biomass partitioning to the roots when the ratio of actual transpiration relative to potential transpiration is less than 1 (Hoogenboom et al., 1992).

Modifying the CROPGRO code to simulate water uptake under conditions of soil salinity presented two main challenges. Firstly, the literature indicates the superior performance of the macro-scale empirical reduction functions in simulating water uptake under saline conditions, but the CROPGRO root water uptake function employs a microscopic approach. The function is designed to predict water uptake in dry soil conditions, as water uptake is not considered limiting under wet soil conditions. The root water uptake function predicts erroneously high values of water uptake when the soil moisture is high (Ritchie, 1998). This is not a problem for the model as actual water uptake is the minimum of potential root water uptake and potential ET. However, this napproach made it impossible to implement a salinity reduction function in all but the driest soils. For example, a 10% reduction in water use for an erroneously high estimate of water uptake is still an erroneously high value of water uptake. Thus modifications to the root water uptake computations were needed to build an appropriate salinity response.

Secondly, when the soil was dry and saline, a second reduction factor was needed to ensure that stomatal closure was greater under saline than non-saline conditions. With the initial hypothesis that salinity effects could be modeled as only water deficit, this second reduction factor was not included with the result that yields increased under salinity if water stress was also experienced! This unrealistic result was caused by a feedback of lower LAI (due to salinity) resulting in a smaller term in the denominator of SWFAC (eq. [5]), and therefore less photosynthetic stress. This problem was not reported for the hydrological models, though they contain only very elementary crop growth models, and it is unclear if they considered this feedback. This topic is elaborated upon in the qualitative analysis section.

Before outlining the modifications to the CROPGRO routines, the following list summarizes the main assumptions and assertions of the modified model:

- Soil salinity may vary by depth in the soil
- Soil salinity is considered constant within the growing season
- When soil salinity is less than the crop tolerance, root water uptake will be determined by the original CROPGRO routines
- Soil salinity should reduce plant water uptake from a potential uptake by an amount equivalent to a reduction function dependent on soil salinity (*SALT(L)*) and crop characteristics of tolerance ($EC_{threshold}$) and relative reduction rate (*SALRDCT*)
- Soil salinity will not reduce plant growth when the soil is *very* moist, i.e. $TRWUP > 1.5\ E_{op}$
- When the soil is moist, potential root water uptake in each layer will be defined by the potential rate of ET, E_{op}, multiplied by the proportion of the total water uptake from that layer
- When the soil is dry, the original CROPGRO routine will be used to simulate potential root water uptake, as it has been designed for these conditions
- At any given soil water content, saline conditions should result in greater stomatal closure and reductions in photosynthesis than non-saline conditions. This implies that salinity should cause SWFAC to be less than (or at least equal to) SWFAC under non-saline conditions, all other factors being equal
- The salinity routines are tested using saline soils dominated by gypsum salts, though it is expected to work for all low to moderately saline soils with appropriate parameterization

Therefore, for conditions of soil salinity, an iterative routine was implemented that replaced *LL(L)* with a new value $LL_{salt}(L)$ for the calculation of RWU(L). It is important to note that $LL_{salt}(L)$ was not passed to any other routines in CROPGRO. The first step was to calculate RWU(L) and TRWUP using the original model. This initial calculation was used to (1) determine if soil water or E_{op} limited water uptake and (2) to determine the proportion of water uptake from each layer, *PWU(L)*. *PWU(L)* was calculated as:

$$PWU(L) = \frac{RWU_{previous}(L)}{TRWUP_{previous}} \qquad [6]$$

where $RWU_{previous}(L)$ and $TRWUP_{previous}$ indicates the previous values of these variable are used to determine the proportion, which is then used to determine new estimates of *RWU(L)* and T*RWUP*.

In wet soils, actual TRWUP is set equal to potential ET, E_{op}, so $LL_{salt}(L)$ was calculated as follows:

$$LL_{salt}(L) = SW(L) - \frac{1}{C_2(L)}\left[\ln\left(\frac{PWU(L)}{d(L)\times RLV(L)} \times ET_{reduced} \times \left(C_3 - \ln\left(\frac{RLV(L)}{C_1}\right)\right)\right)\right] \qquad [6]$$

where

$$ET_{reduced} = f(salt)E_{op} = \left(1 - \frac{SALRDCT}{100}\left(SALT(L) - EC_{threshold}\right)\right) \times \frac{E_{op}}{10\,mm/cm} \qquad [7]$$

Using $LL_{salt}(L)$ new estimates of $C_2(L)$, *RWU(L)*, and *TRWUP* were calculated. If the new value of *TRWUP* was within 0.1 mm of $ET_{reduced}$, the process terminated. Otherwise, the calculation was repeated beginning with an updated value of *PWU(L)*. The process usually converged after two to three iterations.

In dry soils, the same iterative process was used except that a value of $LL_{salt}(L)$ that would result in values of *RWU(L)* that would sum to the original model's estimate of potential root water uptake, $TRWUP_o$, multiplied by the salinity response function was required, such that:

$$LL_{salt}(L) = SW(L) - \frac{1}{C_2(L)}\left[\ln\left(\frac{PWU(L)}{d(L)\times RLV(L)} \times TUP_{o,red} \times \left(C_3 - \ln\left(\frac{RLV(L)}{C_1}\right)\right)\right)\right] \qquad [8]$$

where

$$TUP_{o,red} = TRWUP_o \times \left(1 - \frac{SALRDCT}{100}\left(SALT(L) - EC_{threshold}\right)\right) \qquad [9]$$

Additionally, when the soil was dry and saline, a second reduction factor was needed to ensure that stomatal closure was greater under saline than non-saline conditions. Under these conditions, $SWFAC_{saline}$ is calculated as:

$$SWFAC_{saline} = \frac{TRWUP}{ET_0 \times \left(1 - e^{-0.7 \times LAI}\right)} \times \frac{1}{\left(S_1 \left(SALT - EC_{threshold}\right) + S_2\right)} \qquad [10]$$

where S_1 and S_2 are parameters adjusted to obtain good model fit with observed data. A flow chart outlining the major modifications to the root water uptake routine is presented in Fig. 6.1.

