MODELAÇÃO "ÁGUA-PRODUÇÃO" PARA CULTURAS MEDITERRÂNICAS VISANDO A PRODUTIVIDADE DA ÁGUA NA PRÁTICA DA REGA

TESE APRESENTADA PARA OBTENÇÃO DO GRAU DE DOUTOR EM ENGENHARIA DOS BIOSSISTEMAS

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Resumo

Melhorar a produtividade da água das culturas requer novas aproximações à modelação da produção e da evapotranspiração considerando alternativas na calendarização da rega. A modelação desenvolvida é mais simplificada e menos exigente em parâmetros do que os modelos existentes, dado que visa a sua integração num sistema de apoio à decisão para a gestão da rega. O modelo desenvolvido foi orientado à tomada de decisão ao nível da parcela ajudando no estabelecimento de sistemas agrícolas sustentáveis. Este modelo simplificado resultou da combinação entre o modelo de balanço hídrico SIMDualKc e o modelo de "água-produção" de Stewart. Comparou-se o desempenho do modelo simplificado com o do modelo de produção AquaCrop em termos de predição da água disponível no solo e da produção utilizando dados históricos e de ensaios de campo efetuados em parcelas de um agricultor. Foram desenvolvidos e analisados, em termos de impactos na produção e produtividade da água, vários cenários alternativos de gestão da rega para a convivência com a escassez. O modelo simplificado mostrou ter uma capacidade superior à do AquaCrop para a predição da produção das culturas estudadas e deste modo para o aconselhamento ao agricultor.

Palavras-chave: modelação, evapotranspiração, relações água-produção, balanço hídrico do solo, produtividade da água.

Abstract

Improving crop water productivity requires new modelling approaches to crop yield estimates and crop evapotranspiration considering irrigation scheduling alternatives. A simplified modelling approach was developed requiring less parameterization than existing models, aiming at integrating a decision support tool for irrigation management. The developed model focused on-farm decision support aiming at sustainable agricultural systems. The simplified model combines the soil water balance model SIMDualKc and the “water-yield” Stewart’s model. This simplified approach was compared with the crop growth model AquaCrop for available soil water and yield predictions using historical data and field data collected at a farmers’ field. Several alternative irrigation management scenarios were built and analyzed in terms of yield and water productivity to cope with water scarcity. The simplified model showed to be superior relative to AquaCrop providing good yield prediction results for the studied crops and for farmers’ advice.

Keywords: modeling, evapotranspiration, water-yield relations, soil water balance, water productivity.

Índice

Lista de símbolos e abreviaturas

€	euro
AAE	erro médio absoluto (unidades da variável)
a_D	parâmetro da equação da percolação profunda
A_{inv}	investimento anual (€ year^{-1})
ASW	água disponível no solo (mm)
ASWD	depleção de água no solo permitida ()
B	biomassa (t ha^{-1})
b_D	parâmetro da equação da percolação profunda
BWUF	fração de uso benéfico da água ()
C_a	investimento anual por unidade de área regada (€ ha^{-1} year^{-1})
CC*	fração do solo coberto pela vegetação atual (%)
CC_o	fração inicial do solo coberto pela vegetação
CC_x	fração máxima do solo coberto pela vegetação
C_d	taxa de uso de energia (€ kW^{-1}),
CDC	coeficiente de declínio do coberto
C_{en}	somatório dos custos anuais de energia (€)
CGC	coeficiente de crescimento do coberto
C_{inv}	custos de investimento (€)
C_m	custos anuais de manutenção (€)
CRF	fator de amortização ()
D	dotação líquida aplicada (mm)
DI	rega deficitária
d_{IA}	índice de ajustamento de Willmott ()
DU	uniformidade de distribuição (%)
EF	eficiência de modelação ()
E_r	taxa energética (€ kWh^{-1})
E_s	evaporação do solo (mm)
ET_c	evapotranspiração cultural máxima (mm)
$ET_{c\ adj}$	evapotranspiração cultural actual (mm)
ET_o	evapotranspiração de referência (mm)
EWP	produtividade económica da água (€ m^{-3})
EWP_{irrig}	produtividade económica da água de rega (€ m^{-3})
EWPR	razão da produtividade económica da água ()
$EWPR_{full\ cost}$	razão da produtividade económica da água considerando os custos totais de produção ()
f_c	fração do solo coberto pela vegetação ()
f_{HI}	fator de ajustamento do índice de colheita
f_w	fração do solo molhada ()
h	altura da cultura (m)
HI	índice de colheita

HI_o	índice de colheita de referência
I	dotação de rega sazonal (mm)
I	taxa de infiltração (mm h^{-1})
i	taxa de juro (%)
IWU	uso da água de rega (m^3)
$K_{c\ act}$	coeficiente cultural atual ()
$K_{c\ mid}$	coeficiente cultural relativo ao período intermédio ()
K_c	coeficiente cultural ()
K_{cb}	coeficiente cultural de base ()
$K_{cb\ adj}$	coeficiente cultural de base ajustado ()
$K_{cb\ end}$	coeficiente cultural de base relativo ao período final ()
$K_{cb\ ini}$	coeficiente cultural de base relativo ao período inicial ()
$K_{cb\ mid}$	coeficiente cultural de base relativo ao período intermédio ()
$K_{cTr,x}$	coeficiente máximo de transpiração da cultura (),
K_e	coeficiente de evaporação ()
K_{ex}	coeficiente máximo de evaporação do solo
k_p	parâmetro de Kostidiakov (h^{-a})
K_r	coeficiente de redução da evaporação do solo (0 - 1)
K_s	coeficiente de stress ou de défice de humidade do solo ()
K_{sat}	condutividade hidráulica saturada (cm d^{-1})
K_y	fator de quebra de produção ()
MCA	análise multicritério
p	fração de esgotamento da água do solo ()
pa	percentagem da área adequadamente regada (%)
PELQ	eficiência potencial do quartil mínimo (%)
P_p	potência da estação de bombagem (kW)
RAW	água facilmente utilizável (mm)
REW	água facilmente evaporável (mm)
RMSE	erro médio quadrático (mm)
RYL	perda relativa de produção (%)
S1	modelo global de Stewart
S2	modelo fásico de Stewart
t	tempo (h)
T_a	transpiração cultural atual (mm)
TAW	água disponível total (mm)
T_c	transpiração máxima da cultura (mm)
T_d	défice de transpiração (mm)
$T_{d,f}$	défice de transpiração durante o período da floração (mm)
$T_{d,m}$	défice de transpiração durante o período da maturação (mm)
$T_{d,v}$	défice de transpiração durante o período vegetativo (mm)
TEW	água total evaporável (mm)
T_i	tempo total de operação da bomba (h)

TWU	uso total de água (m^3)
U_j	utilidade relacionada com o critério j [0-1]
WP	produtividade da água ($kg\ m^{-3}$)
WP_b*	produtividade da água normalizada para a concentração de CO_2 da atmosfera e para a ET_o ($g\ m^{-2}$).
WP_{irrig}	produtividade da água de rega ($kg\ m^{-3}$)
x_j	atributo
Y	produção ($t\ ha^{-1}$)
Y_a	produção atual ($kg\ ha^{-1}$)
Y_m	produção máxima ou potencial ($kg\ ha^{-1}$)
Z_e	profundidade da camada evaporativa (m)
Z_r	profundidade radicular (m)
α	declive do gráfico
β	valor da utilidade
β_f	fator de quebra de produção durante o período de floração
β_m	fator de quebra de produção durante o período de maturação
β_v	fator de quebra de produção durante o período vegetativo
θ_{FC}	teor volumétrico de água do solo à capacidade de campo ($m^3\ m^{-3}$)
θ_{sat}	teor volumétrico de água do solo à saturação ($m^3\ m^{-3}$)
θ_{WP}	teor volumétrico de água do solo ao coeficiente de emurchecimento ($m^3\ m^{-3}$)
λ_j	peso do critério j

Capítulo 1 - Introdução

1. Introdução

1.1. Considerações gerais

A agricultura enfrenta o grande desafio de aumentar a produção de alimentos para responder ao aumento da procura, obrigando a desenvolver novas estratégias no sentido de obter maior produção. Uma vez que uma das principais causas da baixa produtividade agrícola é a deficiente gestão dos recursos naturais, nomeadamente os hídricos, torna-se assim primordial uma adequada gestão da rega (Pereira, 1999).

A gestão da rega tem efeitos económicos tanto em termos de redução de usos não benéficos – tais como de desperdícios de água - (Pereira et al., 2009) como em termos de custos de operacionalidade. A gestão de recursos em condições de escassez centra-se na água e na prioridade para a eficiência de utilização desta. O desafio deste tipo de estratégias de gestão é produzir mais utilizando menor quantidade de água (Oweis et al., 1999).

Na gestão da água em agricultura, nomeadamente em condições de escassez de água, podem distinguir-se três aspetos fundamentais (Pereira et al., 2002, 2012): 1) gestão dos abastecimentos de água para uso agrícola; 2) redução dos consumos hídricos focando a gestão da procura, tanto à escala regional como da parcela; e 3) poupança de água resultante da gestão da rega em condições de disponibilidades de água limitadas.

As medidas de restrição ao abastecimento de água à agricultura, têm de ser complementadas com medidas que favoreçam a diminuição da procura de água (Pereira, 1999; Pereira et al., 2002, 2009). Para tal podem adotar-se várias medidas, tais como:

a. Modificação dos sistemas de produção através da substituição das culturas tradicionais por culturas menos exigentes em água;

b. Diminuição da área das culturas mais exigentes em água;

c. Utilização da rega deficitária, ou seja aplicação deliberada de uma quantidade de água inferior às necessidades da cultura, ou utilização da rega de complemento em sistemas de sequeiro;

d. Utilização e aplicação de novas regras de condução da rega; e

e. Controlo do preço da água, com objetivo de otimizar a utilização desta.

A programação e a condução da rega são processos complexos que incluem a gestão e interação de vários fatores - restrições na água disponível, na mão-de-obra e na energia, características dos sistemas e equipamentos, regras de fornecimento de água, características do solo, condições climáticas e práticas agrícolas. Assim, ainda não são práticas modernas utilizadas pela maioria dos agricultores, e somente uma parte restrita da informação é utilizada, por gestores, extensionistas e consultores. A geração de calendários de rega pode ser efetuada por modelos de simulação de rega após a sua calibração e validação para as condições locais.

A condução da rega é o processo decisório tomado pelo agricultor ou gestor relativamente a quando regar e quanta água vai ser aplicada à cultura (Pereira, 2004). A elaboração de calendários de rega requer o conhecimento das necessidades de água da cultura e respostas da produção à água, das limitações inerentes a cada método de rega e respetivo equipamento, das restrições relativas aos sistemas de abastecimento de água e das implicações económicas do regadio (Heermann, 1996; Pereira et al., 2002, 2012). Estes fatores têm de ser considerados no seu conjunto de modo a gerir de forma adequada o processo decisório. A condução da rega deve ser entendida como a procura da combinação ótima entre as necessidades hídricas da cultura, as características do solo e do sistema de rega, associada às condicionantes técnicas, económicas e sociais do meio em que o agricultor está inserido. É reconhecido que a adoção deste tipo de práticas pode levar a melhorias de produção das culturas e de resultados económicos para os agricultores, a poupanças significativas de água, à diminuição de impactos ambientais adversos resultantes da rega e permitem também atingir a sustentabilidade da agricultura de regadio (Smith et al., 1996).

Ao nível da exploração agrícola, a produção é o objetivo principal do agricultor. Assim, a prática mais generalizada na agricultura de regadio é maximizar o rendimento da cultura por unidade de área aplicando a quantidade de água necessária a suprir as necessidades da cultura (rega ótima) e, por vezes, até regar mais do que o necessário (Pereira et al., 2002). No entanto, vários estudos permitiram concluir que existem maiores benefícios quando as decisões de rega se baseiam em objetivos económicos como seja o de maximizar os benefícios específicos (English, 2002; Rodrigues et al., 2013). Alternativamente se o objetivo do agricultor ou gestor for maximizar os benefícios ou o lucro tal significa, de um modo geral, optar pela utilização da rega deficitária controlada, ou seja, regar deliberadamente abaixo do nível de máxima produção que corresponda ao ótimo económico (El Amami et al., 2001; Pereira et al., 2002; Victoria et al., 2005; Rodrigues e Pereira, 2009; Rodrigues et al., 2013). Para uma correta gestão da rega deficitária, há a necessidade de estudar os períodos em que a cultura é mais suscetível ao stress hídrico de modo a elaborar os calendários de rega impondo stress nos momentos em que não existe significativa sensibilidade da produção a esse stress.

A investigação tem disponibilizado um grande número de ferramentas de planeamento e calendarização da rega, incluindo procedimentos para o cálculo das necessidades de água da cultura, simulação do balanço hídrico do solo e estimativa do impacto do défice hídrico na produção. Os primeiros modelos de produção, foram disponibilizados nos anos setenta e destinavam-se a estudar os mecanismos fisiológicos explicativos do desenvolvimento e crescimento das culturas, caso do modelo BACROS (de Wit et al. 1970). Os modelos foram entretanto evoluindo, podendo-se destacar alguns com maior aplicação em termos mundiais: CERES (Ritchie e Otten 1985), WOFOST (van Diepen et al. 1988), SUCROS (Bouman et al. 1996) e CROPGRO (Boote et al. 1998). Surgiram posteriormente modelos mais complexos e mais potentes, e.g. CropSyst (Stöcle et al. 2003), STICS (Brisson et al. 2003); InfoCrop (Aggarwal et al. 2006) e AquaCrop (Steduto et al., 2012). Foram também surgindo modelos mais complexos, e em cuja estrutura se integram outros modelos, casos do DSSAT (Jones et al., 2003; Thorp et al. 2008) e do APSIM (McCown et al. 1996; Delve et al. 2009).

Estes modelos aplicam representações detalhadas da fenologia e fisiologia das plantas, requerendo parametrização e calibração muito laboriosas. As dificuldades adensam-se quando se pretende a integração dos modelos em sistemas de apoio à decisão para a programação das regas visto haver que combinar, em tempo real, a simulação do crescimento e produção com a simulação da rega. Havendo que tratar um grande número de variáveis, parâmetros e hipóteses, a ser manipuladas pelo utilizador e difíceis de obter, resulta uma complexidade demasiado grande para o apoio ao agricultor em tempo real. Decorre a necessidade de desenvolver modelos simples água-produção capazes de simular o comportamento da produção face aos fatores que a condicionam.

Uma aproximação à resolução destes problemas é o uso de modelos determinísticos simplificados que definem o comportamento das plantas com poucas relações. Foram desenvolvidas várias aproximações simplificadas para a determinação dos impactos do défice hídrico na produção. A primeira, tendo por base o cálculo da evapotranspiração cultural, foi apresentada por Jensen (1968), que desenvolveu um modelo multiplicativo para mostrar os efeitos do stress hídrico em várias fases do desenvolvimento das culturas sobre o produto comercializável. O modelo mostrava o impacto que o stress imposto numa dada fase do desenvolvimento se iria repercutir nas fases seguintes. O modelo simplificado de Hanks (1974), PLANTGRO, assumia que a produção matéria seca tinha uma relação linear com a transpiração da cultura. Para a produção de grão Hanks (1974) adaptou o modelo de Jensen (1968) mas utilizando a transpiração em alternativa á evapotranspiração da cultura (Hanks e Hill, 1980).

O modelo água-produção mais geralmente utilizado é o de Stewart et al. (1977), divulgado por Doorenbos e Kassam (1979). Baseia-se no conhecimento do fator de resposta da cultura à água (K_y) que exprime a relação linear entre o défice de evapotranspiração sazonal ($1-ET_a/ET_c$) e as perdas relativas de produção ($1-Y_a/Y_m$), onde Y_a e Y_m representam a produção real e a potencial, respetivamente. A grande utilidade deste tipo de aproximações às relações “défice de produção-défice de ET” é a possibilidade de comparar estratégias de rega e, assim, escolher as que melhor respondem às finalidades do caso em questão (Liu et al., 2000; Popova et al., 2006; Popova e Pereira, 2011; Dominguez et al., 2012). O modelo pode ser aplicado sazonalmente (modelo global) ou por fases do desenvolvimento (modelo fásico). Existem vários modelos de simulação do balanço hídrico que constituem ferramentas preciosas para a determinação das necessidades de rega e avaliação dos impactos da rega na evapotranspiração da cultura e no caso do utilizado neste estudo, o modelo SIMDualKc (Rosa et al., 2012), que permite a partição da ET nas suas componentes, e que provou bem a sua combinação com os modelos de Stewart et al. (1977).

1.2. Objetivos

Os agricultores e gestores confrontam-se diariamente com opções que visam a maximização da produção mas com uma aplicação minimizada de água de rega, *i.e.* maximizando a produtividade da água de rega. Como anteriormente referido, os modelos de produção existentes requerem muitos inputs e deste modo um grande esforço para a sua parametrização tornando-se, assim, dificilmente utilizáveis pelos diferentes atores, ou seja, a sua aplicabilidade é complexa e, assim, questionável na prática da gestão da rega.

O objetivo deste estudo foi, assim, a modelação água-produção, tanto recorrendo a um modelo de produção mais complexo (AquaCrop) como através da conceção e aplicação de um conjunto de aproximações simplificadas de simulação dos principais processos relativos à produção das culturas testando a combinação do modelo de balanço hídrico SIMDualKc com o modelo "água-produção" de Stewart (Fig. 1). No entanto, o modelo de Stewart foi adaptado de forma a utilizar a transpiração da cultura em vez da evapotranspiração (ET) uma vez que a transpiração é a componente da ET diretamente responsável pela produção. Assim, foram avaliadas e comparadas as duas aproximações em termos de capacidade de predição da água disponível no solo e da produção. O desenvolvimento da aproximação mais simplificada tem como propósito a integração num sistema de apoio á decisão para o aconselhamento aos agricultores.

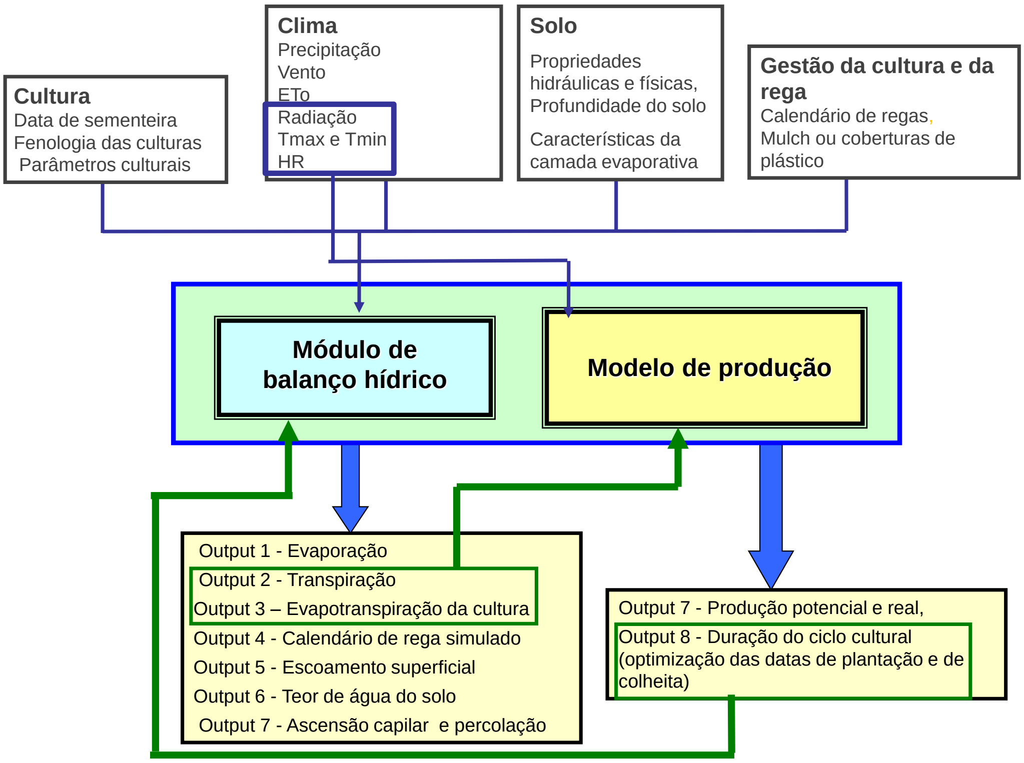

Fig. 1.1. Esquema conceptual do modelo simplificado água-produção.