6.3 MODEL EVALUATION

6.3.1 Qualitative analysis

Having built the salinity response into CROPGRO a number of hypothetical simulations were run to see if the model could capture the general trends in yield and water use expected with increasing soil salinity. As in the analysis of Ferrer-Alegre and Stockle (1999), the model response to different levels of deficit irrigation, atmospheric evaporative demand and cultivar salinity tolerance was evaluated, all of which are reported to change the response to salinity for specific crops (Francois and Maas, 1999). These factors were tested using the common bean cultivar and climatic conditions used for the greenhouse study reported in Chapter 5. As the baseline conditions, an evaporative demand equivalent to that used in the greenhouse study was selected to mimic the field conditions in the Fergana Valley of Uzbekistan in the mid to late summer. The default level of deficit irrigation corresponded to a 50% depletion of the readily available water. The default crop values are a salinity threshold of 4.8 dS m^{-1} as determined for this cultivar of common bean in gypsiferous soil with a reduction factor of 5%/dS m^{-1}. For the simulation, varying the level of deficit irrigation between depletion factors of 30 and 80% was selected. The VPD was varied from the value estimated for the greenhouse by 20% greater than and less than that value. A salt sensitive common bean crop (in gypsiferous soil) was estimated to have a salinity threshold of 3 dS m^{-1} and a relative reduction rate of 10%/ dS m^{-1} and the tolerant cultivar a threshold of 6 dS m^{-1}

and a relative reduction rate of 3.5%/dS m^{-1}. Six levels of soil salinity were simulated, ranging from 2.8 dS m^{-1} (corresponding to gypsum salts only) to 15 dS m^{-1}.

The results of these simulations, for yield and water consumption, are shown in Figs. 6.2 and 6.3, respectively. In these two figures, yield and water consumption are expressed relative to the 2.8 dS m^{-1} salinity level and the (a) 30% depletion factor, (b) typical VPD, and (c) average crop salinity tolerance. The model is responsive to soil salinity under various levels of deficit irrigation. The effects of soil salinity are less severe in humid conditions and greater yield reductions are expected with higher VPDs (Francois and Maas, 1999). Finally, different crop tolerances for salinity are captured with changes in the threshold salinity level and the relative reduction factor. In all cases, the relative reductions in final yield are greater than the corresponding reductions in water use. This highlights the discrepancy between the threshold and relative reduction coefficients of the Maas and Hoffman (1977) reduction function for yield being applied directly in the proposed reduction function for salinity, as appears to have been the case with Homaee et al. (2002b). For the simulations, values obtained in a greenhouse trial with the cultivar under consideration were used. However, Allen et al. (1998) combine the yield response to water stress factor, K_y, of Doorenbos and Kassam (1979) with the Maas and Hoffman salinity yield reduction function, B, to obtain an "effective" relative water use reduction factor, b, calculated as

$$b = \frac{B}{K_y} \qquad [4]$$

This may be a good first approximation to be included as a species default in the CROPGRO models. However, for this common bean cultivar grown in a gypsiferous soil, the value of b obtained from equation [4] (b = 19% (dS $m^{-1})^{-1}$ /1.15 = 16.5 % (dS $m^{-1})^{-1}$) was more than three times higher than the value of b obtained in the greenhouse trial and found to work well in the model.

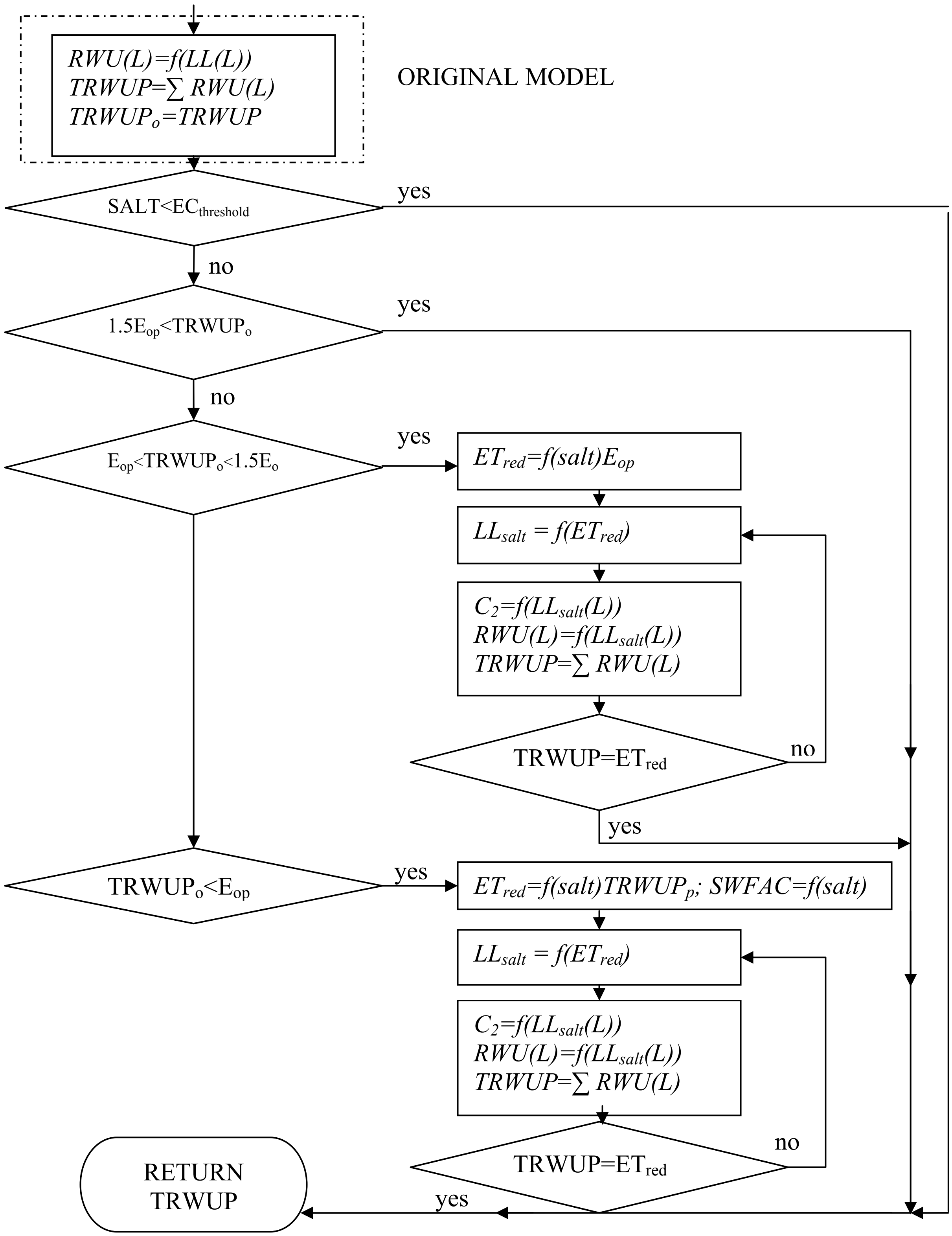

Figure 6.1. Flowchart of the modified model for computing total root water uptake.