A modelação desenvolvida foi aplicada a culturas de regadio em parcelas de agricultores, tendo em consideração as condições edafo-climáticas e as suas práticas de gestão. Os modelos foram calibrados e testados para tais condições. Adicionalmente foram testados utilizando dados de campo de estudos anteriores. Estas aproximações permitiram avaliar diferentes cenários alternativos que foram avaliados em termos económicos para apoiar a tomada de decisão e proceder ao aconselhamento aos agricultores. Em resumo, os objetivos deste estudo visaram:

1. Calibrar e validar o modelo AquaCrop e o modelo simplificado (SIMDualKc-Stewart) para várias culturas de regadio e em distintas condições edafoclimáticas

2. Avaliar os calendários aplicados pelo agricultor e impactos destes na produção obtida

3. Avaliar cenários alternativos de gestão da rega em condições de escassez, nomeadamente em termos de produtividade física e económica da água

1.3. Estrutura da tese

O primeiro Capítulo pretende contextualizar o problema associado á gestão da rega em condições de escassez e o seu impacto na produção, e estabelecer os objetivos onde o estudo assenta.

No Capítulo 2 é efetuada a calibração e validação do modelo de balanço hídrico do solo e calendarização da rega SIMDualKc para diversas culturas, recorrendo a vários métodos de rega, incluindo a rega por gravidade, a aspersão e a microrrega, usando dados de campo recolhidos em várias regiões do Mediterrâneo e na Ásia Central.

Uma primeira aproximação ao cálculo das necessidades da cultura do milho regado por aspersão para vários locais de Portugal continental é apresentada no Capítulo 3. Esta determinação foi efetuada utilizando o modelo SIMDualKc depois de calibrado e validado. Definem-se várias estratégias de rega, nomeadamente a deficitária com o objetivo de reduzir a procura de água de rega em condições de escassez (seca severa e extrema). Estas estratégias foram avaliadas em termos de poupança de água de rega e perdas potenciais de produção, sendo que estas foram calculadas utilizando um modelo água-produção simplificado integrando o modelo de balanço hídrico SIMDualKc com o modelo global de água-produção desenvolvido por Stewart et al. (1977).

No Capítulo 4 apresentam-se os resultados de um modelo água-produção simplificado integrando o modelo de balanço hídrico SIMDualKc com os modelos global e fásico de água-produção desenvolvidos por Stewart et al. (1977). A aplicação foi efetuada á cultura do milho sujeito a diferentes opções de gestão da rega, desde rega para satisfação das necessidades de água da cultura (rega completa) a diferentes níveis de rega deficitária. Os estudos tiveram por base trabalho experimental ao nível da parcela de um agricultor e de campos experimentais. Geraram-se calendários de rega alternativos tendo por base um calendário praticado pelo agricultor. A viabilidade destes calendários alternativos foi avaliada em termos de produtividade física e económica da água.

No Capítulo 5 é efetuada a aplicação de um modelo mais robusto e recentemente desenvolvido e disponibilizado pela FAO (AquaCrop) aos mesmos dados experimentais do Capitulo 4 com o objetivo de testar as suas capacidades de previsão da água disponível no solo, produção de biomassa e de grão de milho, para apoio ao agricultor na sua tomada de decisão de gestão da rega. O modelo foi também testado recorrendo aos parâmetros tabelados com o objetivo de avaliar as capacidades do modelo na previsão da produção no caso de não existirem dados experimentais que permitam a sua calibração.

No Capítulo 6 avalia-se a viabilidade económica da rega completa e deficitária do milho no Perímetro de Rega da Vigia, sob diferentes sistemas de rega e recorrendo a análise multicritério. Avaliam-se e comparam-se os diferentes calendários de rega considerando dois preços do milho e três sistemas de rega.

Os Capítulos 7 e 8 apresentam os resultados da aplicação do modelo água-produção simplificado definido no Capítulo 4 e do modelo AquaCrop para a estimativa da produção respetivamente da ervilha e da cevada para indústria e com o objetivo de apoio ao agricultor na tomada de decisão em termos de gestão da rega. No Capítulo 8 são analisados os impactos na produção de diferentes estratégias de gestão nomeadamente relativa á data da sementeira e calendários de rega em condições de seca severa e extrema. Esta análise não é efetuada para o caso da ervilha pois a sua qualidade é altamente influenciada pelo stress hídrico e deste modo não é viável a outro tipo de gestão da rega que não seja orientada á plena satisfação das necessidades de rega.

No Capítulo 9 é efetuada a calibração e validação do modelo de balanço hídrico do solo e calendarização da rega SIMDualKc para a cultura da soja usando dados de campo experimental recolhidos na China. Procede-se á avaliação do modelo de água-produção simplificado para esta cultura. Avalia-se ainda a produtividade da água.

Por fim no Capítulo 10 apresentam-se as conclusões gerais do estudo em resposta aos objetivos inicialmente propostos e indicam-se perspetivas de desenvolvimentos futuros.

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Chapter 2 - Implementing the dual crop coefficient approach in interactive software: 2. Model testing

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Rosa, R.D., Paredes, P., Rodrigues, G.C., Fernando, R.M., Alves, I., Allen, R.G., Pereira, L.S., 2012. Implementing the dual crop coefficient approach in interactive software: 2. Model testing. Agric. Water Manage. 103: 62-77

Implementing the dual crop coefficient approach in interactive software: 2. Model testing

Abstract

This paper is the second of a two-part series, with the first part describing the SIMDualKc model, an irrigation scheduling simulation tool that employs the dual crop coefficient approach for calculating daily crop ET and then performs a water balance for a cropped soil. The model was applied, calibrated and validated for rainfed and basin irrigated maize (Coruche, Portugal), rainfed and surface irrigated wheat (Aleppo, Syria), and furrow irrigated cotton (Fergana, Central Asia). Results show good agreement between available soil water content observed in the field and that predicted by the model. Results indicate that the calibrated model does not tend to over- or underestimate available soil water over the course of a season, and that the model, prior to calibration, and using standard values for many parameters, also performed relatively well. After calibration, the average growing season maximum estimation errors were 10 mm for maize, 8 mm for winter wheat and 9 mm for cotton, *i.e.*, respectively 3.6, 2.9 and 5.0% of total available water. Results indicate that the separation between evaporation and transpiration and the water balance calculation procedures are accurate enough for use in operational water management. The indicators used for assessing model performance show the model to accurately simulate the water balance of several crops subjected to a variety of irrigation management practices and various climate conditions. In addition, the model was applied to alternative irrigation management scenarios and related results are discussed aiming at assessing the model's ability to support the development of alternative active water management strategies.

Keywords: crop transpiration, soil evaporation, soil water balance, model calibration and validation, alternative irrigation management, maize, winter wheat, cotton.

2.1. Introduction

Most irrigation simulation models that compute crop evapotranspiration (ET_c) use time averaged crop coefficients (K_c), which provide satisfactory results for various time step calculations, including for daily ET_c estimation, with appropriate accuracy for most applications. However, for high frequency irrigation and for partial cover crops, as well as when frequent rainfall events occur, the adoption of the dual K_c approach may produce more accurate ET_c estimates (Allen et al., 2005a). Partitioning the K_c into the soil evaporation component (K_e) and the basal crop ET component (K_{cb}) makes it possible to better assess the impacts of soil wetting by rain or irrigation, as well as the impacts of keeping part of the soil dry or using mulches for controlling soil evaporation (E_s). The SIMDualKc model, described in the companion paper (Rosa et al., 2011), was developed to compute crop ET using many recent refinements and extensions to the dual K_c approach (Allen et al., 1998, 2005b, 2007; Allen and Pereira, 2009) and to perform soil water balance simulations for irrigation scheduling.

The SIMDualKc model was applied to various data sets representing field experiments with maize, winter wheat, and cotton with the purpose of testing its accuracy and flexibility in describing local conditions and cultural practices. The model was calibrated and validated for those crops where different irrigation methods and water management approaches were used by comparing the observed and the simulated soil water content. This paper presents the application of the SIMDualKc model for those crops using standard and calibrated crop and soil evaporation parameters and analyzing the respective performance. The application of the model to alternative management scenarios is also presented and results are discussed aiming at analyzing the model ability to support the development of alternative water management strategies.

2.2. Material and methods

The SIMDualKc model (Rosa et al., 2011) uses the dual crop coefficient approach (Allen et al., 1998, 2005b) to calculate crop evapotranspiration (ET_c), with separate consideration of the soil evaporation and crop transpiration components. It allows for more precise analysis of how water from precipitation and irrigation is used by the crop. The actual crop evapotranspiration, which differs from ET_c when water stress occurs, is defined as:

$$ET_{c\ adj} = \left(K_s K_{cb} + K_e\right) ET_o \tag{2.1}$$

where ETc adj is the actual crop evapotranspiration [mm d^{-1}], K_{cb} the basal crop coefficient [ ], K_s the water stress coefficient [ ], K_e the soil evaporation coefficient [ ] and ET_o the reference crop evapotranspiration [mm d^{-1}]. A complete description of the model is presented in the companion paper by Rosa et al. (2011).

The model was evaluated by comparing observed and simulated available soil water values, over time, for several field experiments involving maize, wheat, and cotton. The simulations were performed using soil, crop, irrigation, and weather data collected during complete crop seasons. Other information needed for running the model that was not collected in the field was estimated or taken from standard tables; this was the case for the basal crop coefficients (K_{cb}), depletion fraction for non-stress (p), total evaporable water (TEW), readily evaporable water (REW), thickness of the evaporation soil layer (Z_e) (Allen et al., 1998, 2007) and, in some cases, the parameter values used to estimate deep percolation and groundwater contribution in the presence of a shallow water table (Liu et al., 2006). All of the standard parameters are designed to be transferred for use in different climates, but they may need to be calibrated according to specific cropping conditions and soil characteristics.

Data from several field experiments were used: (1) at Sorraia irrigation district, Coruche, Portugal, with maize cropped under full and deficit surface irrigation, and rainfed conditions (Fernando, 1993); (2) at Aleppo, Syria, for wheat under rainfed conditions and surface supplemental irrigation (Oweis et al., 2003); and (3) in Fergana Valley, Uzbekistan, for cotton cropped under various furrow irrigation management practices (Cholpankulov et al., 2008).

Soil data collected at the experimental sites included basic soil hydraulic properties and soil water content measured at different depths within effective rooting zones throughout the crop seasons. Crop data included observed crop growth stage dates, crop cover parameters, crop height and root depths from planting to harvesting. Meteorological data from the nearest weather station were used to input precipitation and reference evapotranspiration, which was computed using the FAO Penman-Monteith method (Allen et al., 1998). The capillary rise from a shallow water table was estimated using the parametric equations from Liu et al. (2006) in Coruche (Portugal) and Fergana Valley (Central Asia). For this latter case study, parametric equations of Liu et al. (2006) were also used to estimate deep percolation fluxes caused by the application of large irrigation depths.

The calibration procedure consisted of adjusting the non-observed (*i.e.*, standard) parameters (K_{cb}, p, TEW, REW, initial soil water content, capillary rise and deep percolation parameters) to minimize differences between observed and simulated available soil water values relative to the entire root depth profile (Popova and Pereira, 2011). A first set of soil parameters was estimated according to Rosa et al. (2011). Then a trial and error procedure was initiated for selecting values for K_{cb} and p, starting with the standard tabled values. When K_{cb} and p values were in an acceptable range, trial and error was then applied to the soil parameters and again for crop parameters, until differences between observed and simulated values were approximately minimized and stabilized. The validation of the model consisted of using the calibrated values to simulate other local field experiments. When the results for validation were not appropriate, the process of calibration was repeated as noted. For Coruche, experimental data on rainfed maize were used for calibration and data from the deficit and full irrigation experiments were used for validation. At Aleppo, data from a rainfed wheat experiment were taken for calibration, and supplemental irrigation data were used for validation. For cotton in Fergana, the model was first calibrated for 2001 observations and validated with 2003 data. For all cases, the model was also applied using standard parameters proposed by Allen et al. (1998, 2007) to assess how well the daily time step model performed using general crop coefficients and soil parameters based on soil texture.

Both qualitative and statistical means were used to assess the goodness of fit of SIMDualKc model predictions to observations. The qualitative strategy consisted of graphically presenting soil water content values observed in the field versus those simulated by the model. This strategy provided a good perspective on trends and/or biases in modeling and when they occurred. The second assessment strategy used linear regression forced through the origin between observed and predicted soil water content data. Generally, the observed soil water data were collected on a daily to weekly interval, depending on the time during the growing season and proximity to irrigation events. A regression coefficient (b) is close to 1.0 when the covariance was close to the variance of the observed values, indicating that predicted and observed values were statistically similar; a coefficient of determination (R^2) close to 1.0 indicated that most of the total variance of the observed values was explained by the model. Additionally, a set of indicators describing residual estimation errors was used, as employed in previous studies and applications (Green and Stephenson, 1986; Loague and Green, 1991; Liu et al., 1998; Legates and McCabe, 1999; Cholpankulov et al., 2008; Moriasi et al., 2007; Popova and Pereira, 2011)

The goodness of fit was assessed through the indicators listed below, where O_i and P_i (i = 1, 2, …, n) represent pairs of observed and predicted values for a given variable, and $\overline{O}$ and $\overline{P}$ are the respective mean values:

- The coefficients of regression and determination relating observed and simulated data, b and R^2 respectively, are defined as:

$$b = \frac{\sum_{i=1}^{n} O_i \, P_i}{\sum_{i=1}^{n} O_i^{\,2}} \tag{2.2}$$

$$R^2 = \left\{ \frac{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)}{\left[\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2\right]^{0.5} \left[\sum_{i=1}^{n} \left(P_i - \overline{P}\right)^2\right]^{0.5}} \right\}^2 \tag{2.3}$$

- The root mean square error, RMSE, which characterizes the variance of the estimation error:

$$\mathrm{RMSE} = \left[\frac{\sum_{i=1}^{n} \left(P_i - O_i\right)^2}{n} \right]^{0.5} \tag{2.4}$$

- The average absolute error, AAE, which expresses the mean size of estimation error:

$$\mathrm{AAE} = \frac{1}{n} \sum_{i=1}^{n} \left| O_i - P_i \right| \tag{2.5}$$

- The average relative error, ARE [%], that expresses the size of error in relative terms:

$$\mathrm{ARE} = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{O_i - P_i}{O_i} \right| \tag{2.6}$$

- The modeling efficiency, *EF*, that is the ratio of the mean square error to the variance in the observed data, subtracted from unity:

$$\mathrm{EF} = 1.0 - \frac{\sum_{i=1}^{n} \left(O_i - P_i\right)^2}{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2} \tag{2.7}$$

As suggested by Legates and McCabe (1999), if the square of the differences between model simulations and observations is as large as the variability in the observed data, then *EF* tends toward 0.0 and the observed mean, $\overline{O}$, is as good a predictor as the model, while negative values indicate that $\overline{O}$ is an even better predictor than the model. *EF* can vary between – ∞ and 1.

- The index of agreement (non-dimensional):

$$d_{IA} = 1 - \frac{\sum_{i=1}^{N}\left(O_i - P_i\right)^2}{\sum_{i=1}^{N}\left(\left|P_i - \overline{O}\right| + \left|O_i - \overline{O}\right|\right)^2} \tag{2.8}$$

This index corresponds to the ratio between the mean square error and the "potential error" defined as the sum of the square of summed absolute differences between P_i and O_i to $\overline{O}$. d_{IA} represents the largest relative value that can occur from each observation-model simulation pair of values (Legates and McCabe, 1999; Moriasi et al., 2007). The maximum and best value for d_{IA} is 1.0.

2.3. Case study on maize

2.3.1. Site characteristics

Field data were collected at the António Teixeira Experimental Station, Coruche, which is located inside a 15000 ha irrigation project in the Sorraia Valley of southern Portugal. The meteorological station is located inside the experimental site (38.57º N, 8.31º W, altitude 30 m) over clipped grass. The maximum and minimum temperatures (ºC), minimum relative humidity (%), reference evapotranspiration (mm), and precipitation (mm) observed at Coruche during the year of the experiments (1989) are shown in Fig. 2.1. The area has a typical Mediterranean climate, with little precipitation during summer.

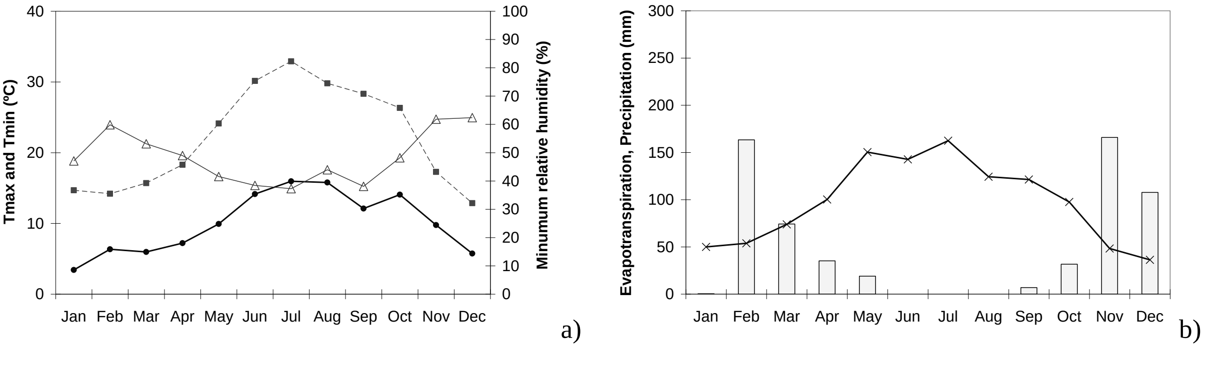


Fig. 2.1. Climatic data from Coruche meteorological station, 1989: a) average monthly maximum (- -■- -) and minimum (—●—) air temperature, and minimum (—△—) relative humidity; and b) monthly precipitation (▯) and monthly reference evapotranspiration (ET_o) (—×—).

Soil types in the experimental area are silty loam of recent alluvial origin. Main characteristics are presented in Table 2.1. Total available soil water (TAW) averaged 260 mm m^{-1}. Measured maximum rooting depth for the maize crop was 1.40 to 1.65 m, based on the collection of soil samples with an Eldeman type probe and visually checking the existence of roots. Because the water table was close to these depths, a steady soil moisture profile near saturation was observed below 1.1 m (Fernando, 1993). These conditions induced little root water uptake from depths deeper than 1.1 m. Therefore, model computations were performed using an average maximum effective rooting depth of 1.1 m. A FAO 600 maize variety was grown, whose crop development stages are given in Table 2.2. Plant density was 85000 plants per hectare. The crop was harvested (chopped) for animal feed when the grain reached a milky stage, so that the foliage was still green and actively transpiring. Basin irrigation was used. Irrigation water was metered with a modified broad crested weir (Replogle and Bos, 1982). Root growth was simulated assuming a constant value of 0.25 m for the initial stage and using a linear interpolation for the crop growth period, from 0.25 to 1.1 m at the start of midseason. Root depth was assumed constant thereafter (see item 2.5 of the companion paper).

Table 2.1. Textural and basic soil hydraulic properties of the maize experimental site, Coruche, Portugal (Fernando, 1993).

Soil layer (m)	Sand (%)	Silt (%)	Clay (%)	θ_{FC} ($m^3\ m^{-3}$)	θ_{WP} ($m^3\ m^{-3}$)
0.0-0.20	53.3	30.5	16.2	0.36	0.10
0.20-0.40	53.7	31.1	15.3	0.35	0.09
0.40-0.60	66.2	21.0	12.8	0.36	0.09
0.60-0.80	62.8	22.5	14.8	0.35	0.10
0.80-1.10	60.9	24.3	14.8	0.34	0.10

θ_{FC} and θ_{WP} represent the soil water content at field capacity and the wilting point

Table 2.2. Maize crop development stages (Fernando, 1993).

Crop Growth stages	Dates
Planting/Initiation	08 Jun
Start rapid growth	24 Jun
Start mid-season	18 Jul
Start senescence/maturity	25 Aug
End-season/harvesting	20 Sep

Soil water content was observed using a gravimetric method for the surface layer (0 - 0.10 m) and neutron scattering from 0.20 to 1.40 m at intervals of 0.1 m. Measurements were performed once per week during the period before irrigation; after irrigation began, observations were made daily or on a 2-day interval, with progressively decreasing frequency until the next irrigation event. Measurements were also performed on the days before and after each scheduled irrigation event (Fernando, 1993). The full irrigation and deficit irrigation schedules are presented in Table 2.3. A brief report on this experiment was provided by Fernando et al. (1988).

Table 2.3. Irrigation dates and depths (mm) relative to the maize trials (Fernando, 1993).

Irrigation strategy	Date	Net irrigation depth (mm)
Full irrigation	21 Jul	80
	08 Aug	80
	29 Aug	54
Deficit irrigation	25 Jul	100
	22 Aug	54

Continuous observation of water table depth showed an almost monotonic increase from 1.45 m, at planting, to 1.80 m, at harvesting. Water tables in the area were relatively shallow due to rice cultivation.

2.3.2. Results

2.3.2.1. Calibration, validation and model fitting

The base, standard values of K_{cb} and p proposed in FAO-56 (Allen et al. 1998) for the maize crop were applied in initial model simulations: $K_{cb\ ini} = 0.15$, $K_{cb\ mid} = 1.15$, $K_{cb\ end} = 0.50$, p = 0.55. The adopted value for $K_{cb\ end}$ resulted from the early harvest for animal feed. Recommended values for REW and TEW for silty loam soils by FAO-56 were initially used, 10 and 31 mm, respectively, with $Z_e = 0.10$ m (Table 2.4). The initial depletion in the evaporable layer was set for the 3 cases at 0% of TEW for the initial runs and for the calibration. Based on soil water observation, the initial depletion for the entire effective root zone (1.1 m) was set at 2, 3 and 10% of TAW for rainfed, deficit irrigation, and full irrigation experiments, respectively, indicating relatively moist initial conditions.

Groundwater contribution was computed using the parametric equations proposed by Liu et al. (2006). The initial parameters, based on soil characteristics, were those proposed by Liu et al. (2006) for silty loam soils (Table 2.4). The fraction of the soil wetted by irrigation (f_w), needed for the computation of K_e together with the fraction of soil covered (f_c), was $f_w = 1.0$. The observed values of f_c at days 21-06, 18-07, 01-08, 10-08, 25-08 and 20-09 were 0.01, 0.50, 0.75, 0.80, 0.80 and 0.70 for both irrigated plots, and 0.01, 0.50, 0.70, 0.70, 0.65 and 0.50 for the rainfed crop.

Table 2.4. Standard (initial) and calibrated basal crop coefficients, p depletion fractions, soil evaporation parameters and capillary rise parameters for simulation of the maize experiments at Coruche.

	Standard *	Calibrated
$K_{cb\ ini}$	0.15	0.15
$K_{cb\ mid}$	1.15	1.05
$K_{cb\ end}$	0.50	0.55
p_{ini}	0.55	0.65
p_{dev}	0.55	0.65
p_{mid}	0.55	0.65
p_{end}	0.55	0.65
REW (mm)	10	11
TEW (mm)	31	46
Z_e (m)	0.10	0.15
a_1	360	360
b_1	-0.17	-0.17
a_2	240	240
b_2	-0.27	-0.27
a_3	-1.3	-1.6
b_3	6.6	6.6
a_4	4.6	3.0
b_4	-0.65	-0.65

* From Allen et al., (1998, 2005b) and Liu et al., (2006)

Simulated and observed available soil water (ASW, mm) during calibration and validation are presented in Fig. 2.2. The figure shows observed soil water content had a wide range, and that the model simulated the three cases well. The computed total capillary rise was 131, 94 and 86 mm for the rainfed, deficit and full irrigation experiments, respectively, and was supplied by the high water table throughout the season.

The crop parameters (K_{cb} and p), soil evaporation parameters (Z_e, TEW and REW) and parameters of the equations used to estimate the groundwater contribution obtained through calibration and used during validation are presented in Table 2.4. The $K_{cb\ ini}$ and $K_{cb\ mid}$ parameters, as well as the p parameters, are not far from the standard values presented in Allen et al. (1998, 2007); $K_{cb\ end}$ reflect the early cut of the crop for silage. The larger value for p indicates that higher than normal depletions of water could be tolerated by the maize crop before stress. Some of this could be an artifact of the shallow water table and the use of averaged ASW over the total root zone even though the soil water content profile was wetter toward the water table. The $K_{cb\ mid}$ values are slightly smaller than those obtained by Zhao and Nan (2007), Jiang et al. (2008), Greenwood et al. (2008) and Liu and Luo (2010).

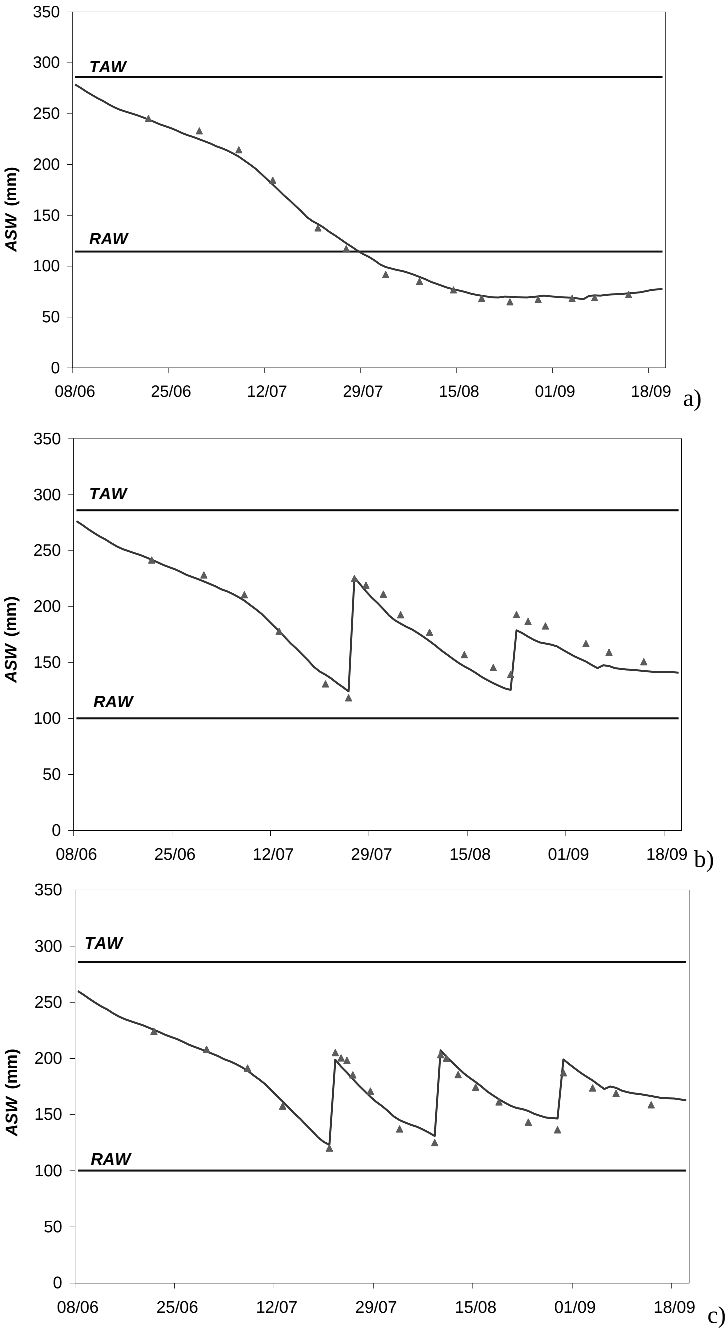


Fig. 2.2. Comparison between observed (▲) and simulated (—) available soil water (ASW) curves for maize in Coruche, Portugal: (a) rainfed (calibration); (b) under deficit irrigation (validation); and (c) under full irrigation (validation). TAW and RAW are respectively the total and readily available soil water

The computed goodness of fit indicators are summarized in Table 2.5. The regression coefficient was close to 1.0 for all three experimental conditions, thus showing that predicted soil water was close to observed values. The coefficients of determination ranged from 0.96 to 0.99, indicating that most of the variance was explained by the model. The RMSE values were lower than 11 mm, representing less than about 4% of TAW; the AAE were less than 9 mm and the ARE values were below 6% with EF ranging from 0.91 to 1.00 and d_{IA} greater than 0.98 for all three conditions. All of these statistics suggest good model performance and agreement between simulated and observed ASW. When analyzing the experiments together, b = 0.99 and R^2 = 0.98 (Fig. 2.3), indicating good model prediction of ASW for full, deficit and no irrigation conditions. Values obtained for combined RMSE and AAE were low, 7.6 and 6.3 mm, respectively, and values for EF and d_{IA}, 0.98 and 0.99 respectively, were quite high (Table 2.5). In summary, results indicate that the model was able to perform well in simulating soil water balances for a maize crop using the dual crop coefficient approach under irrigated and rainfed conditions, taking into account groundwater contributions.

Table 2.5. Indicators of goodness of fit relative to the model tests for the maize crop, when using crop, soil evaporation, and capillary rise calibrated values parameters.*

Goodness of fit indicators	b	R^2	RMSE (mm)	RMSE/TAW (%)	ARE (%)	AAE (mm)	EF	d_{IA}
Calibration (Rainfed)	1.00	0.99	4.5	1.6	3.5	3.8	1.00	1.00
Validation (Deficit irrigation)	0.96	0.96	10.2	3.6	5.3	8.9	0.91	0.98
Validation (Full irrigation)	1.01	0.96	6.4	2.2	3.4	5.6	0.95	0.99
All experiments	*0.99*	*0.98*	*7.6*	*2.6*	*4.1*	*6.3*	*0.98*	*0.99*

* Parameter values presented in Table 2.4.

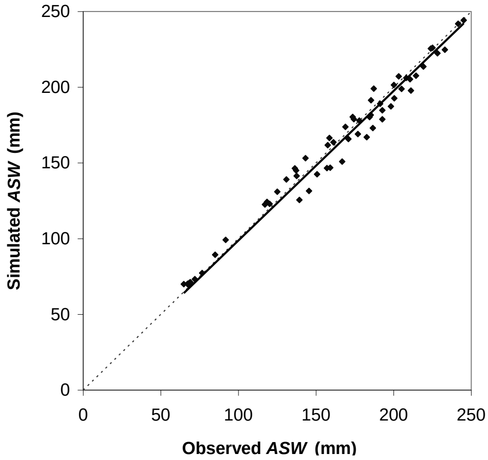


Fig. 2.3. Comparison between observed and simulated available soil water (ASW) using calibrated parameters and all maize experiments data, Coruche, Portugal

An evaluation was made on model behavior when measured soil water data are not available for model calibration, so that the model is applied using: a) standard data for REW, TEW, Z_e, K_{cb} and p from Allen et al. (1998, 2007), but calibrated parameters for the capillary rise computation (Table 2.4); and b) standard data for REW, TEW, Z_e, K_{cb} and p, and standard capillary rise data as tabled in Liu et al. (2006). For both cases, the dates of crop stages as observed in the field were adopted, which is recommended practice. The dates are different from the general values in FAO-56. The resulting indicators of goodness of fit are shown in Table 2.6. These indicators show lower, but still acceptable, accuracy relative to the use of calibrated values for the above parameters. When using calibrated parameters for capillary rise computation and standard values for REW, TEW, Z_e, K_{cb} and p (case a), the results for the rainfed experiment had a RMSE of 9.3 mm as compared to 4.5 mm when these parameters were calibrated. These RMSE values represent about 5 and 2% of TAW. When using standard values for the capillary rise estimation (case b) results become less accurate, with RMSE of 23.1 mm for the rainfed experiment, thus indicating the importance for careful calibration of these capillary rise parameters. Overall, results show that the model, when used without calibration/validation of soil and crop parameters, provided acceptable results, but users should exercise caution, especially if textbook crop stage dates are used that substantially deviate from actual ones. When standard values for REW, TEW, Z_e, K_{cb} and p were used together with standard values for the capillary rise parameters, ASW was overestimated by 2%, on average, which is probably within tolerance for useful irrigation scheduling.

Table 2.6. Indicators of goodness of fit relative to the model tests for the maize crop, Coruche, when using: a) standard values for crop and soil evaporation parameters and calibrated capillary rise parameters; and b) standard values for crop, soil evaporation and capillary rise parameters.*

Goodness of fit indicators	b	R^2	RMSE (mm)	RMSE/TAW (%)	ARE (%)	AAE (mm)	EF	d_{IA}
Rainfed $^{a)}$	1.04	0.99	9.3	3.2	10.4	8.4	0.98	0.99
Deficit irrigation $^{a)}$	0.96	0.92	13.7	4.8	7.2	12.1	0.84	0.96
Full irrigation $^{a)}$	1.03	0.98	6.3	2.2	3.4	5.5	0.95	0.99
All experiments $^{a)}$	*1.00*	*0.96*	*10.2*	*3.5*	*6.5*	*8.5*	*0.96*	*0.99*
Rainfed $^{b)}$	1.05	0.98	23.1	8.1	25.3	19.2	0.87	0.96
Deficit irrigation $^{b)}$	0.98	0.99	4.8	1.7	2.5	4.3	0.98	0.99
Full irrigation $^{b)}$	1.05	0.88	14.0	4.9	7.0	11.5	0.75	0.93
All experiments $^{b)}$	*1.02*	*0.95*	*14.9*	*5.2*	*10.2*	*11.0*	*0.91*	*0.97*

* Parameter values presented in Table 2.4

2.3.2.2. Evaporation and transpiration components

The SIMDualKc model provides computations for both $ET_{c\ adj}$ components, soil evaporation (E_s, mm) and plant transpiration (T_a, mm), where the basal K_{cb} can be assumed to represent primarily T_a, with a small amount of baseline E_s (Wright, 1982); however, during the initial crop growth stage, baseline (diffusive) E_s may be more important than T_a, thus caution is needed when referring to K_{cb} ET_o as plant transpiration during this stage. Results for E_s and T_a relative to crop growth stages are presented in Table 2.7. Seasonal E_s was 12, 14, and 16% of the seasonal $ET_{c\ adj}$ for the rainfed, deficit, and full irrigation experiments respectively; these values are slightly lower than those observed (Fernando, 1993). Evaporation was the primary $ET_{c\ adj}$ component during the initial crop growth stage, representing about 81% of $ET_{c\ adj}$ for that period. The large E_s component resulted from high water content in the soil evaporation layer and a low fraction of soil covered by the vegetation (f_c) during the initial stage. During the crop development stage, which is the transition stage between the initial period and the midseason period, there was no precipitation or irrigation, thus the upper soil layer remained dry and estimated E_s (mm) decreased to about 6% of $ET_{c\ adj}$. During the mid-season period the fraction of wet soil exposed to radiation was low, thus the evaporation during this period was essentially zero for the rainfed treatment and very low for both irrigation treatments. During the late season, because f_c decreased as the crop dried out and lost leaves, the proportion of E_s relative to $ET_{c\ adj}$ increased relative to the mid-season period, supplied by a small rain. As expected, E_s was smaller for the rainfed crop because the soil evaporation layer was dry during much of the crop season. However $ET_{c\ adj}$ was not very different from the other cases because capillary rise was high, 131 mm, as indicated above.

Table 2.7. Evaporation (E_s) and transpiration (T_a) for each development stage of the maize crop, Coruche.

	Initial stage		Vegetative growth		Mid season		Late season		Full crop season		
	E_s (mm)	T_a (mm)	E_s (mm)	T_a (mm)	E_s (mm)	T_a (mm)	E_s (mm)	T_a (mm)	E_s (mm)	T_a (mm)	$E_s/ET_{c\ adj}$ (%)
Rainfed	34	8	5	75	0	165	3	52	42	300	12
Deficit irrigation	34	8	5	75	9	185	9	74	57	342	14
Full irrigation	34	8	5	75	14	185	12	74	65	342	16

Estimates for $E_s/ET_{c\ adj}$ of irrigated treatments, 14 and 16% respectively for 2 and 3 irrigation applications, are comparable with those published by several authors: Bethenod et al. (2000) reported $E_s/ET_{c\ adj}$ of about 10-12%; Allen et al., (2005b) estimated $E_s/ET_{c\ adj}$ of 24% for irrigated maize (sweet corn) at Kimberly, Idaho; Grassini et al. (2009) reported $E_s/ET_{c\ adj}$ ranging from 7 to 34% in the Corn Belt of the USA, with lower values for irrigated maize; Katerji et al. (2010) indicated values of 17 to 34%, where the lower ratio corresponds to well-irrigated maize. Observations by Zhao et al. (2009) for monsoon rainfed maize reported $E_s/ET_{c\ adj}$ of 27.4%, and Jiang et al. (2008) have found $E_s/ET_{c\ adj}$ ranging 18 to 23% for a maize-wheat crop sequence. Results for the rainfed crop, $E_s/ET_{c\ adj}$ = 13%, are lower than values reported in literature because rain was extremely low in the Mediterranean climate during most of the growing season and because the ET from the crop was essentially supplied by capillary rise; hence the upper soil layer, from where evaporation originates, was dry during much of the crop season.