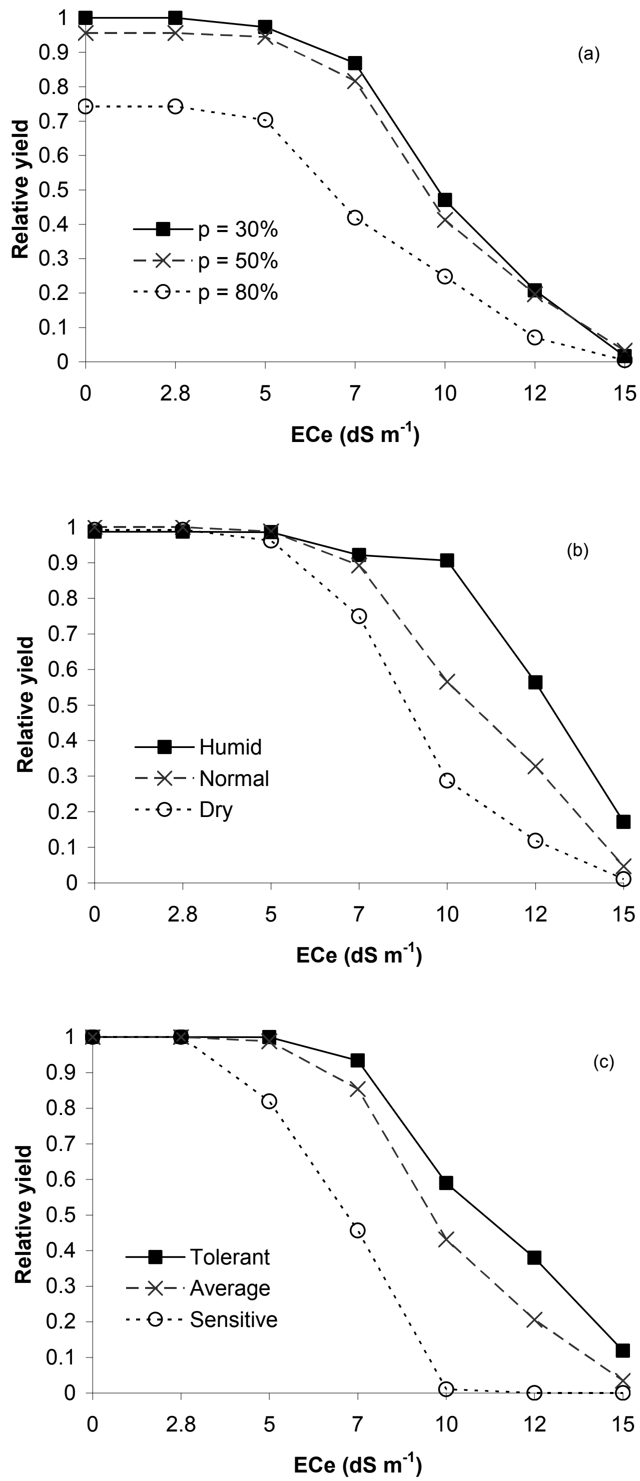

Figure 6.2. Simulated relative yield response of common bean to soil salinity and (a) level of deficit irrigation, (b) VPD of the atmosphere, and (c) crop salinity sensitivity.

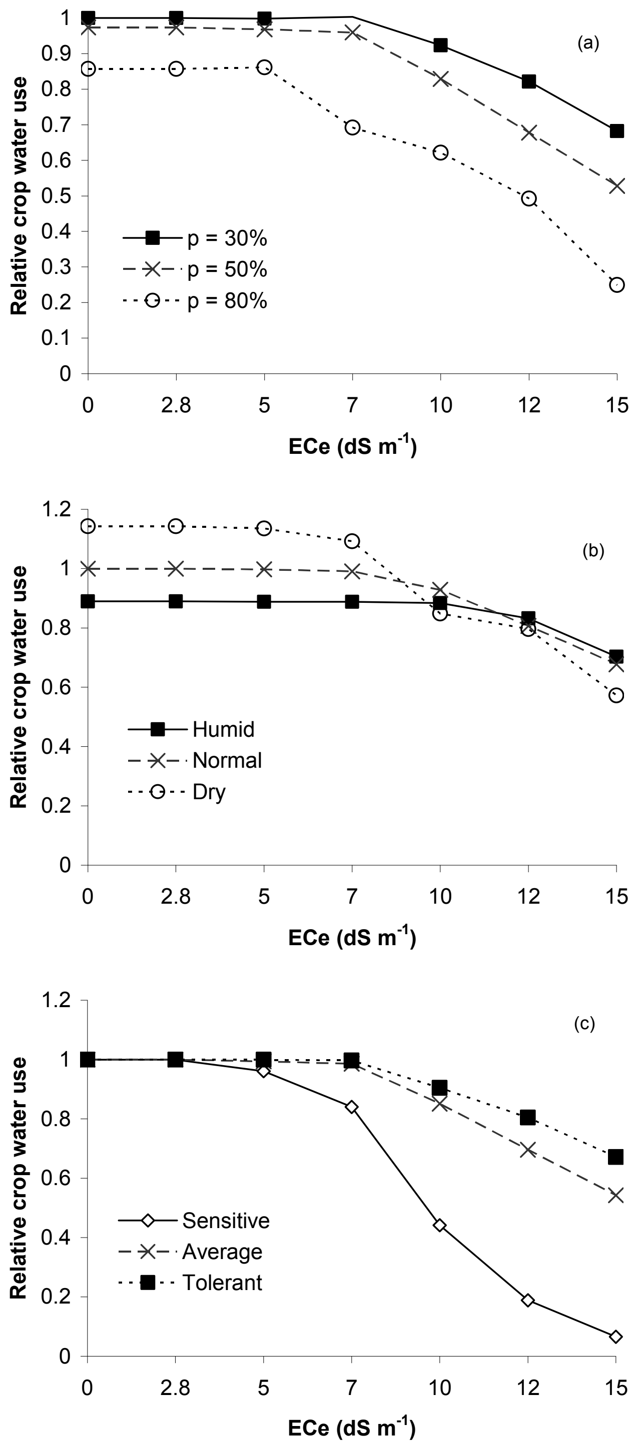

Figure 6.3. Simulated relative crop water use in response of common bean to soil salinity and (a) level of deficit irrigation, (b) VPD of the atmosphere, and (c) crop salinity sensitivity.