Results for the evaporation and basal crop coefficients, K_e and K_{cb}, for the water stress adjusted K_{cb} ($K_{cb\ adj} = K_s\ K_{cb}$), as well as for the groundwater contribution (GW_c) and precipitation are shown in Fig. 2.4 for the rainfed and deficit irrigated maize. These results show that daily K_e was only significant during the earlier stages of the crop and remained quite low or null until a few small rains occurred near the end of the season. Differences in K_e between treatments were small. Values for K_e were constrained during the midseason period for the irrigated crop by high K_{cb} coupled with the total constraint imposed by $K_{c\ max}$. The non-stressed K_{cb} values were the same for both treatments but the $K_{cb\ adj}$ values were different, with the rainfed treatment showing a large deviation from K_{cb} due to some late season stress. The rainfed crop was only sustained because the groundwater contribution was quite high after soil water was depleted from the root zone. Peak values for GW_c were caused by variation in the water table depth, which occurred during water management of surrounding fields, mainly paddies. Results illustrate the use of the model to improve the understanding of differences in water use among irrigation treatments.

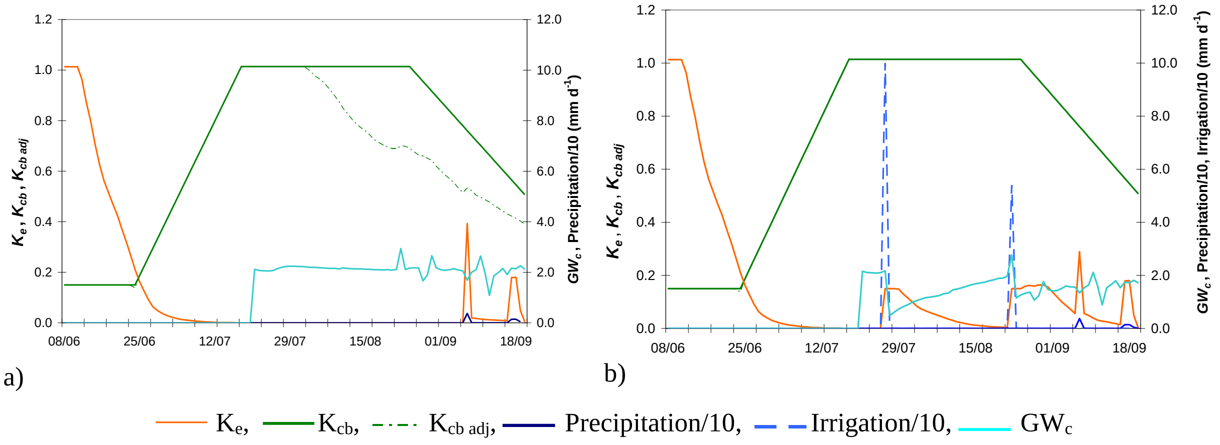
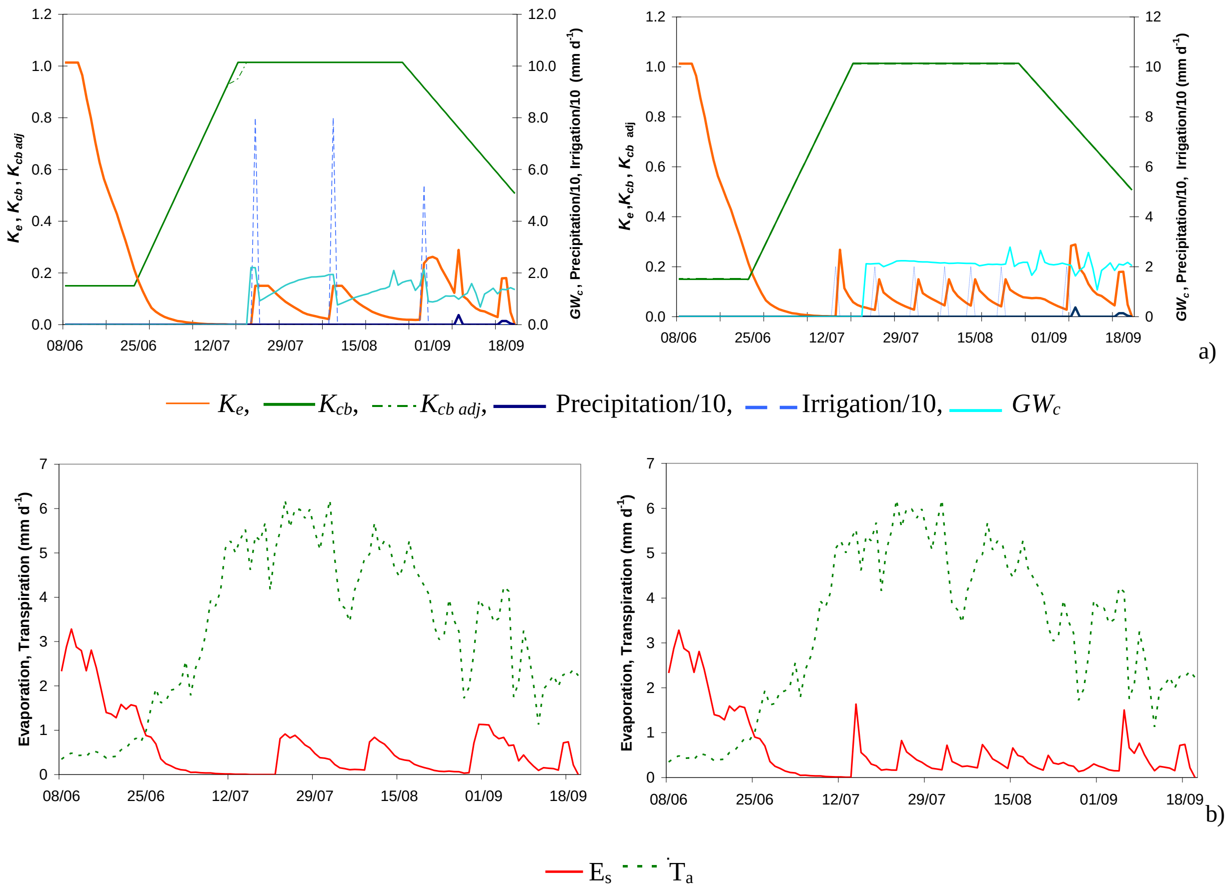


Fig. 2.4. Variation of the evaporation and basal crop coefficients K_e, K_{cb}, and K_{cb} adj, precipitation/10, irrigation/10 and groundwater contribution (GW_c) for: a) rainfed and b) deficit irrigated maize in Coruche, PT (for easier reading of the Figure, irrigation and precipitation are divided by 10).

2.3.2.3. Assessing an alternative irrigation management strategy

Surface irrigation in the Sorraia Valley has been progressively replaced by sprinkler irrigation, mainly with center-pivot laterals. Thus, once calibrated, the model was applied for this alternative irrigation method to assess differences in water use caused by changes in irrigation management. The model was used with the previously calibrated parameters (Table 2.4) and with the same climatic, soil and crop data. Irrigation data were modified to reflect net application depths (D) of 20 mm and an irrigation schedule aimed at producing no stress. As observed by Klepper (1991), crop roots may not grow the same when large irrigation depths are infrequently applied, 2 or 3 times in the crop season as under surface irrigation, as compared to where smaller and frequent irrigations are applied as under center pivot irrigation, where the effective rooting depth may be less. In this application, the groundwater table was feeding the crop in conditions similar to surface irrigation, which may suppose a similar root growth until the first sprinkler irrigation by 14-07, when root depth was estimated at 0.9 m. Because frequent irrigation were considered thereafter, root growth was assumed smaller than for surface irrigation, hence the effective rooting depth was set at 1.0 m.

Fig. 2.5 compares impacts of using center pivot sprinkler on total ET, along with the basin full irrigation case in terms of the time variation in coefficients K_{cb}, $K_{cb\ adj}$ and K_e, as well as of the water balance terms GW_c, I, P, E_s, T_a and the seasonal variation of soil water, ΔSW. Results show that adopting high frequency center pivot sprinkler irrigation when the water table remains high leads to maintaining soil evaporation relative to basin irrigation despite increasing the number of irrigation events. This negligible change in E_s is also due to the fact that irrigations were applied when f_c was large, *i.e.*, when plant cover was high. GW_c increased from 86 to 130 mm because more soil water was depleted as indicated by a higher decrease in ΔSW over the growing season (Fig. 2.5). Thus, the same crop transpiration (TA around 342 mm) was supplied by a smaller sum of I + P which decreased from 221 to 147 mm due to increased GW_c, *i.e.*, with net irrigation decreasing by 74 mm when changing from basin to sprinkler irrigation (Fig. 2.5). Estimated E_s/ET_c = 16% was maintained.



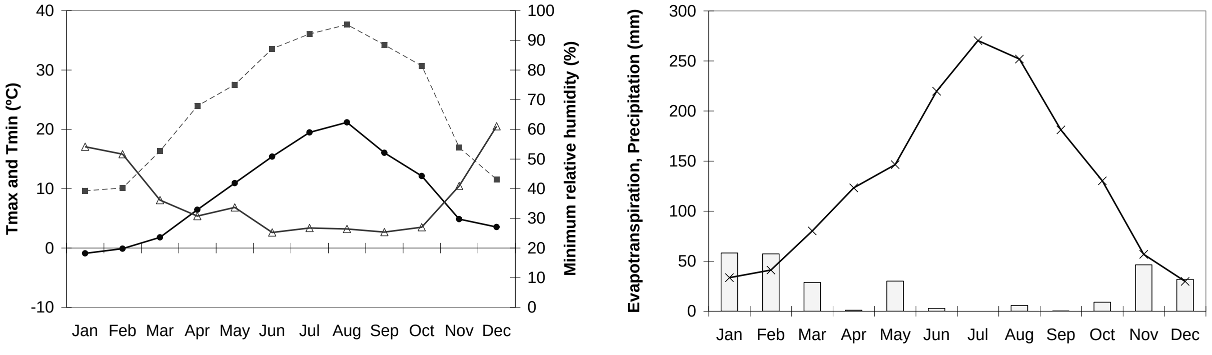
Irrigation + rainfall (mm)	221	147
GW_c (mm)	86	130
ΔSW (mm)	-97	-127
E_s (mm)	65	65
T_a (mm)	342	342

Fig. 2.5. Variation of K_e, K_{cb}, $K_{cb\ adj}$, GW_c, I/10, P/10 (a) and E_s and T_a (b) for fully irrigated maize under basin irrigation (left) and center-pivot sprinkler irrigation (right) (for easier reading of the Figure, irrigation and precipitation are divided by 10)

2.4. Case study on wheat

2.4.1. Site characteristics

ICARDA's headquarters and research farm are located at Tel Hadya, 30 km south of Aleppo, within a major dryland farming area of northern Syria. Wheat is the primary research crop at ICARDA, and on going field trials include responses to supplemental irrigation (e.g., Oweis et al., 1998; Zhang et al., 1998; Zhang and Oweis, 1999; Oweis and Hachum, 2001; Sato et al., 2006). Climatic characteristics of Tel Hadya (36.01º N latitude; 36.56º E longitude; altitude 284 m) during 1992-93 are given in Fig. 2.6, including the reference evapotranspiration computed with the FAO-PM method (Allen et al., 1998). Tel Hadya also has a Mediterranean climate with little rainfall during summer.



a) b)

Fig. 2.6. Climatic data of the ICARDA meteorological station (1992-93): a) average monthly maximum (– ■ –) and minimum (—●—) temperature, and minimum (—△—) relative humidity; and b) monthly precipitation (□) and reference evapotranspiration (ET$_o$) (—×—).

The primary soil type is a red brown calcareous loamy soil. Principal soil characteristics are presented in Table 2.8. The soil depth ranges from 1.0 to 1.8 m and the measured maximum rooting depth during the experimental year (1992-93) was 1.5 m (Zhang and Oweis, 1999). Considering these soil characteristics and the effective maximum rooting depth, a maximum TAW value of 282 mm was utilized during modeling. An initial rooting depth of 0.25 m was assigned until the start of rapid growth, increasing to 1.5 m at the start of midseason. Observations of soil water content were made weekly. The gravimetric method was used for the upper soil layer and the neutron scattering method was used for soil depths below 0.15 m at every 0.15 m until 1.80 m (Zhang and Oweis, 1999).

Table 2.8. Textural and basic soil hydraulic properties of the experimental site at Tel Hadya, Aleppo, Syria (Oweis et al., 2003).

Soil layer (m)	Sand (%)	Silt (%)	Clay (%)	θ_{FC} (m^3 m^{-3})	θ_{WP} (m^3 m^{-3})
0.0 - 0.45	16.0	24.0	60.0	0.40	0.24
0.45 - 1.80	17.0	25.0	58.0	0.40	0.22

The wheat crop development stages are defined in Table 2.9. Plant density at mid season was near 150 plants m^{-2}. Impacts of plant density on the partition of ET into crop T$_a$ and soil E$_s$ were analysed by Eberbach and Pala (2005). Supplemental irrigation was applied using basin irrigation and the scheduled dates for the experiment are listed in Table 2.10. Crop practices were the same for both plots except for irrigation. Treatments analyzed herein are described by Oweis et al. (2003).

Table 2.9. Crop stage dates for the winter wheat crop, Aleppo, Syria (Oweis et al., 2003)

Crop growth stages	Dates
Planting/Initiation	11 Dec
Start rapid growth	17 Feb
Start mid-season	10 Apr
Start senescence/Maturity	15 May
End-season/Harvest	27 May (rainfed) 06 Jun (supplemental irrigation)

Table 2.10. Irrigation dates and depths (mm) for the test trial of irrigated wheat, 1992-93 crop season (Oweis et al., 2003).

Date	Net irrigation depth (mm)
12 Apr	82
26 Apr	75
12 May	45

2.4.2. Results

2.4.2.1. Calibration, validation and model fitting

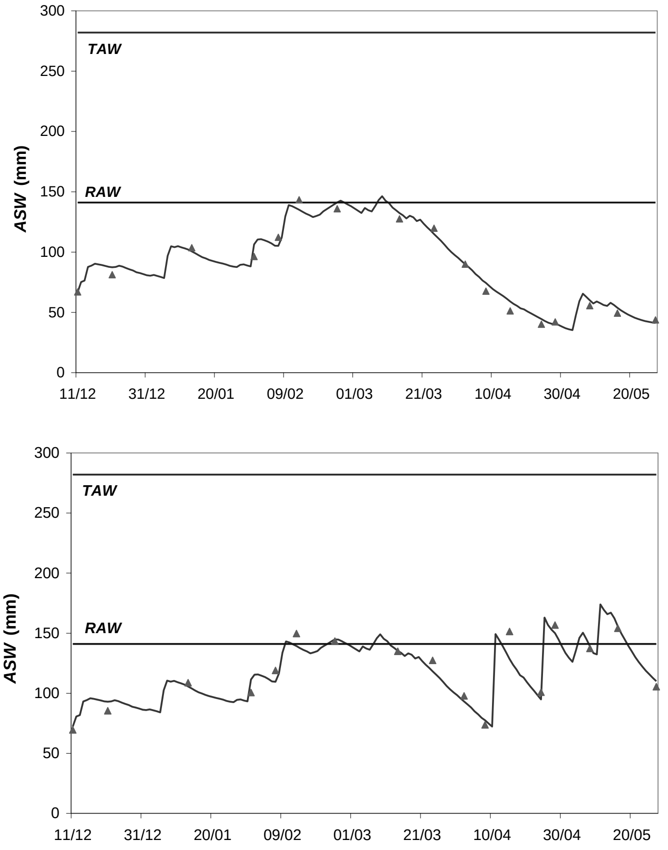
The K_{cb} and p values proposed by FAO-56 were used during initial model simulation, as well as REW, TEW and Z_e values recommended by Allen et al. (2005b) for loamy soils, which are given in Table 2.11. The initial depletion of the evaporable layer was set as 85% of TEW. The depletion of the entire root depth was initialized at 75% of TAW on the date of planting. Estimated values for f_c during the initial period varied from 0.0 to 0.30, and increased to 0.80 during the crop development period for both rainfed and irrigation treatments. The value $f_c = 0.8$ was maintained during midseason and decreased to 0.2 at harvesting in case of supplemental irrigation; differently, for the rainfed crop, due to severe water stress, f_c decreased to 0.5 at the end of midseason and thereafter to 0.2 at harvesting.

Table 2.11. Standard (initial) and calibrated basal crop coefficients, p depletion fractions, and soil evaporation parameters for the wheat experiments, Tel Hadya, Aleppo.

	Standard	Calibrated
$K_{cb\ ini}$	0.15	0.15
$K_{cb\ mid}$	1.10	1.05
$K_{cb\ end}$	0.15	0.25
p_{ini}	0.55	0.50
p_{dev}	0.55	0.50
p_{mid}	0.55	0.50
p_{end}	0.55	0.50
REW (mm)	10	8
TEW (mm)	28	22
Z_e (m)	0.15	0.10

* From Allen et al., (1998, 2005b)

Figure 2.7 presents results comparing simulated with observed available soil water following calibration. As with case 1, calibration was conducted by varying $K_{cb\ mid}$, $K_{cb\ end}$ and p to decrease or increase total fluxes of ET from the root zone so that simulated ASW came closest to observed values during midseason and late season periods. REW and TEW were adjusted to cause simulated change in ASW to match observed ASW over the periods following wetting events. The calibrated crop and evaporation parameters are presented in Table 2.11.



a)

b)

Fig. 2.7. Comparison between observed (▲) and simulated (—) available soil water (ASW) for wheat near Aleppo, Syria: a) rainfed (after calibration), and b) supplemental irrigation (validation). TAW and RAW are respectively the total and readily available soil water

The calibrated values for K_{cb} and p (Table 2.11) are close to the standard values proposed by Allen et al. (1998, 2007). Values of $K_{cb\,mid}$ are slightly lower than the values presented by Hunsaker et al. (2007), López-Urrea et al (2009), Liu and Luo (2010) and Zhao et al. (2010). The reduction of 0.05 at midseason relative to the starting value from FAO-56 may reflect a slight reduction in $K_{cb\,mid}$ caused by impacts of water stress, plant variety or reduced vigor, or may be an artifact of soil water measurement error or compensation for other model uncertainties including estimates for p and ET_o. The proximity of calibrated and standard K_{cb}

values does support the validity of using general, transferable values for K_{cb} for routine modeling.

During the validation run (Fig. 2.7b), where supplemental irrigation was applied, simulated ASW came close to observed values during the late season. Both water treatments were estimated to incur mild stress during the development period (March) so that $K_s < 1.0$. The rainfed experiment transitioned into severe water stress during midseason (April-June) when ASW became less than 1/3 of RAW so that K_s also went below 1/3 (Fig. 2.7a). The relatively simple, linear reduction function of FAO-56 for K_s performed well for the wheat crop.

Goodness of fit indicators are presented in Table 2.12. Results show that the coefficients of regression were close to 1.0 and the coefficients of determination ranged from 0.92 to 0.98. The estimation error RMSE for ASW were 5.5 and 8.2 mm respectively for the rainfed and irrigated treatment; for the same treatments, AAE results were 4.8 to 6.3 mm, respectively. These values represent less than 3% of TAW, which is considered to be quite satisfactory. EF and d_{IA} indicators were high. Fig. 2.8 presents the comparison between observed and simulated ASW (mm) when using all data from both experiments. The data adhere relatively well to the 1:1 line with similar variance over the range of ASW. Some underestimation in ASW occurred at high ASW. Results indicate that the model was able to reproduce the observed available soil water over a wide range of observed values, with only minor calibration.

*Table 2.12. Indicators of goodness of fit relative to the model tests for the wheat crop, when using crop and soil evaporation calibrated parameters**

Goodness of fit indicators	b	R^2	RMSE (mm)	RMSE/TAW (%)	ARE (%)	AAE (mm)	EF	d_{IA}
Calibration (Rainfed)	1.01	0.98	5.5	2.0	6.3	4.8	0.97	0.99
Validation (Supplemental irrigation)	0.97	0.92	8.2	2.9	5.4	6.3	0.91	0.97
All experiments	*0.99*	*0.96*	*7.0*	*2.5*	*5.9*	*5.6*	*0.96*	*0.99*

* Parameter values presented in Table 2.11

To assess the simulation errors when observed soil water data are not available for model calibration/validation, the SIMDualKc model was applied to both experiments using only standard data (REW, TEW, Z_e, K_{cb} and p) from Allen et al. (1998, 2007) but adopting observed dates for crop stages. The respective indicators for goodness of fitting are shown in Table 2.13.

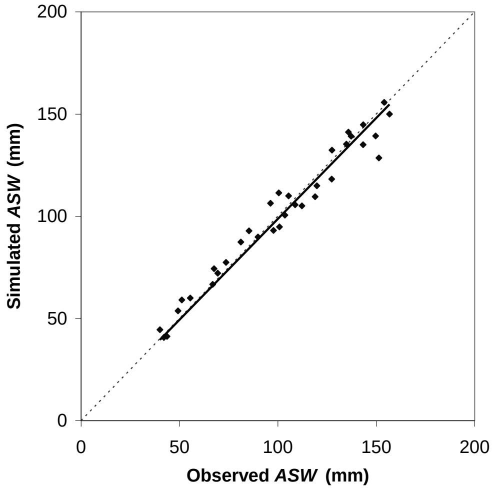


Fig. 2.8. Comparison between observed and simulated available soil water (ASW) using all experimental data for a wheat crop near Aleppo, Syria, after model calibration.

As observed for the maize applications, using standard data produced less accuracy as compared to using calibrated parameters, but results were still quite acceptable with RMSE averaging 12.5 mm, ARE around 9%, and relatively high EF and d_{IA} values, averaging 0.90 and 0.97, respectively. These results suggest that the model could have been used with standard parameters provided dates for crop growth stages were specified as those observed in the field.

*Table 2.13. Indicators of goodness of fit relative to the model tests for the wheat crop, when using crop and soil evaporation standard parameters**

Goodness of fitting indicators	b	R^2	RMSE (mm)	RMSE/TAW (%)	ARE (%)	AAE (mm)	EF	d_{IA}
Rainfed	0.94	0.97	7.8	2.8	8.3	6.5	0.95	0.99
Supplemental irrigation	0.91	0.89	14.0	5.0	9.9	12.1	0.74	0.92
All experiments	*0.92*	*0.95*	*11.3*	*4.0*	*9.1*	*9.3*	*0.90*	*0.97*

* Parameter values presented in Table 2.11

2.4.2.2. Evaporation and transpiration components

The model results for E_s (mm) and T_a (mm) for both treatments averaged over each of the four crop growth stages and total growing season are presented in Table 2.14. Results show that E_s was the dominant component of $ET_{c\ adj}$ during the initial crop growth stage, representing 85% of $ET_{c\ adj}$. This was due to a high moisture content in the evaporable layer during this period, which occurred during the rainy season. Total precipitation was 133 mm during the initial period, and numerous precipitation events occurred. In addition, crop cover was low, creating a large fraction of wetted soil that was exposed to radiation, thus favoring evaporation. During the vegetative growth period, E_s decreased to 25% of $ET_{c\ adj}$ while f_c increased. The precipitation during this period was 42 mm. During both crop stages, there were no differences between treatments because there was no irrigation at that time. During the mid-season period, the irrigation treatment produced large increases in both T_a and $ET_{c\ adj}$. E_s was also larger for the irrigated treatment due to soil wetting by irrigation. Differences between treatments were also high during the late season. Growing season evaporation was of the same magnitude for both treatments because it mostly originated from rainfall. However, the percentages of soil evaporation in total growing season ET were different, 25% for the supplemental irrigated treatment, and 38% for the rainfed treatment. These differences illustrate the importance of supplemental irrigation of wheat and its impact on partitioning total water consumption into E_s and T_a and associated marketable yields (Oweis and Hachum 2001). Results on the ratios of $E_s/ET_{c\ adj}$ are similar to those reported by Zhang et al, (1998) for the same area: 29 to 43 % with higher values for rainfed wheat. These values are higher than other results reported in literature: Hunsacker et al. (2005) reported much lower values for a low rainfall area near Phoenix, AZ, USA, of 6 to 8%; Er Raki et al. (2007) reported 10 to 17% for a dry climate in Morocco; López-Urrea et al. (2009) indicated 24 % for Spain; Yu et al. (2009) have shown a range of 20 to 28% for China, with the higher values occurring when insufficient irrigation was practiced; Zhao et al. (2010) reported 16 to 22% for well irrigated wheat in North China; and Sadras and Rodriguez (2010) reported a range of 22-34% in Australia, depending on the variety.

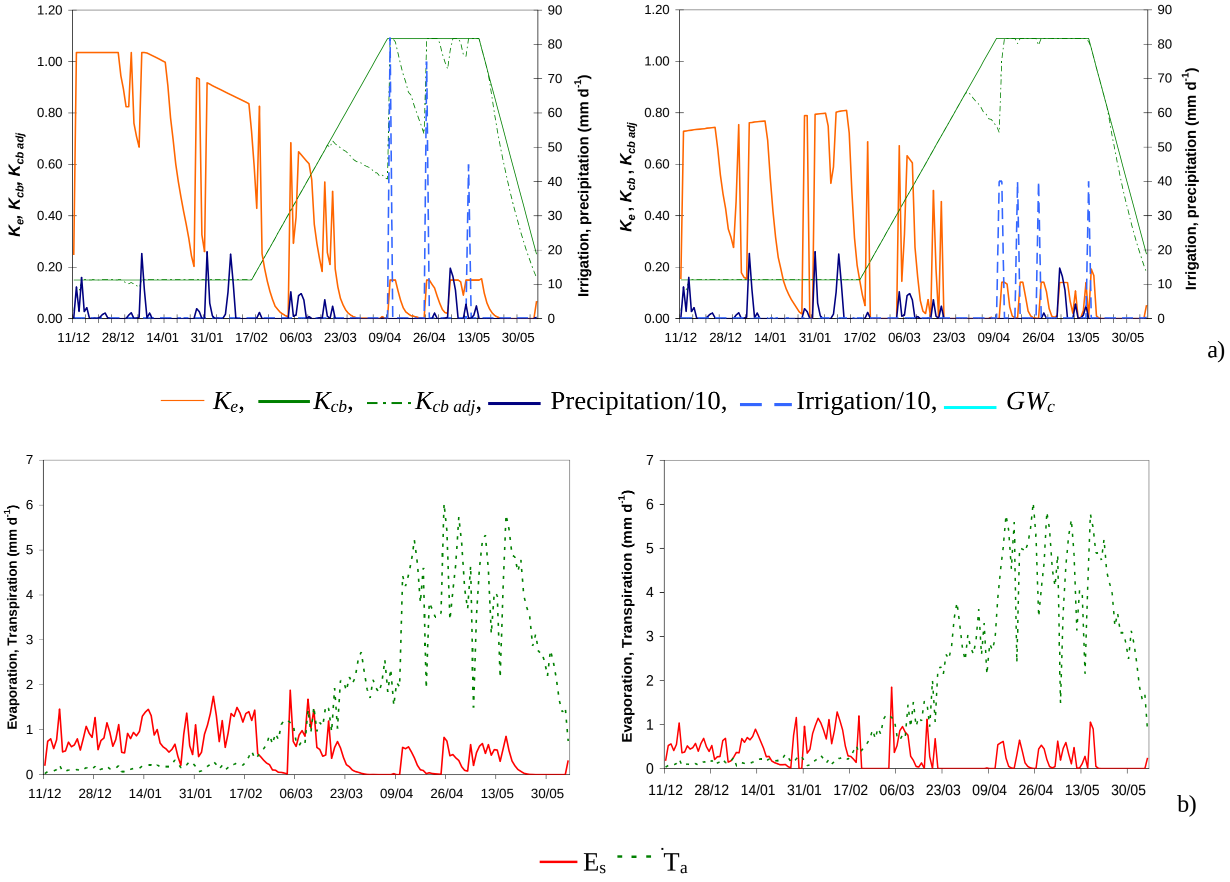
Table 2.14. Evaporation (E_s) and transpiration (T_a) during each crop development stage for the wheat crop (1992-93) at Tel Hadya, Aleppo, Syria.

	Initial crop stage		Vegetative growth		Mid season		End season		Entire growing season		
	E_s (mm)	T_a (mm)	E_s (mm)	T_a (mm)	E_s (mm)	T_a (mm)	E_s (mm)	T_a (mm)	E_s (mm)	T_a (mm)	$E_s/ET_{c\ adj}$ (%)
Rainfed	60	11	24	70	5	55	2	15	91	150	38
Supplemental irrigation	60	11	24	71	12	143	3	75	99	300	25

2.4.2.3. Assessing an alternative irrigation management issue

An alternative modeling scenario was considered using the same climatic, soil and crop data as for validation and the previously calibrated parameters (K_{cb}, p, TEW, REW and Z_e) but with the objective of assessing the influence of the irrigation system type and management and maintaining a soil mulch on soil evaporation dynamics. The alternative scenario used sprinkler irrigation having application depths of D = 40 mm (Zhang et al., 1998) and with direct seeding, thus preserving a surface mulch (crop residue). The impact of the mulch was modeled assuming a mulch density of 0.6, a covered fraction of 1.0 and a soil evaporation reduction of 30%. The 30% reduction in evaporation under the residues mulch was an arbitrary setting following the recommendation in FAO-56 and was selected primarily to assess the sensitivity of total E_s and ET under those conditions. The irrigation schedule was set similar to that observed for supplemental irrigation: a) the first irrigation was scheduled on the same date (12/04); b) after this date and until grain filling by 20/05, irrigation was set to fulfill full wheat water requirements; and c) no irrigation was considered after 20/05.

Fig. 2.9 shows the time-wise variation of coefficients K_{cb}, $K_{cb\ adj}$, and K_e, as well as a summary of components of the water balance, E_s, T_a, P, I, and ΔSW. Results show: a) a large decrease in soil E due to mulching, mainly during the early stages of the crop if a 30% reduction in evaporation were realized; b) a smaller associated value for K_e during the initial and crop development stages; c) a smaller reduction of $K_{cb\ adj}$ relative to K_{cb} in late March prior to irrigation due to higher availability of soil water made available via a smaller E_s; d) associated higher T_a, mainly during the last part of the crop development stage and mid season. This simulation suggests that even when adopting the same irrigation thresholds, the maintenance of mulch on the surface may lead to the transfer of a valuable amount of water from soil E_s into crop T_a. ET was still about the same, which shows the positive impacts of mulching. This application illustrates the utility of employing the dual crop coefficient approach when investigating impacts on soil evaporation. More sophisticated models and experimentation on surface residue effects, including surface energy balance measurements, can be used to calibrate or validate the dual K_c approach of SIMDualKc.



Irrigation + rainfall (mm)	423	421
GW_c (mm)	18	29
ΔSW (mm)	99	57
E_s (mm)	300	332
T_a (mm)	423	421

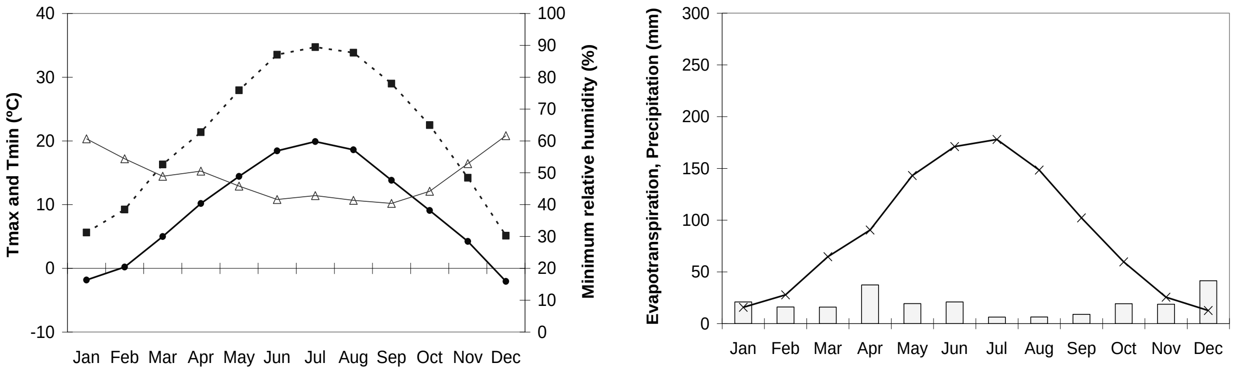
Fig. 2.9. Comparing the current surface irrigation (left) with an alternative sprinkler irrigation with surface mulching (right): seasonal variation of K_e, K_{cb}, $K_{cb\ adj}$, irrigation and precipitation (a), and of E_s and T_a (b)

2.5. Case study on cotton

2.5.1. Site characteristics

The SIMDualKc model was applied to furrow irrigated cotton using field and meteorological data collected near Fergana, in the Fergana Valley, Uzbekistan. The Fergana Valley is bordered by the Fergana ridge to the East, the Alai and Turkestan ridges to the South and the Kurama and Chatkal ridges to the Northwest and the North. The valley is drained by the SyrDarya River, which is fed by numerous mountain streams. All experiments occurred south of the SyrDarya River. Data relative to all cotton treatments were reported by Cholpankulov et al. (2008).

The Fergana meteorological station located near the experimental site has coordinates 40.77º N, 71.09º E and altitude 439 m. The respective monthly average maximum and minimum temperatures, minimum relative humidity, precipitation and reference evapotranspiration computed with the FAO-PM method are shown in Figure 2.10.



a)

b)

Fig. 2.10. Climatic data of the Fergana meteorological station (2001-2003): a) average monthly maximum (-■-) and minimum (—●—) air temperature, and minimum (—△—) relative humidity; and b) monthly precipitation (□) and monthly reference evapotranspiration (ET_o) (—×—).

The primary soils in the experimental sites are loamy and clay-loam soils. Principal soil characteristics for the two plots of Fergana are presented in Table 2.15. These experimental plots are identified by the year experiments were performed, 2001 and 2003. The effective root depths were 1.10 and 1.00 m for 2001 and 2003, respectively, based on field observations and depleted soil water (Cholpankulov et al., 2008). Therefore, TAW was estimated as 198 and 176 mm for 2001 and 2003, respectively.

The dates for crop growth stages for the two experiments are defined in Table 2.16. The planting density was 8 plants per m^2. The irrigation schedules and depths adopted are summarized in Table 2.17. Further information on these experiments and measurement details are provided by Cholpankulov et al. (2008).

Table 2.15. Textural and soil hydraulic properties for two experimental sites near Fergana, Uzbekistan (Cholpankulov et al., 2008).

	Soil layer (m)	Sand (%)	Silt (%)	Clay (%)	θ_{FC} ($m^3 m^{-3}$)	θ_{WP} ($m^3 m^{-3}$)
Site A, 2001	0.00-0.35	34.0	46.0	20.0	0.30	0.13
	0.35-0.50	45.0	48.0	7.0	0.30	0.12
	0.50-0.62	43.0	41.0	16.0	0.31	0.12
	0.62-0.76	41.0	44.0	15.0	0.30	0.11
	0.76-0.91	51.0	42.0	7.0	0.30	0.13
	0.91-1.10	44.0	49.0	7.0	0.30	0.11
Site B, 2003	0.00-0.15	34.0	46.0	20.0	0.34	0.17
	0.15-0.35	38.0	47.0	15.0	0.35	0.17
	0.35-.050	45.0	48.0	7.0	0.35	0.17
	0.50-0.62	43.0	41.0	16.0	0.34	0.18
	0.62-0.76	41.0	44.0	15.0	0.36	0.18
	0.76-0.91	51.0	42.0	7.0	0.35	0.17
	0.91-1.00	44.0	49.0	7.0	0.34	0.16

Table 2.16. Cotton crop growth stages for the Fergana experiments (Cholpankulov et al., 2008).

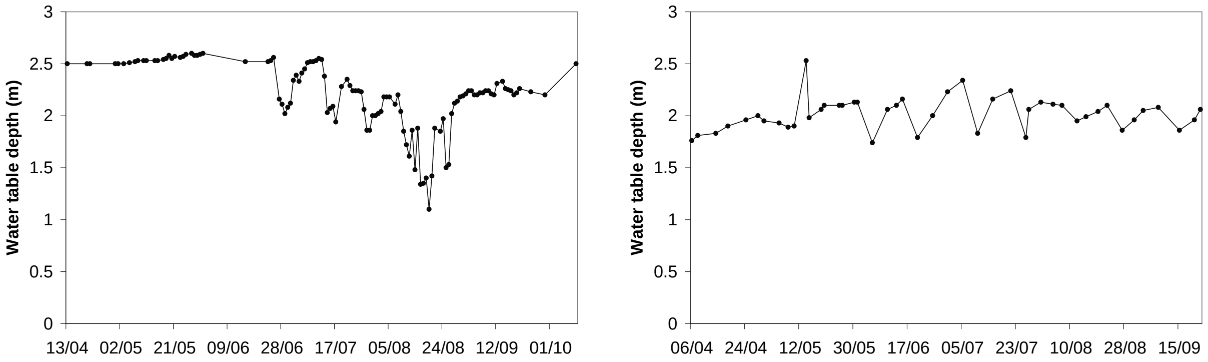
Crop Growth stages	2001	2003
Planting/Initiation	13 Apr	06 Apr
Start rapid growth	18 May	21 May
Start mid-season	18 Jul	20 Jul
Start senescence/Maturity	01Sep	01 Sep
End-season/Harvest	10 Oct	14 Oct

Table 2.17. Irrigation dates and depths (mm) for the furrow irrigated cotton experiments at Fergana, Uzbekistan (Cholpankulov et al., 2008).

Year	Date	Net Irrigation depth (mm)
2001	02-06-2001	127
	25-06-2001	174
	11-07-2001	123
	25-07-2001	111
	07-08-2001	86
2003	15-06-2003	125
	09-07-2003	103
	24-07-2003	123
	10-08-2003	114
	26-08-2003	91
	12-09-2003	93

At Fergana the water table was high and was observed frequently (Fig. 2.11). During 2001, the water table depth decreased from 2.5 m at the beginning of the crop season to 1.1 m at mid season, increasing again to a depth of 2.5 m at harvest; during 2003, the water table depth varied between 1.8 m and 2.5 m (Fig. 2.11). The variation and presence of the water table reflects the impact of deep percolation associated with excess water applications.