The need for the second reduction factor acting on SWFAC is explained by considering case (a) in which different levels of deficit irrigation are employed. In the case with frequent irrigations (p = 30%) when soil moisture does not limit transpiration, reductions in yield and water uptake are affected. Likewise, when the irrigations were simulated less frequently, yield and water use were also reduced though by greater amounts. This approximately accurate representation of reality was only achieved in the model with the addition of the factor promoting stomatal closure. When this factor was not included, and the only effect of salinity was to reduce water uptake the simulations actually predicted increased yield with salinity if deficit irrigation was practiced. This is explained by the effect of water uptake (and salinity) on leaf expansion rates. Under water stress, leaf area is reduced and the plant loses less water. Under this condition, salinity was acting as a drought avoidance mechanism. Stomatal closure is simulated in the term SWFAC. This term was actually increasing with salinity and deficit irrigation, as the reductions in root water uptake were less than the reductions in potential transpiration, as this term is very much a function of leaf area.

6.3.2 Quantitative Analysis

Two experiments and a third 'quasi-quantitative' approach were used to evaluate the model performance. The first experiment used was conducted in a greenhouse on the Macdonald Campus of McGill University, Montreal, Canada during the spring and summer of 2007; the full details of this experiment are presented in Chapter 5 of this thesis.. In this experiment, soil salinity and deficit irrigation level comprised the main treatments to determine the crop response to increasing salinity in a soil dominated by gypsum salts. An Uzbek variety of common bean was grown in large soil bins measuring 43 cm wide by 74 cm long by 50 cm deep, at an initial density of 20 plants per box. The boxes, which were drained along their length by 5 mm perforated drain pipe, were filled with a Soulanges fine sandy loam soil (67% sand; 20% silt; and 13% clay). Gypsum ($CaSO_4{\cdot}2H_2O$) and NaCl were added to the boxes with a small portable cement mixer to give EC_e values of 2.8 dS m^{-1} (no NaCl), 5.4 dS m^{-1}(low NaCl) and 7.5 dS m^{-1} (high NaCl). The boxes were irrigated with one of three levels of deficit irrigation, roughly corresponding to depletion levels of 45%, 60% and 70%. The greenhouse temperature was 32°C during the day and 20°C at night with the photoperiod set at 14 hours per day. The entire experiment was conducted twice.

The second experiment was conducted in the the Fergana Valley of Uzbekistan during the summers of 2003 and 2004. This experiment was designed to determine the crop response of a local variety of common bean to deficit irrigation and alternate furrow irrigation grown as a second crop after winter wheat harvest. The same seed stock was used in both greenhouse and field experiments. The soil type ranged between a sandy loam and silt loam. Each plot measured 15 by 15 m and contained 23 furrows 12 m in length, and was replicated four times. Deficit irrigation levels were the same as in the previous experiment. A weather station in an adjacent field measured daily minimum and maximum temperature and relative humidity, wind speed at 2m, and precipitation. Soil moisture was measured gravimetrically at the soil surface, 10 and 20 cm, and with a neutron probe at 40 and 60 cm two days before and two days after irrigating and every 5 to 7 days to calculate the water balance and determine crop consumptive use. Full experimental details are in Chapter 3 (Webber et al., 2006) and Chapter 4 of this thesis.

In both experiments, destructive samples were taken four times during the growing period from 2 plants per plot to determine different components of above ground biomass and leaf area. Seed harvest was conducted at physiological maturity to determine the various yield components and threshing percentage.

The third, ‘quasi-quantitative’, analysis was performed using the greenhouse salinity trials and data, with one exception. Rather than using exact irrigation amounts as an input, the simulation control was set to automatic irrigation for the average depletion levels obtained in the greenhouse trial. This depletion was adjusted to get the correct number and timing of irrigations that had been applied in the real trials, with as close as possible to the same irrigation water volume applied. This removes the effect of irrigation volume from the comparison of the two models.

Initial model calibration for the cultivar traits was performed with the non-saline treatments (three levels of deficit irrigation) in the first greenhouse trial following the methodology outlined by the model developers (Boote, 1999). Validation for the non-saline treatments was performed with the same treatments from the second greenhouse trial. Since all of the soil bins contained gypsum (as does all of the soil in the region studied in the Fergana Valley), any osmotic effects due to the gypsum will only appear in the soil fertility factor (SLPF). This factor is used to describe reductions in photosynthesis due to any soil nutrient deficiencies other than nitrogen (Boote et al., 2001). Calibration for the salinity response was performed using all nine treatments (three salt levels and three levels of deficit irrigation) from the first greenhouse trial. Model validation was performed with the second trial from the greenhouse and the two field experiments from Uzbekistan. The 'quasi-quantitative' analysis is used to compare the original and modified models.

The evaluation criteria used were: the root mean squared error (RMSE), the mean absolute error (MAE), the relative error (RE) and the Willmott (1981) agreement index (i). All measures are defined in Wallach (2006), and when used in combination with graphical representation of the simulated and observed variables, provided sound evidence for evaluating and modifying models (Wallach, 2006; Willmott, 1981).

6.4 RESULTS AND DISCUSSION

6.4.1. Calibration and validation of cultivar data

The cultivar traits obtained in the calibration routine were all within the range of values listed for other cultivars and are summarized together with the soil fertility factor and parameters related to the new salinity response in Table 6.1. The measures of agreement for the cultivar calibration are listed in Table 6.2. The units of agreement all indicate a good initial calibration of the model for cultivar traits with no imposed salinity stress. The predicted above ground biomass was considerably lower than the observed values during the validation simulations. The model was calibrated with data collected under spring growing conditions, whereas the validation data set was from the summer. One of two possibilities is suspected. Either the original model is not adequately sensitive to changing photoperiods, or the additional staking of the plants during the summer experiment due to the longer day lengths lessened the degree of senescence.

Table 6.1. Soil fertility factor, soil salinity and cultivar parameters obtained during model calibration for the greenhouse dataset.

Parameter	Value
Soil fertility factor (SLPF)	0.86
Soil salinity beyond which water use is depressed, ($EC_{threshold}$)	4.8 dS m^{-1}
Relative salinity reduction factor (SALRDCT or b)	4.6 %/dS m^{-1}
S1	0.19
S2	1.08
Critical Short Day Length below which reproductive development progresses with no daylength effect (CSDL)	12.17 pd*
Slope of response of development to photoperiod with time (PPSEN)	0.010 hr^{-1}
Time between plant emergence and flower appearance (EM-FL)	24.0 pd*
Time between first flower and first pod (FL-SH)	4.0 pd*
Time between first flower and first seed (FL-SD)	13.5 pd*
Time between first seed and physiological maturity (SD-PM)	24.0 d
Time between first flower and end of leaf expansion (FL-LF)	21.0 pd*
Maximum leaf photosynthesis rate under optimal conditions (LFMAX)	1.00 mg CO_2 $m^{-2}s^{-1}$
Specific leaf area of cultivar under standard growth conditions (SLAVR)	320 cm^2 g^{-1}
Maximum size of full leaf (SIZLF)	150 cm^2
Maximum fraction of daily growth that is partitioned to seed & shell (XFRT)	1.00
Maximum weight per seed (WTPSD)	0.500 g
Seed filling duration for pod cohort at standard growth conditions (SFDUR)	11.0 pd*
Average seed per pod under standard growing conditions (SDPDV)	4.00 pod^{-1}
Time for cultivar to reach final pod load (PODUR)	8.0 pd*

*pd, photothermal days, i.e. the number within a specific ranges of temperatures and day lengths

Table 6.2. Evaluation of the calibration (C) and validation (V) of the cultivar traits for the greenhouse experiment using only treatments without salt stress

Variable of interest*		**N****	**Obs. mean**	**Sim. mean**	**RMSE**	**RE**	**MAE**	**i**
Seasonal ET	C	3	311	305	8.7	0.03	8	0.991
(mm)	V	3	409	384	25.4	0.06	25	0.973
Final biomass	C	3	4469	4335	276	0.06	181	0.989
(kg ha^{-1})	V	3	6713	4018	2806	0.42	2695	0.59
Final yield	C	3	903	898	37	0.04	31	0.998
(kg ha^{-1})	V	3	1386	1450	130	0.09	123	0.993
Leaf area index	C	3	3.95	3.58	0.4	0.10	0.37	0.919

* Note on units: Obs. mean, Sim. mean, R.M.S.E. and M.A.E all have the same units as the variable of interest; RE and i are unitless; ** N is the number of observations used in each simulation

6.4.2. Calibration and validation of the new salinity response factor

Calibration of the salinity response function required tuning of the four new parameters. The values obtained are given in Table 6.1. The values of $EC_{threshold}$ and *SALRDCT* (the relative reduction coefficient) did not need to be changed from the initial starting values obtained in the greenhouse. This was largely a result of the way the modified program was designed. The real calibration exercise was with the two parameters, S_1 and S_2, which control the degree of stomatal closure due only to salinity-independent of water deficit. The fit was generally very good for yield and seasonal ET for both calibration and validation data sets as shown by the measures of agreement in Table 6.3 and Fig. 6.4. For comparison, the measures of agreement for the original model are also included. At first glance, the results are puzzling and it may appear that the original model was also responsive to salinity, as the two versions perform equally well for yield and water use. However, this is an artifact of the experimental design, which determined the response to soil salinity. In this experiment, all treatments with the same level of deficit irrigation were irrigated on the same day (i.e. no NaCl, depletion i; low NaCl, depletion i; and high NaCl, depletion i, where i is the level of deficit irrigation). The day before irrigating, soil moisture was measured in all salt treatments (at that level of deficit irrigation) to determine the actual soil moisture deficit and irrigations needed to bring the treatment soil moisture back to field capacity. In almost all cases, the salt treated plants used less water, and therefore needed smaller irrigations, to return their soil moisture to field capacity. Therefore, the original model's apparent responsiveness to salinity is actually responsiveness to irrigation amount. To ensure the modified model is responsive to the salinity, which results in reduced water uptake and stomatal closure, and not simply irrigation amount the qualitative analysis and the 'quasi-quantitative' simulation were performed. The results of this simulation are presented in Table 6.4 and Fig. 6.5. When the effect of irrigation amount has been removed the original model was not sensitive to salinity while the modified model predicted crop growth very well, with the exception of the biomass for the validation set.

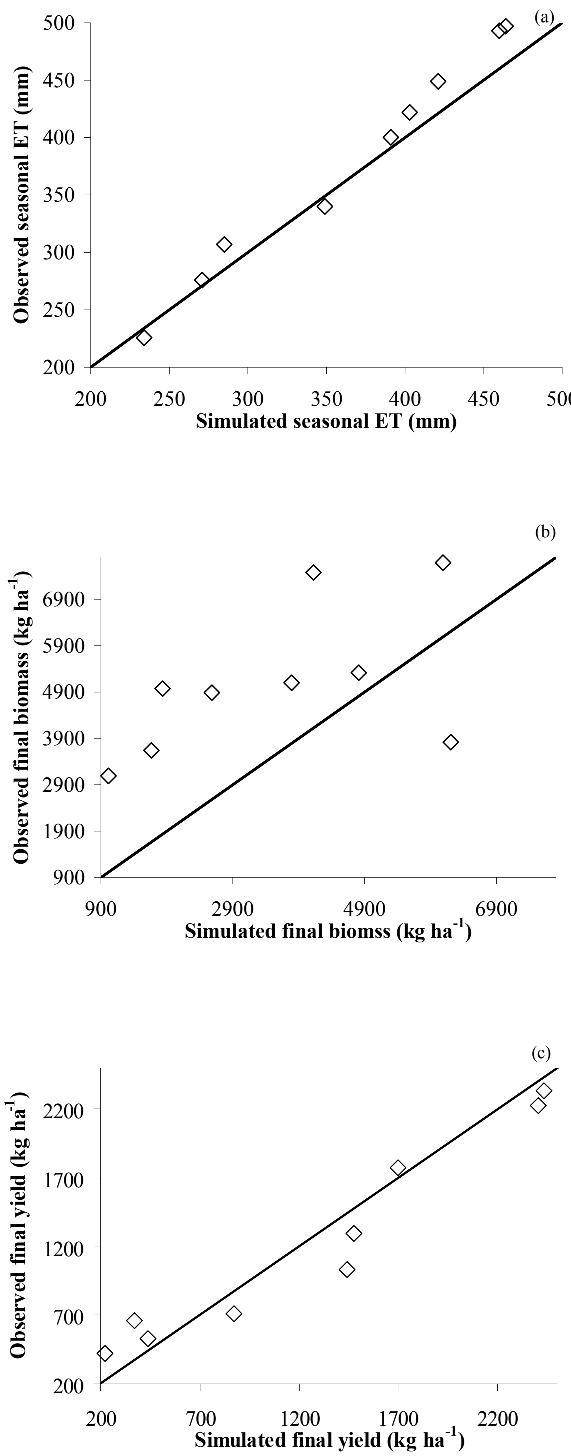

Figure 6.4. Comparison of simulated and observed (a) seasonal water consumption, (b) final biomass, and (c) final yield for the modified CROPGRO model. Points falling on the 1:1 line represent perfect model simulation and model performance was determined by the vertical distance a point falls from that line. Data are from the validation set with three levels of deficit irrigation and three levels of soil salinity