Observation of soil water content was performed weekly or more frequently between irrigation events, as well as before and after irrigations. Measurements were made at 27.5, 42.5, 67.5, 82.5 and 97.5 cm, with the gravimetric method used for the upper soil layer, and the neutron scattering method used for the remaining soil depths.



a) b)

Fig. 2.11. Water table depth at Fergana throughout the cotton crop seasons of (a) 2001 and (b) 2003 (dots refer to observations).

2.5.2. Results

2.5.2.1. Calibration, validation and model fitting

The base values proposed by FAO-56 for K_{cb}, p, REW, TEW and Z_e were used during initial model simulations (Table 2.18). The initialization parameters for the capillary rise and percolation equations are also presented in Table 2.18. For the year 2001, the initial depletion in the evaporation upper soil layer was assumed to be 70% of TEW because the soil surface was nearly dry at planting, and 55% of TEW in 2003. The initial soil water depletion in lower layers of the root zone was estimated from field measurements as 4 and 7% of TAW for 2001 and 2003, respectively. Effective rooting depth was assumed to be 0.2 m at planting and linearly increasing to 0.4 m at the start of rapid growth, then increasing to 1.1 and 1.0 m at midseason, respectively for the 2001 and 2003 experiments. Values for f_c were: 0 to 0.1 over the initial period, 0.1 to 0.85 over the development period, 0.85 during the mid-season, and 0.3 at harvest. f_w was equaled to 0.8 for furrow irrigation.

Table 2.18. Standard (initial) and calibrated basal crop coefficients, p depletion fractions, soil evaporation parameters, groundwater contribution parameters and deep percolation parameters for the cotton experiments at two sites in Fergana.

	Standard *		Calibrated	
$K_{cb\ ini}$	0.15		0.20	
$K_{cb\ mid}$	1.15		1.15	
$K_{cb\ end}$	0.50		0.50	
$p_{\ ini}$	0.65		0.65	
$p_{\ dev}$	0.65		0.65	
$p_{\ mid}$	0.65		0.65	
$p_{\ end}$	0.65		0.65	
			Site A, 2001	*Site B, 2003*
REW (mm)	10		11	11
TEW (mm)	28		37	30
Z_e (m)	0.10		0.15	0.12
	Site A, 2001	*Site B, 2003*		
a_1	300	348	300	348
b_1	-0.32	-0.32	-0.32	-0.32
a_2	230	286	200	286
b_2	-0.16	-0.16	-0.5	-0.16
a_3	-1.4	-1.4	-1.4	-1.4
b_3	6.8	6.8	6.8	6.8
a_4	1.11	1.11	1.00	1.11
b_4	-0.98	-0.98	-0.98	-0.98
a	360	410	310	390
b	-0,017	-0,017	-0,05	-0,05

* From Allen et al. (1998, 2005b) and Liu et al. (2006)

Simulated and observed available soil water values are compared in Fig. 2.12. The simulations show a large range of variation in ASW over time and the impact of different irrigation scheduling strategies between the two years, with a later start for irrigation in 2003. Irrigation additions were estimated to be typically in excess of retainable water as represented by field capacity and the TAW line in the figures. SIMDualKc simulated initially high values for ASW exceeding TAW, with drainage to TAW (*i.e.*, field capacity) within one or two days following irrigation. The calibrated parameters for Fergana are presented in Table 2.18, where the values for $K_{cb\ mid}$ and $K_{cb\ end}$ were unchanged from those proposed by FAO-56, and $K_{cb\ ini}$ was slighty increased. The values for $K_{cb\ ini}$ and $K_{cb\ mid}$ are smaller than those presented by Hunsaker et al. (2003) but the $K_{cb\ end}$ is similar; however, the cotton varieties were different. When comparing with K_{cb} values for cotton presented by Howell et al. (2004), the $K_{cb\ ini}$ and $K_{cb\ mid}$ values are similar but estimates for $K_{cb\ end}$ are higher, probably reflecting impacts of excess irrigation as analyzed by Pereira et al. (2009). The calibrated p values are equal to those proposed by FAO-56. Results for $K_{cb} + K_e$ are similar to those presented by Cholpankulov et al. (2008) for the same experiments.

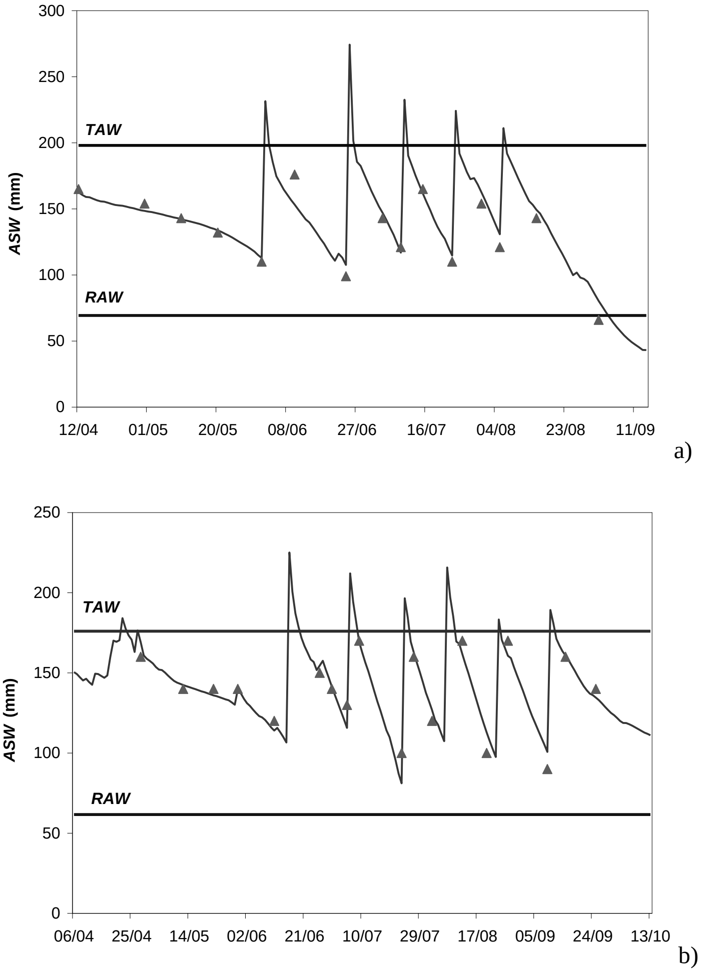


Fig. 2.12. Comparison between observed (▲) and simulated (—) available soil water (ASW) for the cotton crop in Fergana for (a) 2001 (calibration), (b) 2003 (validation). TAW and RAW are respectively the total and readily available soil water

Errors and other goodness of fit indicators yielded similar values for both studies (Tables 2.19 and 2.20). The goodness of fit indicators show good agreement between simulated and observed soil water content data for calibration (2001) and validation (2003) years. Only small differences occurred to *ASW* following calibration because changes were only made to TEW and REW. The regression coefficients b were all close to 1.0 and the coefficients of determination were high, ranging from 0.89 to 0.93. The regression for all Fergana results combined is presented in Fig. 2.13; it shows the regression slope to be close to the 1:1 line. The errors of estimation were small: RMSE was less than 9 mm and AAE was 7 mm, which are less than 5% of TAW. ARE were small, approximately 6%. The index of efficiency (EF) ranged from 0.88 to 0.91 and the indices of agreement (d_{IA}) were 0.97.

Table 2.19. Indicators of goodness of fit relative to the model tests for cotton in Fergana when using calibrated values for REW, TEW, Z_e, K_{cb} and p.

Goodness of fit indicators	b	R^2	RMSE (mm)	RMSE/TAW (%)	ARE (%)	AAE (mm)	EF	d_{IA}
Calibration (2001)	1.00	0.93	8.6	4.4	5.6	6.7	0.91	0.97
Validation (2003)	0.99	0.89	8.3	4.7	5.4	6.6	0.88	0.97
All experiments	*1.00*	*0.90*	*8.6*	*4.6*	*5.7*	*6.8*	*0.89*	*0.97*

* parameter values presented in Table 2.18

Table 2.20. Indicators of goodness of fit relative to the model tests for cotton in Fergana when using standard values (Allen et al., 1998, 2007) for REW, TEW, Z_e, K_{cb} and p.

Goodness of fit indicators	b	R^2	RMSE (mm)	RMSE/TAW (%)	ARE (%)	AAE (mm)	EF	d_{IA}
2001	1.02	0.94	9.0	4.5	6.4	7.2	0.90	0.97
2003	1.00	0.89	8.1	4.6	5.4	6.6	0.89	0.97
All experiments	*1.01*	*0.90*	*8.6*	*4.6*	*5.8*	*6.9*	*0.89*	*0.97*

* parameter values presented in Table 2.18

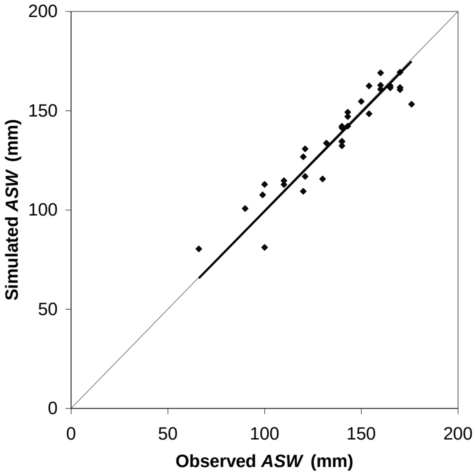


Fig. 2.13. Comparison between observed and simulated available soil water (ASW) using all experimental data for the cotton crop in Fergana, Uzbekistan, after model calibration, with the solid line representing the regression and the dashed line a 1:1 relationship.

To investigate how well the model simulates the soil water without calibration of parameters, the model was applied to the same experiments using only standard data (REW, TEW, Z_e, K_{cb} and p) from Allen et al. (1998, 2007) but adopting the same, observed dates for crop stages taken from field notes. The equations for computing GW_c and DP were parameterized as for the calibration and validation applications. Results are shown in Table 2.20, with errors being only slightly higher than for the simulations using calibrated parameters. The RMSE remained at 8.6 mm and ARE increased from 5.7 to 5.8%. All EF and d_{IA} values are high, thus indicating that the model performed well in simulating soil water content when both standard and calibrated parameters were used. Therefore, as for maize and wheat, results for cotton show that the model may be used with standard values if dates for crop growth stages correspond to local field observations, as is recommended by FAO-56, and when groundwater contribution and deep percolation are adequately parameterized when a shallow ground-water table is present.

2.5.2.2. Evaporation and transpiration components

The results for E_s (mm) and T_a (mm) for each experiment and crop growth stage are presented in Table 2.21. Soil evaporation E_s was the main component of $ET_{c\ adj}$ during the initial crop growth stage for 2003, representing 68% of $ET_{c\ adj}$ for that period. For 2001 E_s was only 49% of $ET_{c\ adj}$ because the soil surface was relatively dry. Comparing results for the initial period at Fergana (Table 2.21), crop transpiration was 19 mm in 2001 and 29 mm in 2003 while soil evaporation was 18 and 63 mm, respectively in 2001 and 2003. During the crop development stage, E_s decreased substantially in relation to T_a, but for the experiment of 2001 the application of irrigation water increased soil evaporation in absolute terms when compared with the initial stage. During mid season, because soil shading effects were dominant, estimated E_s values were negligible when compared to T_a for both years. For the late season, E_s remained low, especially during 2001. Ratios of $E_s/ET_{c\ adj}$ of 10 and 17%, are in agreement but smaller than those previously reported for Uzbekistan for different locations: Forkutsa et al. (2009) reported $E_s/ET_{c\ adj}$ in the range of 32-40%, and Qureshi et al. (2011) reported an average of 22%. Results by Farahani et al. (2009) ranged from 16 to 34%, with the highest value for a water stressed crop.

Table 2.21. Evaporation (E_s) and transpiration (T_a) over each development stage for the cotton crop, Fergana.

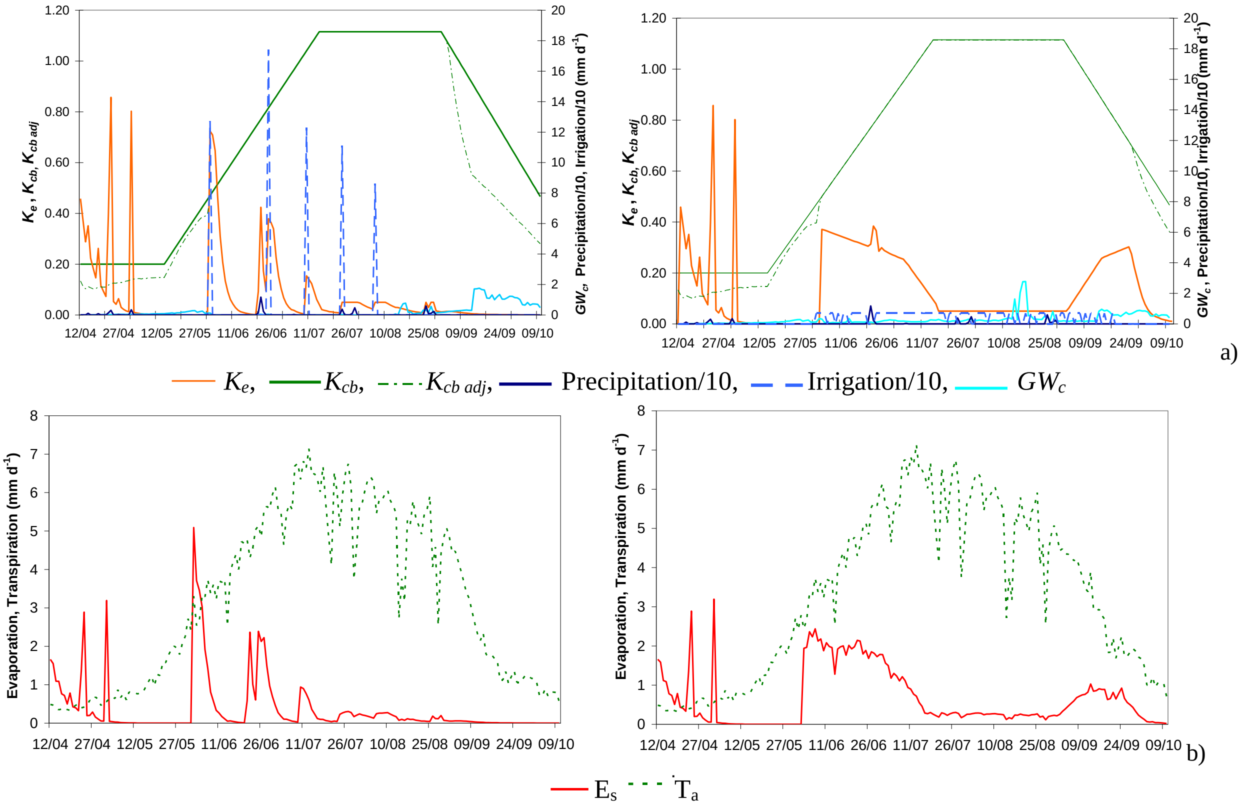
	Initial crop stage		Vegetative growth		Mid season		End season		Entire growing season		
	E_s (mm)	T_a (mm)	E_s (mm)	T_a (mm)	E_s (mm)	T_a (mm)	E_s (mm)	T_a (mm)	E_s (mm)	T_a (mm)	$E_s/ET_{c\ adj}$ (%)
Cotton (2001)	18	19	40	235	7	258	1	75	66	586	10
Cotton (2003)	63	29	41	223	7	249	14	112	124	613	17

The computed capillary rise estimated for Fergana was 42 mm for 2001 and negligible (8 mm) for 2003 because of high available soil water maintained throughout the crop growing season (Fig. 2.12); Deep percolation was high, 184 and 170 mm for the same years, thus reflecting poor control of irrigation water as analyzed by Pereira et al. (2009).

2.5.2.3. Assessing an alternative irrigation method

An alternative scenario was developed for management purposes to assess the impact of using drip irrigation on the water balance components. Climatic, soil and crop data for 2001 were used as well as the previously calibrated parameters K_{cb}, p, TEW, REW and Z_e. Simulations assumed a drip irrigation system having small application depths of D = 7 mm, *i.e.*, daily frequencies during the peak period as suggested by DeTar (2008); for management purposes the date of the last irrigation was set at 20 days before harvest because cotton lint quality is affected when its moisture content at harvest is higher than 8% (Barker, 1996). The f_w term, representing the fraction of soil surface wetted by irrigation was set to 0.4. Due to the small irrigation depths and very frequent water application specified for the drip system, deep growth of roots may not be promoted (Klepper, 1991). Z_r was assumed to grow at the same rate as for surface irrigation until the 4th micro-irrigation was applied, when root depth was around 0.8 m; therefore, Z_r was set to 0.8 m. The simulated irrigation schedule was targeted for no stress and for management of deep percolation. Fig. 2.14 presents the variation of coefficients K_{cb}, $K_{cb\ adj}$, and K_e over time as well as a summary for components of the water balance, E_s, T_a, P, I, GW_c and ΔSW.

The model application to the alternative drip irrigation scenario estimated total water use (rainfall and irrigation) to be slightly lower than for furrow irrigation but with water balance components substantially changed. The simulated results show: a) an increase of soil E_s, from 66 to 120 mm, due to high irrigation frequency during the development stage and in the late season, when the crop does not completely cover the soil, even though f_w was estimated to be small; b) a small increase in capillary rise from 42 to 53 mm; c) maximum values for K_e during the crop development stage were smaller than for furrow irrigation due to smaller f_w, but the average K_e was considerably higher; d) a negligible reduction of potential K_{cb} (*i.e.*, $K_{cb\ adj} \approx K_{cb}$), hence a higher T_a due to more soil water availability during late season; e) a full control of deep percolation because applied depths were small (this assumes an effective and accurate water measurement and management program is in place); f) a decrease in soil water use, with ΔSW decreasing by 48 mm, likely related to smaller root development.



Irrigation + rainfall (mm)	666	605
GWc (mm)	42	53
ΔSW (mm)	-120	-72
Percolation (mm)	184	-
E_s (mm)	66	120
T_a (mm)	587	612

Fig. 2.14. Comparison of seasonal variation of K_e, K_{cb}, $K_{cb\ adj}$, irrigation/10 and precipitation/10 (a), and of E_s and T_a (b) for the current surface irrigation (left) with an alternative micro-irrigation (right) (for easier reading of the Figure, irrigation and precipitation are divided by 10).

Overall, transpiration slightly increased because the simulated irrigation scheduling provided more adequate irrigation, although irrigation was stopped 20 days before harvest. The results show that drip irrigation by itself does not seem more beneficial than furrow irrigation since it leads to higher water losses by evaporation, changing from 66 to 120 mm, and may not allow for leaching, which is often required in the region. Evaporation would have been even higher if a larger value for f_w had been employed, which would be the case for many forms of surface drip irrigation. If an irrigation schedule for adequate furrow irrigation is adopted, deep percolation may be controlled and E_s losses are minimized when compared with drip irrigation. The value of adopting a dual crop coefficient approach in simulating ET is again evidenced from this modeling study.

2.6. Conclusions

The SIMDualKc model was tested using data from experiments that were independently performed. Tests consisted of comparing model results with field measurements of *ASW* before and after calibration of basic model components of K_{cb}, threshold for stress, rooting depth, fraction of soil cover, and potential evaporation depths (REW and TEW) for maize, wheat and cotton cropped under different climates and irrigation management conditions. Soils generally had high silt and clay contents. Experimental treatments included rainfed, full and deficit irrigation, and a variety of irrigation methods. Thus, the field data represented a relatively broad spectrum of field and cultural conditions.