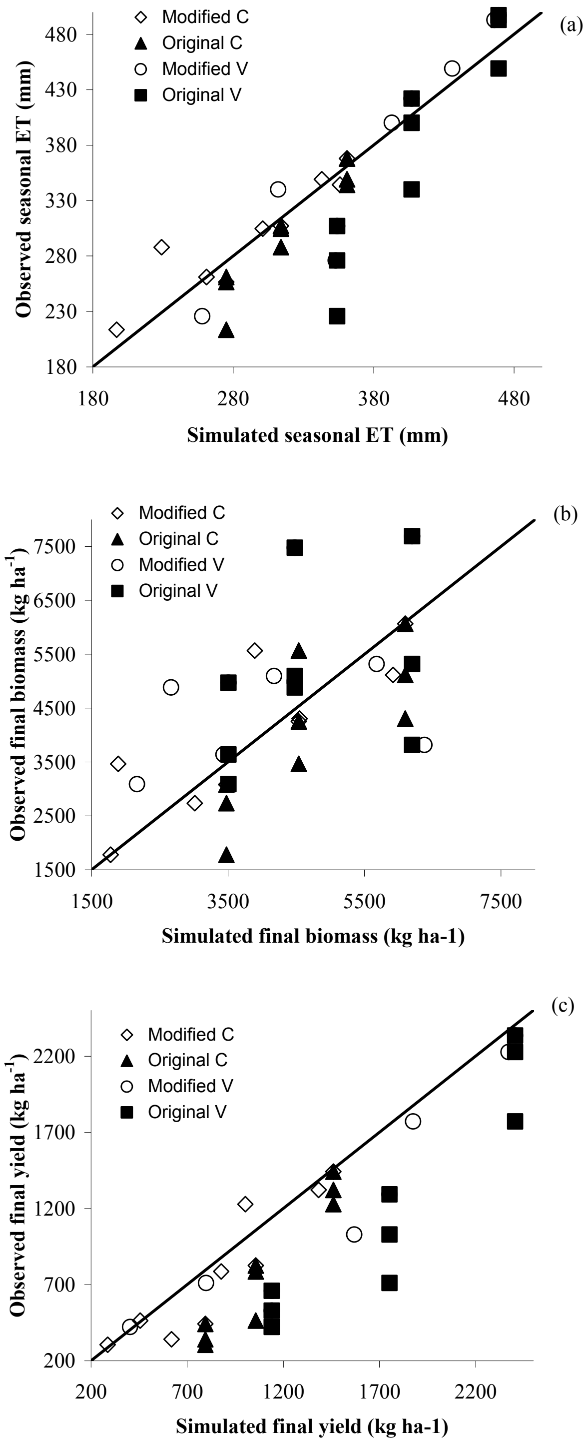

Figure 6.5. Comparison of simulated and observed (a) seasonal water consumption, (b) final biomass, and (c) final yield for the original and the modified CROPGRO model. Points falling on the 1:1 line represent perfect model simulation and model performance was determined by the vertical distance a point falls from that line. Data are from both the validation and calibration sets from the greenhouse experiment with three levels of deficit irrigation and three levels of soil salinity

Table 6.3. Performance evaluation of the original and modified version of CROPGRO using the calibration (C) and validation (V) greenhouse data sets

Variable of interest*		Model version	N**	Obs. mean	Sim. mean	RMSE	RE	MAE	i
Seasonal ET	**C**	original	9	299	298	11.4	0.04	10.54	0.986
(mm)		modified	9	299	296	10.4	0.03	9	0.988
	V	original	9	379	366.1	19.5	0.05	17.2	0.987
		modified	9	379	364	21.3	0.06	18	0.985
Final biomass	**C**	original	9	4042	4109	1059	0.26	733	0.853
(mm)		modified	9	4042	3875	957	0.24	633	0.886
	V	original	9	5109	3575	2216	0.43	2041	0.604
		modified	9	5109	3569	2231	0.44	2071	0.601
Final yield	**C**	original	9	795	831	134	0.17	106	0.977
(mm)		modified	9	795	800	108	0.14	85	0.983
	V	original	9	1220	1225	200	0.16	179	0.982
		modified	9	1220	1262	212	0.17	187	0.979

*Note on units: Obs. mean, Sim. mean, RMSE and MAEall have the same units as the variable of interest; RE and i are unitless; ** N is the number of observations used in each simulation

Table 6.4. Comparison of the original and modified version of CROPGRO using the calibration (C) and validation (V) greenhouse data sets with simulation control set for automatic irrigation

Variable of interest*			N**	Obs. mean	Sim mean	RMSE	RE	MAE	i
Seasonal ET	C	original	9	299	316	24.8	0.08	19.0	0.912
(mm)		modified	9	299	293	22.1	0.07	14.0	0.951
	V	original	9	378	410	59.0	0.16	46.0	0.826
		modified	9	379	383	36.4	0.10	30.0	0.945
Final biomass	C	original	9	4042	4704	1057	0.26	891	0.805
(kg ha^{-1})		modified	9	4042	3906	837	0.21	587	0.903
	V	original	9	5109	4729	1511	0.30	1199	0.637
		modified	9	5109	4298	1723	0.34	1461	0.645
Final yield	C	original	9	795	1104	353	0.44	308	0.794
(kg ha^{-1})		modified	9	795	881	188	0.24	143	0.942
	V	original	9	1220	1766	612	0.50	546	0.800
		modified	9	1220	1495	358	0.29	280	0.930

*Note on units: Obs. mean, Sim. mean, RMSE and MAE all have the same units as the variable of interest; RE and i are unitless; ** N is the number of observations used in each simulation

6.4.3 Field testing of the modified model

The results of the simulations of the Fergana Valley field experiments are shown in Table 6.5 and Fig. 6.6. The cultivar data calibrated in the greenhouse trial were used in these simulations, leaving only the soil fertility factor (*SLPF*) and the

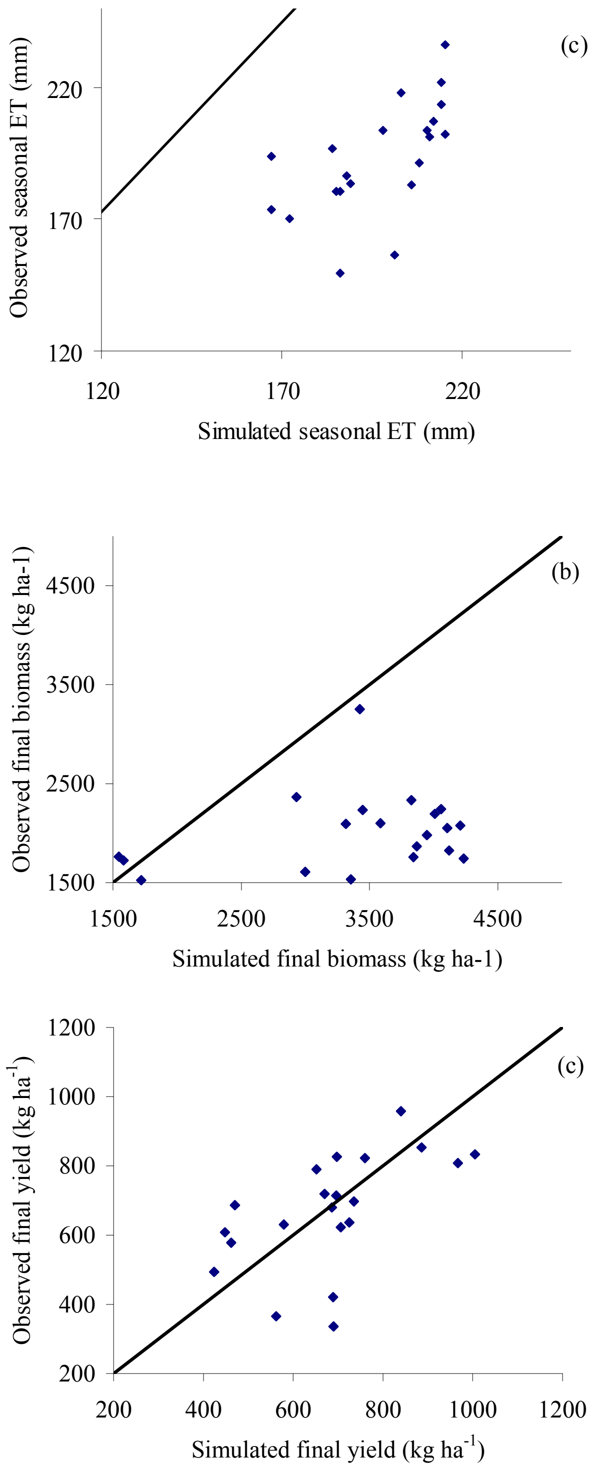

Figure 6.6. Comparison of simulated and observed (a) seasonal water consumption, (b) final biomass, and (c) final yield for the field experiment in Uzbekistan. Points falling on the 1:1 line represent perfect model simulation and model performance is determined by the vertical distance a point falls from that line. Data are from three levels of deficit irrigation and alternate conventional furrow irrigation treatments.

nodule number to be calibrated. The nodule number and effectiveness are two parameters that strongly influence growth of legumes in the CROPGRO model as they act as estimators of nitrogen availability. This was performed with the treatments with no water stress (depletion 45%, conventional and alternate furrow irrigation). Individual plots were treated as individual observations, as significant block effects existed for soil type and planting date. The model agreement is considered fair for yield and water use. Model calibration was complicated because of uncertainty in both the soil fertility and nodule number parameters. Both of these factors have a strong influence on biomass production, which was poorly predicted. In a sensitivity analysis, 10% increases in the nodule number and the soil fertility factor produced 6 and 8% increases in yield, whereas 20% increases in these values produced 10 and 15% increases in yield. By contrast, yield was much less sensitive to the two new parameters controlling the salinity stomatal response, S_1 and S_2. When S_1 was increased by 10 and 20%, yield increased by less than 1%. Yield decreased by 2 and 5% when S_2 was increased by these same amounts. This difficulty could be overcome by either (1) evaluating a crop that is well nodulated and assuming the nodule number and effectiveness was a maximum or (2) by testing the model with a non-nitrogen fixing crop to obtain a good estimate of the soil fertility factor.

Table 6.5. Performance indicators for the modified CROPGRO model applied to the field conditions of the Fergana Valley, Uzbekistan using three levels of deficit irrigation and conventional and alternate furrow irrigation.

Variable of interest*		**N****	**Obs. mean**	**Sim. mean**	**RMSE**	**RE**	**MAE**	**i**
Seasonal ET (mm)	V	21	193	197	17.2	0.09	13	0.749
Biomass (kg ha^{-1})	V	21	1984	3438	1680	0.85	1488	0.259
Yield (kg ha^{-1})	V	21	670	683	147.8	0.22	120	0.735

*Note on units: Obs. mean, Sim. mean, RMSE and MAE all have the same units as the variable of interest; RE and i are unitless; ** N is the number of observations used in each simulation

6.4 CONCLUSIONS

Crop models offer farmers and planners a safe and inexpensive method of evaluating different cropping systems and strategies. The CROPGRO model was selected as it is sufficiently responsive to crop physiology and a number of agronomic inputs to be of interest for application to crop growth responses to irrigation technologies in the Fergana Valley, Uzbekistan. Of particular interest are legume crops that could be grown after winter wheat harvest and offer rural people an opportunity to improve their food security. However, the current model is not sensitive to soil salinity and thus limits its applicability in the region. A salinity response function was successfully added a CROPGRO that correctly predicts yield and water use over a range of salinities, atmospheric conditions, levels of deficit irrigation and crop tolerances. The model was developed using data from soils dominated by gypsum salts, and thus the hypothesis that osmotic effects dominate was considered valid. The model's ability to correctly predict biomass under saline and water stressed conditions was less successful, though it performed as well as the original model. The model performed well for the conditions of the Fergana Valley.

6.5 ACKNOWLEDGEMENTS

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CHAPTER 7: GENERAL SUMMARY AND CONCLUSIONS

7.1 GENERAL SUMMARY AND CONCLUSIONS

The goal of this research was to investigate methods optimizing irrigation water use to improve food security for rural people living the Fergana Valley of Uzbekistan. While farmers have limited access to many resources, their obligation to produce the state ordered cotton and wheat and the lack of water are the most serious constraints to increasing food production. This study proposed cultivating short season food legumes in the late summer following winter wheat harvest, using water saving irrigation techniques, as a method to overcome these limitations. Crop growth modeling is proposed to be an effective and inexpensive way for farmers and planners to evaluate alternate cropping systems and technologies.

A field study in the Fergana Valley determined the water use efficiency of two legume crops irrigated with both deficit irrigation and alternate furrow irrigation. The study considered a number of parameters related to water use in a comparison of the response of the two crops to water stress to highlight the factors that lead to water savings while maintaining yields. A greenhouse study investigated the growth response of the same two legumes to soil salinity when irrigated with deficit irrigation in simulated gypsiferous soils typical of the region. The study was unique in that the literature on crop tolerance to salinity is generally not valid in these soils. Finally, a salinity response function was added to the crop growth model, CROPGRO, to enable its use in the Fergana Valley.