Comparison of simulated and observed soil water showed, for all cases, regression slopes close to the target value of 1.0, even when using standard (FAO-56) values for K_{cb}, p and soil evaporable water parameters (TEW, REW and Z_e), and indicated that the model does not show any tendency to over- or underestimate the ASW or the soil water content during the different crop growth stages. The coefficients of determination ranged from 0.89 to 0.99. The errors of estimates were small in terms of both RMSE and AAE. The average relative errors ranged from around 3 to 6%. The model efficiency and the index of agreement, EF and $d_{IA,}$ ranged from 0.88 to 1.00 and 0.97 to 1.00, respectively. In conclusion, all indicators support the ability of the model to accurately estimate the soil water content for the crops and irrigation systems considered. These results suggest that one can analyze the partitioning of actual crop evapotranspiration into soil evaporation and crop transpiration under different water management and irrigation system types and rainfall frequencies. The respective results tend to support the assumptions underlying the dual crop coefficient approach.

In general, adjustments to standard model parameters required during calibration were small. However, computations confirmed the importance of using appropriate observations of the fractions of soil covered by vegetation, of soil wetted by irrigation and of soil wetted and exposed to solar radiation. A challenge in this study, using past observed data, was that these variables were not purposefully observed at the time of experiments. However simulations could still be performed because it was possible to reconstruct these types of observed data. It is likely that if those variable fractions had been purposefully observed simulations would have been more accurate.

The model accuracy is considered to be good, considering the conditions of this study, where observation data collected in the past with objectives that were different from this particular model testing were utilized. Results indicate that the model effectively implemented the dual crop coefficient approach for assessing crop irrigation water uses and scheduling and that the dual K_c approach was adequate to simulate the observed ASW data. This study also shows that using standard K_{cb}, p and soil evaporable water parameters from FAO-56 provides soil water and ET estimates having acceptably small errors, provided that dates for crop growth stages corresponding to field conditions are observed or approximated and that fractions of ground cover, soil wetted and soil exposed and wetted are selected that effectively characterize the crop canopy throughout the season.

All three case studies were also used to develop and assess scenarios for changes in irrigation methods and management. Results demonstrated the ability of the model to deal with those different conditions and to assess changes in the water balance components due to adopting different irrigation depths and schedules. However, conclusions for these simulations should be interpreted with caution despite that results are in agreement with common knowledge on these topics.

Acknowledgements

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Capítulo 3 - Necessidades de água para a rega de milho em Portugal continental considerando condições de seca

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Paredes, P, Rodrigues, G.C., 2010. Necessidades de água para a rega de milho em Portugal continental considerando condições de seca. In: LS Pereira, JT Mexia, CA Pires (eds.) Gestão do Risco em Seca. Métodos, Tecnologias e Desafios. Edições Colibri e CEER, pp. 301-319

Necessidades de água para a rega de milho em Portugal continental considerando condições de seca

Resumo

O milho é uma das principais culturas regadas em Portugal. A identificação de estratégias de rega deficitária, que reduzam a procura de água com impactos aceitáveis na produção, constitui uma medida de preparação para enfrentar as secas e a escassez de água. O modelo de balanço hídrico e de simulação de calendários de rega SIMDualKc, anteriormente calibrado e validado para a cultura do milho em Portugal, foi utilizado para simular vários cenários de rega para condições de seca severa e extrema. Este estudo foi realizado para milho regado por aspersão e aplicado a várias localidades: Vila Real, Bragança e Miranda do Douro no Norte, Coimbra e Viseu no Centro e Beja, Évora e Elvas no Sul. As alternativas de calendários de rega foram avaliadas tendo em consideração a poupança de água de rega e o impacto nas produções. Os resultados mostram que as estratégias de rega deficitárias poderão ser viáveis quando os défices hídricos forem muito baixos. Como alternativa poder-se-á optar pela satisfação das necessidades totais da cultura diminuindo no entanto, a área cultivada.

Abstract

Maize is a main irrigated crop in Portugal. The identification of deficit irrigation strategies that provide for a reduced water demand with acceptable impacts on yields is part of the preparedness measures required to cope with drought and water scarcity. The water balance and irrigation scheduling simulation model SIMDualKc, which was previously calibrated and validated for the maize crop in Portugal, is used to simulate various irrigation schedules under severe and extreme drought conditions. Strategies include full irrigation and mild to moderate deficit irrigation to cope with water scarcity conditions. This study applies to the maize crop under sprinkler irrigation in several regions of Portugal; Vila Real, Bragança and Miranda do Douro in North, Coimbra and Viseu in Center, and Beja, Évora and Elvas in South. The alternative irrigation schedules are assessed taking into consideration the reduction in demand for irrigation water (water savings) and related impacts on yields. Results show that deficit irrigation strategies for maize may be feasible only when the irrigation deficit is small. Otherwise, the best practice is to fully satisfy crop needs while reducing the cropped area.

3.1. Introdução

A gestão da água em agricultura desempenha um papel fundamental no restabelecimento do equilíbrio ambiental e na manutenção dos recursos hídricos em situação de carência de água (Pereira, 2004). A gestão de recursos em condições de seca centra-se na água e na prioridade para a eficiência de utilização desta, i.e., na produtividade da água. O desafio deste tipo de estratégias de gestão é produzir mais utilizando menor quantidade de água (Oweis et al., 1999). No entanto, como analisado por Rodrigues et al. (2010), as relações económicas da produção são determinantes.

Ao nível da exploração agrícola, a gestão da procura para combater a escassez de água engloba quer a adopção de práticas de rega apropriadas que conduzam a poupança de água, quer a determinação do calendário de rega óptimo para condições de aplicação de volumes de água limitados (ver Pereira et al., 2009). Se o objectivo é, no entanto, a maximização dos benefícios da produção, a gestão da rega requer uma abordagem diferente. A maximização da produção implica que se efectue a rega necessária a suprir as necessidades das plantas; se o objectivo for maximizar os benefícios ou o lucro tal pode significar a opção pela rega deficitária controlada, ou seja, regar deliberadamente abaixo do nível de máxima produção que corresponda ao óptimo económico (Pereira, 2000, 2004; Pereira et al., 2002).

O milho é uma cultura com elevada exigência de água, mas é também uma das mais eficientes na produção de matéria seca e no uso da água. Em condições óptimas, o milho usa toda a água disponível e a eficiência de uso está estreitamente relacionada com a produção obtida. No entanto, se ocorrer stress nas fases críticas do seu desenvolvimento, como seja a floração, frutificação e enchimento do grão a produção será afectada reduzindo-se em quantidade e qualidade (Doorenbos e Kassam, 1979).

A programação e a condução da rega desempenham um papel importante na gestão da rega em condições de escassez de água, dado permitir determinar quando e quanto regar de forma a maximizar o uso de água pelas culturas e a minimizar as perdas por excesso de aplicação. Existem vários modelos de simulação do balanço hídrico que constituem ferramentas preciosas para a determinação das necessidades de rega e para a condução da rega. Neste estudo foi utilizado o modelo SIMDualKc (Rosa et al., 2010a).

A avaliação de calendários de rega alternativos pode mostrar-se útil no apoio à decisão quer dos agricultores como de gestores de projectos de rega. Assim, desenharam-se e avaliaram-se diferentes estratégias de rega deficitária em termos de poupanças de água e consequente redução da produção. A aplicação foi efectuada em 8 localidades de Portugal Continental: Vila Real, Bragança e Miranda do Douro no Norte, Coimbra e Viseu no Centro e Beja, Évora e Elvas no Sul. O estudo dos impactos económicos devidos a rega deficitária, que necessariamente complementa este trabalho, é apresentado por Rodrigues et al. (2010).

3.2. Materiais e métodos

3.2.1. Modelação

A evapotranspiração cultural (ET_c, mm d^{-1}) em condições padrão é definida como a taxa de evapotranspiração de uma cultura que se desenvolve numa extensa área de solo, com um teor de humidade óptimo, sujeita a uma gestão excelente e com as condições ambientais mais adequadas de modo a que a sua produção potencial seja atingida (Allen et al., 1998; Pereira, 2004; Pereira e Alves, 2005). Os factores que induzem um crescimento vegetativo deficiente, tais como a salinidade do solo, a baixa fertilidade do solo, a aplicação insuficiente de fertilizantes, a presença de camadas impermeáveis no perfil do solo, a ausência de controlo de pragas e doenças, a gestão inapropriada (mobilização) do solo e práticas agrícolas inadequadas, assim como rega que não satisfaça por completo as necessidades da planta, levam a uma diminuição da ET_c que passa a ser referida como evapotranspiração cultural real ou ajustada ($ET_{c\ adj}$) (Allen et al., 1998; Pereira, 2004).

O modelo SIMDualKc (Rosa et al., 2010a) utiliza a aproximação dual e a ET_c é calculada pelo produto entre a evapotranspiração de referência (ET_o, mm d^{-1}) e a soma dos coeficientes cultural basal (K_{cb}) e de evaporação do solo (K_e); sendo que o primeiro é ajustado pelo coeficiente de stress ou de défice de humidade do solo (K_s) no caso de existir stress (Allen et al., 1998; Pereira e Allen, 1999; Pereira, 2004; Allen et al., 2005, 2007):

$$ET_{c\ adj} = (K_s\, K_{cb} + K_e)\, ET_o \qquad (3.1)$$

A ET_o define-se como a taxa de evapotranspiração de uma cultura de referência hipotética, a qual se assume ter uma altura de 12 cm, uma resistência de superfície constante (70 s m^{-1}) e um albedo também constante (0.23), semelhante à evapotranspiração de um coberto extenso de relva verde de altura uniforme, em crescimento activo, cobrindo totalmente o solo e bem abastecido de água (Allen et al., 1998; Pereira, 2004). Esta definição, com recurso a parâmetros constantes, foi adoptada de forma a evitar problemas de calibração local (Allen et al., 1994a). O método de Penman-Monteith com aplicação dos parâmetros culturais assumidos na definição acima (ver Allen et al., 1994a, b) é o que conduz à melhor padronização do cálculo da ET_o. A equação de Penman-Monteith para o cálculo da ET_o para períodos diários toma a forma (Allen et al., 1998):

$$ET_o = \frac{0.408\,\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T + 273} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34\,u_2\right)} \tag{3.2}$$

onde ET_o, evapotranspiração de referência (mm d^{-1}), R_n, radiação líquida à superfície da cultura (MJ m^{-2} d^{-1}), G densidade do fluxo de calor do solo (MJ m^{-2} d^{-1}), T temperatura média diária do ar medida a 2 m de altura (ºC), u_2 velocidade média diária do vento medida a 2 m de altura (m s^{-1}), (e_s - e_a) défice da pressão de vapor do ar (kPa), Δ declive da curva de pressão de vapor (kPa ºC^{-1}) para a temperatura do ar T, γ constante psicrométrica (kPa ºC^{-1}). Quando a velocidade do vento é medida a uma altura superior a 2.0 m tem de se efectuar a respectiva correcção $U_2 = U_z \dfrac{4.87}{\ln\left(67.8\, z_m - 5.42\right)}$, onde z_m (m) é a altura a que foi medida a velocidade do vento U_z (m s^{-1}).

Os parâmetros da equação 3.2 devem ser calculados de modo padronizado a partir de observações da temperatura do ar, da humidade do ar, da radiação solar e da velocidade do vento (Allen et al., 1998; Pereira, 2004). Quando nem todas as variáveis são observadas pode recorrer-se a processos de estimação como os propostos pelos mesmos autores, entretanto comprovados para Portugal por Adaixo (1999) e analisados em detalhe por Popova et al. (2006b).

3.2.2. Calendarização da rega

Os factores que devem ser considerados quando se elabora um calendário de rega são: quantidade de água disponível, limitações de água, estado de desenvolvimento da cultura e rendimento potencial, precipitação e evapotranspiração, método de rega e limitações do sistema, e conteúdo de água do solo (Pereira, 2004). Na condução da rega, e se esta se faz de forma a evitar que ocorra défice hídrico, a data limite para realizar a rega será quando o teor de água do solo (θ_i, m^3 m^{-3}) atinja o limiar:

$$\theta_i = (1-p)\left(\theta_{FC}-\theta_{WP}\right)+\theta_{WP} \tag{3.3}$$

onde θ_{FC} e θ_{WP} são respectivamente o teor de água do solo à capacidade de campo e no coeficiente de emurchecimento e em que p é uma fracção da capacidade máxima de armazenamento (TAW, mm) que pode ser extraída sem produzir stress hídrico. Este procedimento, tomando como limiar a fracção de extracção *p*, é assumido quando se pretende evitar stress hídrico e atingir a produção potencial. A quantidade de água facilmente disponível para as plantas (RAW, mm) é uma fracção da água total e é obtida pelo produto p TAW.

A rega pode ser conduzida para um limiar diferente, o qual traduz a extracção desejada em termos de gestão (MAD, "management allowed depletion"), como definido por Martin et al. (1990). A fracção correspondente a MAD pode ser superior ou inferior a p conforme os objectivos de gestão. Toma-se MAD < p quando se pretende diminuir o risco de ocorrência de stress ou as incertezas ligadas à gestão da rega. Ao contrário, toma-se MAD > p quando se assume intencionalmente a gestão da rega com stress em determinados períodos, ou quando os recursos hídricos disponíveis são insuficientes para que a rega se pratique em conforto hídrico. A data de rega será então determinada por:

$$\theta_i = \theta_{MAD} = (1-MAD)\left(\theta_{FC}-\theta_{WP}\right)+\theta_{WP} \tag{3.4}$$

Em ambos os casos, a dotação (*I*, mm) a aplicar para restabelecer a água do solo à capacidade de campo é dada por:

$$I_{ni} = 1000 z_{ri}\left(\theta_{FC}-\theta_i\right) \tag{3.5}$$

A dotação líquida assim calculada constitui a maior quantidade a aplicar para que não ocorra percolação. Por outras palavras, podem utilizar-se dotações mais pequenas, seja definindo um valor máximo para θ inferior à capacidade de campo, seja adoptando uma dotação fixa conforme o método de rega utilizado. A dotação bruta a aplicar deverá ser $G = I_{ni} / E_a$, em que E_a é a eficiência do sistema de rega, podendo esta ser corrigida para casos de remoção de sais acumulados no perfil conforme descrito por Pereira (2004).

Necessidades líquidas de rega (*NIR*) – são calculadas mediante o balanço hídrico para todos os anos das séries meteorológicas disponíveis (precipitação e evapotranspiração de referência) determinando uma nova série referente às NIR e efectuando uma análise de frequência para esta série. A esta série é ajustável uma função de distribuição normal que permite estimar as necessidades de rega para o ano de seca severa (correspondente a uma probabilidade de não excedência de 80%) e para o ano de seca extrema (correspondente a uma probabilidade de não excedência de 95%). O balanço hídrico é depois simulado para as condições climáticas dos anos correspondentes a estes níveis de procura climática.

Rega para maximização da produção - a prática mais generalizada na agricultura de regadio é maximizar o rendimento da cultura por unidade de terra aplicando a quantidade de água necessária a suprir as necessidades da cultura. No entanto, existe a tendência para maximizar o rendimento da cultura por unidade de água, i.e., maximizar a produtividade da água; acontece porém que tal implica menor produtividade da terra e consequentes rendimentos (Pereira, 2007), o que não é aceitável a não ser quando haja condicionamento da água disponível.

Rega deficitária - é uma estratégia de optimização na qual as culturas são deliberadamente sujeitas a um certo grau de défice de água e de redução de rendimento (English e Raja, 1996). A cada estratégia de rega deficitária corresponde uma evapotranspiração relativa $ET_{c\ adj}/ET_c$ que induz uma diminuição do rendimento da cultura $Q_y = (1- Y_a/Y_c)$, em que ET_c e $ET_{c\ adj}$ são respectivamente a evapotranspiração potencial da cultura e a ET real deficitária, e Y_c e Y_d são respectivamente os rendimentos das culturas correspondentes a ET_c e $ET_{c\ adj}$. A adopção da rega deficitária implica a adopção de calendários apropriados que são construídos após a validação de campo dos modelos de simulação (e.g. Teixeira et al., 1995; Liu et al., 2000; Sawar and Bastiaanssen, 2001; Zairi et al., 2003; Popova et al., 2006a; Cholpankulov et al., 2008; Rosa et al., 2010a).

Nas estratégias de rega definidas neste estudo optou-se por considerar uma dotação fixa I = 15 mm e fixar os limiares θ_{MAD} como segue:

(a) MAD = p;

(b) MAD = 1.05 p; 1.05 p, 1.05 p; 1.05 p, respectivamente para as fases inicial, de desenvolvimento, média e final do ciclo cultural;

(c) MAD = 1.05 p; 1.10 p, 1.05 p; 1.10 p para as mesmas fases do ciclo;

(d) MAD = 1.10 p; 1.20 p, 1.05 p; 1.20 p para as mesmas fases do ciclo;

(e) MAD = 1.10 p; 1.30 p, 1.05 p; 1.30 p para as mesmas fases do ciclo.

De modo a determinar as quebras de produção decorrentes do stress hídrico utilizou-se o modelo água-produção descrito por Stewart et al. (1977) e divulgado por Doorenbos e Kassam (1979) e validado para milho por Alves e Pereira (1998), Liu et al. (2000) e Popova et al. (2006a). Baseia-se no conhecimento do factor de resposta da cultura à água (K_y) que exprime a relação linear entre o défice relativo de evapotranspiração sazonal ($1\text{-}ET_a/ET_c$) e as perdas relativas de produção ($1\text{-}Y_a/Y_m$), onde Y_a e Y_m representam a produção real e a potencial, respectivamente. No presente estudo utilizou-se $K_y = 1.25$ (Alves e Pereira, 1998).

3.2.3. Características climáticas, da cultura e solo

A criação de calendários de rega foi aplicada a várias localidades do país cujas estações meteorológicas se referem na Tabela 3.1.

Tabela 3.1. Características das estações meteorológicas utilizadas no estudo.

Local	Latitude (º)	Altitude (m)	Altura do anemómetro z_m (m)	Comprimento das séries de dados
Beja	38.02	246	10.0	1965 a 2009
Évora	38.57	309	22.9	1965 a 2009
Elvas	38.88	208	4.0	1965 a 2000
Coimbra	40.16	141	4.0	1998 a 2008
Viseu	40.71	636	4.0	1998 a 2008
Vila Real	41.27	481	6.0	1998 a 2008
Bragança	41.49	720	2.0	1985 a 1997
Miranda do Douro	41.50	693	13.7	2000 a 2008

Na Tabela 3.2 apresentam-se as características climáticas médias (ET_o e precipitação) de cada local. A ET_o foi determinada pelo método FAO-PM referido atrás (Eq. 3.2, Allen et al., 1998); quando faltaram observações para o cálculo da pressão de vapor real substituiu-se a temperatura do ponto de orvalho pela temperatura mínima, ao faltarem observações da velocidade do vento utilizou-se o valor médio 2 m s^{-1} e na falta de observações da radiação e de insolação recorreu-se à diferença entre temperaturas máxima e mínima diárias ($T_{max}\text{-}T_{min}$) através da relação linear

$$R_s = k_{Rs} \, (T_{max} - T_{min})^{0.5} \, R_a \qquad (3.6)$$

onde R_s é a radiação solar incidente (MJ m^{-2} d^{-1}), R_a é a radiação extraterrestre (MJ m^{-2} d^{-1}) e k_{Rs} é um coeficiente empírico que, entre nós, toma em geral os valores 0.16 ou 0.17. Estas aproximações foram comprovadas para Portugal por Adaixo (1999) e verificadas para as estações referidas na Tabela 3.1.