The field experiment revealed that both common bean and green gram can be successfully grown as second crops after winter wheat harvest in the region. Implementing alternate furrow and deficit irrigation enable considerable water savings to be realized. Use of alternate furrow irrigation produced water savings of 9 to 15% in crop consumptive use and by as much as 25% of the irrigation water applied; rainfall during the winter can replenish the soil profile accounting for the difference. Water savings with deficit irrigation were highly dependent on the crop. In green gram, average water savings of 33% were realized compared to an average of 12% for common bean. Likewise, under both techniques water use efficiency increased for green gram with increasing water stress whereas it was constant for common bean.

Patterns of root water extraction were markedly different between the crops when deficit irrigation was implemented. For common bean, treatments irrigated with deficit irrigation used less water than the control at depths 0 – 40 cm. However, at 60 cm depth, the stressed treatments extracted more water than the control. Conversely, for green gram, treatments irrigated with deficit irrigation used less water at all depths in the profile. This evidence, together with root biomass data, suggests that in response to water stress, common bean increases partitioning of assimilated carbon stores to root production to extract more water deeper in the soil profile. The result is that water savings are minimal as transpiration rates remain high and seed yield is decreased as root biomass increases. Green gram seems to employ a very different strategy including reduced root biomass and transpiration rates resulting in decreased water use at all depths in the soil.

Strategies to increase food production and reduce agricultural water use must be developed within the context of increasing land degradation due to salinization. Much of the available literature on crop salinity tolerance is not valid for the region's soils because of the large amounts of gypsum salts. For common bean and green gram, acceptable yields were attained at the highest level of salinization (EC_e of 7.5 dS m^{-1}). Biomass and leaf area accumulation were reduced by approximately 20% as the salinity was increased from 2.8 to 7.5 dS m^{-1}, which is considerably less than expected from the literature. These results indicate that in gypsiferous soils, not only is the yield reduction threshold higher, but the rate of yield decline with increasing salinity is less severe than in soils dominated by sodium and chloride salts. Finally, no interactions were found to exist between the application of reduced deficit irrigation and the degree of land salinization.

In an effort to make these finding more general and accessible, a commonly used crop growth model, CROPGRO, was modified and tested for use in the region. The root water uptake routine of the CROPGRO model was modified to account for the effects of soil salinity on water use and growth. The original hypothesis considered the only effect of salinity to be one of water deficit, as is common in most hydrological models.

However, unexpected results under conditions of combined dry and saline soil necessitated the addition of a second factor to reduce photosynthesis, mimicking stomatal closure under these conditions. It is unclear whether the hydrological models would have detected this error as they typically employ only statistical crop growth models. The modified CROPGRO model includes an iterative process that enabled an approach very similar to the empirical reduction functions. A qualitative analysis of the model indicated that the model performed as expected under a range of atmospheric, irrigation and crop tolerance scenarios. The Willmott agreement index, root mean square error, mean absolute error and relative error were employed to evaluate the model. The modified model performance was excellent for yield and ET when evaluated for the greenhouse study. The modified model was successfully tested with field data on common bean (*Phaseolus vulgraris*) from the experiment in the Fergana Valley, though the sensitivity of the model to a soil fertility function and relative nodule number made it difficult to assess the model performance.

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

This study investigated different aspects of improving irrigated food production in the Fergana Valley. There are several areas where further research is needed:

1 Develop a methodology for scheduling alternate furrow irrigations. This investigation showed the water saving ability of the technique, though scheduling was done relative to the conventional furrow irrigation strategy. Specifically, the study could investigation whether the use of the soil moisture in a dry furrow, wet furrow or an average of the two would be most appropriate.
2 Test the hypothesis that salinity effects in gypsiferous soils are due to water deficit effects by conducting the salinity response experiments reported in this thesis using weighing lysimeters to determine daily ET rates.
3 Evaluate the seasonal and longer term impact of the proposed cropping systems on soil salinity and water table depths. This study would involve the

parameterization of a two dimensional water and solute transport model. Currently, heavy irrigations are applied at the beginning of each year for leaching salts from the root zone, though this practice accelerates soil salinization by raising the water table.

4 Compare the water use and yield of plants in soils at equivalent values of soil salinity in soils with and without gypsum to enable the transfer of the coefficients of Maas and Hoffman (1977) to (1) soils containing gypsum and (2) the empirical salinity reductions functions for predicting root water uptake

5 Evaluate the salinity response function in the modified CROPGRO model for other crops currently modeled with CROPGRO

6 Evaluate the salinity response function in the modified CROPGRO model for soils in which the dominate salt is not gypsum. The modified model is expected to be valid under all conditions of low to moderate soil salinity for short season crops. However, if the toxic salt effects are found to be non-negligible, a factor to speed senescence could be implemented.

7 Adapt CROPGRO to model green gram. The work conducted for this thesis has amassed a great deal of data on the crop response to water deficit and salinity response that could be used in testing the model. However, to construct a species file for the model, experiments should be conducted using different cultivars and in a variety of environments.

7.3. CONTRIBUTIONS TO KNOWLEDGE

The work presented in this thesis provides original contributions to the body of knowledge concerning irrigated legume production under conditions of soil salinity. Specifically:

- **Green gram was shown to offer considerable water savings and high water use efficiency when irrigated with alternate furrow and deficit irrigation using a**

depletion factor of at least 65% when grown as a second crop in the Fergana Valley.

- **Green gram increased water use efficiency with deficit irrigation and alternate furrow irrigation by reducing root growth and soil water extraction. Water use efficiency in common bean was constant when either technology was implemented as the crop increased root biomass to access water deeper in the soil profile, evidently at the expense of seed yield.**

- **The salinity tolerance of common bean in a simulated gypsiferous soil was found to equal 4.8 dS m^{-1} and the relative rate of reduction in water use 4.6%/dSm^{-1}. The salinity tolerance of green gram in a simulated gypsiferous soil was found to be 2.8 dS m^{-1} and the relative rate of reduction in water use 3.5%/dSm^{-1}.**

- **A salinity response function was incorporated into the CROPGRO model. The modifications to the model were designed to predict crop growth in response to low to moderate soil salinity.** The model performance was verified in a qualitative analysis under conditions of increasing salinity for scenarios with variable climate, water stress and crop characteristics and in a quantitative comparison of simulated and measured greenhouse and field results.

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