Analisando a Tabela 3.2 verifica-se que em todas as regiões estudadas nos meses de verão a ET_o é muito superior à precipitação pelo que a rega é condicionante para que se atinjam as produções potenciais.

De modo a verificar a coerência da estimação da ET_o quando existem dados em falta, foi efectuada a comparação entre os valores calculados pela equação ET_o FAO-PM utilizando todas as variáveis climáticas observadas e com as variáveis estimadas como referido acima. Os indicadores de ajustamento utilizados foram: coeficiente de regressão (b), coeficiente de determinação (R^2), o erro médio quadrático (EMQ), erro máximo absoluto (EM_a); erro máximo (E_{max}), a eficiência da modelação (EF), e índice de ajustamento (d_{IA}) descritos em Cholpankulov et al. (2008) e Rosa et al. (2010a).

Para evitar que os resultados fossem afectados pela natureza do solo nos diversos locais, optou-se por realizar todas as simulações para um solo franco-limoso com as propriedades hidráulicas descritas na Tabela 3.3. O solo apresenta uma quantidade de água disponível total (TAW) de 253 mm, tendo-se considerado que a camada evaporativa tem 0.15 m, com um teor total de água evaporável TEW = 38 mm e um teor de água facilmente evaporável REW = 12 mm.

Tabela 3.3. Propriedades hidráulicas do solo (capacidade de campo (θ_{FC}), coeficiente de emurchecimento (θ_{WP})), de um solo franco-limoso (Fernando, 1993)

Camadas (m)	θ_{FC} (m^3 m^{-3})	θ_{WP} (m^3 m^{-3})
0.00-0.20	0.36	0.10
0.20-0.40	0.35	0.09
0.40-0.60	0.36	0.10
0.60-0.80	0.35	0.10
0.80-1.00	0.34	0.10

Tabela 3.2. Média ($\bar{x}$) das séries de dados de ET_o e precipitação (mm) para as estações meteorológicas em estudo

Meses	Beja		Évora		Elvas		Coimbra		Viseu		Vila Real		Bragança		Miranda do Douro	
	ET_o (mm)	Prec. (mm)	ET_o (mm)	Prec. (mm)	ET_o (mm)	Prec. (mm)	ET_o (mm)	Prec. (mm)	ET_o (mm)	Prec. (mm)	ET_o (mm)	Prec. (mm)	ET_o (mm)	Prec. (mm)	ET_o (mm)	Prec. (mm)
Jan	29.9	70.3	28.5	76.4	29.9	62.2	27.0	102.7	27.5	142.9	18.6	114.3	21.0	126.9	16.8	63.3
Fev	40.3	58.5	41.8	65.7	40.2	44.2	31.4	52.0	41.5	83.9	31.4	67.9	30.1	70.2	29.2	45.6
Mar	73.1	44.5	68.0	49.6	81.0	35.6	61.3	73.4	67.7	127.2	57.1	107.6	57.5	35.6	59.1	58.1
Abr	96.3	51.1	92.9	56.4	102.8	43.8	85.9	82.1	83.0	128.9	78.1	99.2	74.3	58.2	85.0	48.7
Mai	130.8	41.8	123.1	46.1	130.3	45.6	112.9	49.6	112.5	76.4	112.6	61.7	101.1	71.5	120.8	44.1
Jun	174.6	17.0	150.6	18.7	173.3	18.8	140.8	19.2	150.3	30.7	148.8	26.1	123.8	32.1	164.3	24.0
Jul	203.8	2.0	185.2	4.9	196.8	4.1	146.5	12.3	165.1	21.7	156.4	13.8	150.1	14.0	176.6	13.6
Ago	183.0	4.1	169.3	6.5	174.1	2.2	135.3	19.1	156.8	31.1	139.9	31.3	129.6	16.1	152.9	28.3
Set	121.8	25.1	117.8	34.3	109.4	25.8	97.0	54.0	106.8	70.9	88.5	67.1	83.0	43.4	99.1	32.6
Out	73.5	73.0	67.4	80.5	69.0	51.7	58.4	125.0	57.3	178.9	46.1	141.9	46.7	95.0	47.0	115.2
Nov	38.1	70.4	37.8	78.4	34.5	82.8	35.4	98.1	34.5	128.7	23.4	105.2	23.2	107.2	21.5	79.4
Dez	26.6	86.5	26.9	85.9	25.9	100.0	25.1	106.1	25.5	152.0	18.9	136.8	18.4	128.5	12.8	69.1

O ciclo cultural utilizado (Tabela 3.4) foi o observado em experimentações de campo efectuadas na campanha de 2010. Os parâmetros culturais são os obtidos por calibração do modelo SIMDualKc, como apresentado por Rosa et al. (2010a) com excepção do $K_{cb\ end}$, que foi modificado para produção de grão relativamente ao valor calibrado que fora para milho de silagem, colhido com grão leitoso.

Tabela 3.4. Coeficientes culturais basais do milho (K_{cb}) e fracção de água do solo esgotável sem causar stress hídrico (p) e datas das fases de desenvolvimento da cultura

Parâmetros culturais	Estágios de desenvolvimento da cultura			
	Período inicial	Período de crescimento rápido	Período intermédio	Período final
Coeficiente cultural basal, K_{cb}	0.15	0.15-1.15	1.15	1.15-0.35
Fracção de água do solo esgotável sem causar stress hídrico, p	0.50	0.50-0.50	0.50	0.50-0.50
Datas	25-05 a 10-06	11-06 a 17-07	18-07 a 03-09	04-09 a 13-10

3.3. Resultados e discussão

3.3.1. Avaliação do cálculo da ET_o quando há dados em falta

Como referido anteriormente, quando não existem dados de humidade relativa ou das temperaturas do psicrómetro, a estimação da pressão de vapor é efectuada a partir da T_{min}. Compararam-se os valores da ET_o FAO-PM quando calculada com dados completos e com os obtidos por esta estimação mediante regressões forçadas à origem. Verifica-se por análise da Tabela 3.5 que a estimação é boa a muito boa, com coeficientes de regressão a variarem entre 0.99 e 1.06, com maior sobre-estimação da ET_o no caso de Beja e Coimbra (1.06 e 1.04 respectivamente); estes dois locais apresentam os maiores EMQ (0.65 e 0.42 mm d^{-1}). Quando verificamos os EM_a os valores mais elevados referem-se a Beja e Viseu (0.46 e 0.37 mm d^{-1}) e os E_{max} mais elevados são observados em Beja e Elvas (2.9 e 4.2 mm d^{-1}). No entanto em todos os locais a eficiência de modelação EF e o índice de ajustamento d_{IA} são elevados, indicando que a estimação é adequada.

Quando são os dados de vento que se encontram em falta utilizou-se o valor médio 2 m s^{-1}, sendo os resultados apresentados na Tabela 3.6. Verifica-se uma sobre-estimação dos valores ET_o calculados para os casos de Vila Real, Bragança e Miranda do Douro, o que é explicado pelo facto de a média da série de dados de vento destas estações ser de 1.5 m s^{-1}. Opostamente, a subestimação que ocorre para Beja, Évora e Viseu deve-se a que a média da série de dados de vento destas estações ser de 3.0 m s^{-1}. Os erros médios quadráticos e absolutos são baixos variando respectivamente 0.20 - 0.40 e 0.11 - 0.25 mm d^{-1}; os erros máximos variam de 1.9 a 3.2 mm d^{-1}. EF e d_{IA} encontram-se próximos de 1.0. Conclui-se que na ausência de valores de vento será aconselhável a utilização da média dos valores da estação (ou da região) em vez do valor médio 2 m s^{-1}. Porém, este valor é de utilizar para locais onde não haja valores observados nem valores regionais.

Tabela 3.5. Parâmetros de avaliação do desempenho do cálculo da ET_o pelo método FAO-PM com dados de humidade relativa em falta.

	b	R^2	EMQ (mm d^{-1})	EM_a (mm d^{-1})	E_{max} (mm d^{-1})	EF	d_{IA}
Beja	1.06	0.94	0.65	0.46	2.9	0.91	0.98
Évora	1.02	0.95	0.49	0.34	3.4	0.95	0.99
Elvas	1.01	0.96	0.42	0.30	4.2	0.96	0.99
Coimbra	1.04	0.97	0.35	0.27	2.0	0.96	0.99
Viseu	0.99	0.95	0.47	0.37	2.3	0.95	0.99
Vila Real	1.02	0.99	0.17	0.13	0.8	0.99	1.00
Bragança	1.02	0.99	0.19	0.12	1.7	0.99	1.00
Miranda do Douro	1.01	0.99	0.19	0.14	1.2	0.99	1.00

Se são os valores da radiação solar ou de insolação que se encontram em falta, pode-se utilizar a Eq. 3.6 com valores de k_{Rs} 0.16 ou 0.17. Os resultados da aplicação desta metodologia quando comparada com a utilização dos todos os dados encontra-se na Tabela 3.7.

Tabela 3.6. Parâmetros de avaliação do desempenho do cálculo da ET_o pelo método FAO-PM com dados de velocidade do vento em falta

	b	R^2	EMQ (mm d^{-1})	EM_a (mm d^{-1})	E_{max} (mm d^{-1})	EF	d_{IA}
Beja	0.93	0.99	0.37	0.24	2.9	0.97	0.99
Évora	0.95	0.99	0.30	0.19	3.2	0.98	0.99
Elvas	1.01	0.97	0.35	0.22	3.0	0.97	0.99
Coimbra	1.00	0.99	0.20	0.11	2.0	0.99	1.00
Viseu	0.94	0.97	0.38	0.20	2.1	0.96	0.99
Vila Real	1.07	0.98	0.33	0.20	1.9	0.97	0.99
Bragança	1.10	0.97	0.40	0.25	1.9	0.93	0.99
Miranda do Douro	1.06	0.98	0.37	0.22	2.8	0.97	0.99

Os resultados apresentados na Tabela 3.7 mostram que b e R^2 são próximos da unidade, e os erros são baixos para ambos os valores de k_{Rs}. EMQ variam entre 0.26 - 0.35 e 0.25 - 0.34 mm d^{-1} respectivamente para k_{Rs} = 0.16 e 0.17 e E_{max} variam de 0.13 - 0.24 mm d^{-1} As eficiências EF e d_{IA} são em qualquer caso próximas de 1.0. No entanto, verifica-se que para o caso de Beja e Elvas é mais adequado o valor k_{Rs} = 0.16 enquanto para as outras estações k_{Rs} = 0.17 apresenta melhores resultados.

Tabela 3.7. Parâmetros de avaliação do desempenho do cálculo da ET_o pelo método FAO-PM com dados de insolação/radiação em falta

		b	R^2	EMQ (mm d^{-1})	EM_a (mm d^{-1})	E_{max} (mm d^{-1})	EF	d_{IA}
Beja	k_{Rs} = 0.16	1.00	0.99	0.26	0.26	0.17	0.99	1.00
	k_{Rs} = 0.17	1.03	0.98	0.30	0.30	0.19	0.98	1.00
Évora	k_{Rs} = 0.16	0.96	0.98	0.31	0.22	2.3	0.98	0.99
	k_{Rs} = 0.17	0.99	0.98	0.30	0.20	2.5	0.98	0.99
Elvas	k_{Rs} = 0.16	0.99	0.98	0.31	0.31	0.21	0.98	0.99
	k_{Rs} = 0.17	1.02	0.98	0.34	0.34	0.22	0.97	0.99
Coimbra	k_{Rs} = 0.16	0.94	0.97	0.34	0.34	0.22	0.96	0.99
	k_{Rs} = 0.17	0.97	0.97	0.29	0.29	0.16	0.97	0.99
Viseu	k_{Rs} = 0.16	0.93	0.98	0.35	0.35	0.24	0.97	0.99
	k_{Rs} = 0.17	0.96	0.98	0.30	0.30	0.21	0.98	0.99
Vila Real	k_{Rs} = 0.16	0.96	0.97	0.33	0.33	0.23	0.97	0.99
	k_{Rs} = 0.17	0.99	0.97	0.31	0.31	0.20	0.97	0.99
Bragança	k_{Rs} = 0.16	1.04	0.97	0.32	0.21	1.9	0.96	0.99
	k_{Rs} = 0.17	1.09	0.97	0.40	0.27	2.2	0.93	0.98
Miranda do Douro	k_{Rs} = 0.16	0.96	0.99	0.27	0.27	0.18	0.98	1.00
	k_{Rs} = 0.17	0.99	0.99	0.25	0.25	0.13	0.99	1.00

Na Tabela 3.8 apresentam-se os resultados da comparação entre o método de cálculo da ET_o com dados completos e na ausência simultânea de dados de pressão de vapor, vento e insolação/radiação, isto é, recorrendo apenas a observações da temperatura, como referido acima. Verifica-se que os resultados mostram comportamentos diferentes dos assinalados anteriormente constatando-se pouca adequação, não explicável facilmente, para o caso de Bragança, por isso requerendo análise posterior de melhor detalhe. Quanto às restantes estações, a adopção de k_{Rs} = 0.16 parece mais adequada para Beja, Elvas, Coimbra, Vila Real e Miranda do Douro, e k_{Rs} = 0.17 parece mais adequado para Évora e Viseu. Para Bragança, k_{Rs} = 0.15 pode ser adequado.

Tabela 3.8. Parâmetros de avaliação do desempenho do cálculo da ETo pelo método FAO-PM com dados de humidade relativa, vento e insolação/radiação em falta

		b	R^2	EMQ (mm d^{-1})	EM_a (mm d^{-1})	E_{max} (mm d^{-1})	EF	d_{IA}
Beja	k_{Rs} = 0.16	1.06	0.91	0.74	0.58	2.9	0.88	0.97
	k_{Rs} = 0.17	1.09	0.91	0.82	0.64	3.1	0.86	0.96
Évora	k_{Rs} = 0.16	0.92	0.91	0.68	0.52	4.1	0.90	0.97
	k_{Rs} = 0.17	0.95	0.91	0.65	0.50	3.9	0.90	0.97
Elvas	k_{Rs} = 0.16	1.01	0.89	0.71	0.57	3.0	0.88	0.97
	k_{Rs} = 0.17	1.04	0.89	0.74	0.60	3.1	0.87	0.97
Coimbra	k_{Rs} = 0.16	0.99	0.90	0.54	0.41	3.2	0.90	0.97
	k_{Rs} = 0.17	1.02	0.90	0.56	0.44	3.4	0.89	0.97
Viseu	k_{Rs} = 0.16	0.87	0.87	0.80	0.57	3.0	0.84	0.95
	k_{Rs} = 0.17	0.90	0.87	0.77	0.56	2.9	0.86	0.96
Vila Real	k_{Rs} = 0.16	1.03	0.95	0.47	0.38	2.1	0.93	0.98
	k_{Rs} = 0.17	1.07	0.95	0.51	0.41	2.3	0.92	0.98
Bragança	k_{Rs} = 0.16	1.23	0.91	0.87	0.71	3.3	0.68	0.93
	k_{Rs} = 0.17	1.27	0.91	0.96	0.78	3.5	0.62	0.92
Miranda do Douro	k_{Rs} = 0.16	1.04	0.94	0.58	0.46	2.5	0.92	0.98
	k_{Rs} = 0.17	1.08	0.94	0.62	0.49	2.7	0.91	0.98

3.3.2. Calendários de rega

A simulação da rega em condições de disponibilidade de água limitada foi estudada tomando em consideração dois níveis de procura climática, forte e a muito forte, correspondendo a seca severa e seca extrema. Estes níveis estão directamente relacionados com as reservas de água do solo e com as necessidades de rega da cultura.

Na Fig. 3.1 são apresentadas as séries estatísticas das necessidades de rega para a cultura do milho para as diferentes localidades estudadas, as quais serviram para identificar, nas séries de dados disponíveis, os anos de seca severa e extrema a simular. Na Tabela 3.9 são apresentadas as condições correspondentes aos dois níveis de procura climática. Verifica-se que as necessidades de rega do milho são mais elevadas nas regiões do Sul onde a ET_c é mais elevada e a precipitação mais reduzida; as NIR variam entre 392 e 797 mm nos anos de seca severa e 467 a 830 mm nos anos de seca extrema. De salientar que, para todos os casos, o ano de seca severa foi o de 2005, com excepção de Elvas pois a série de dados utilizada é mais curta não contemplando o ano de 2005. Estes resultados estão de acordo com os apresentados por Rosa et al. (2010b).

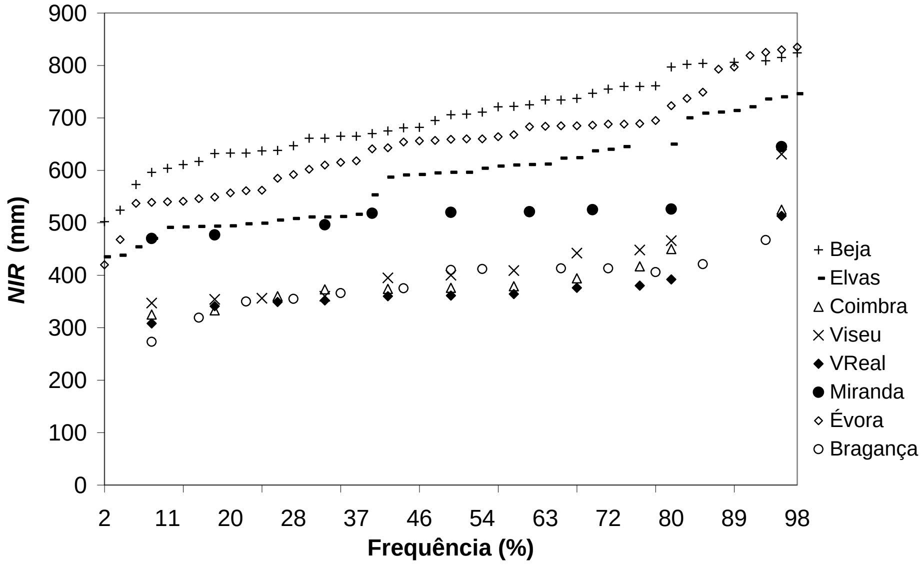

Fig. 3.1. Necessidades de água de rega (NIR) do milho para várias localidades de Portugal Continental.

Tabela 3.9. Características dos anos de seca severa e extrema para as localidades estudadas.

Local	Condição de procura climática	Anos	Precipitação sazonal (mm)	ET_c (mm)	Necessidades de rega (mm)
Beja	Severa	1991	38	892	797
	Extrema	2005	43	893	810
Évora	Severa	2008	61	832	723
	Extrema	2005	66	921	830
Elvas	Severa	1965	175	752	650
	Extrema	1991	32	805	740
Coimbra	Severa	2006	153	619	450
	Extrema	2005	79	620	525
Viseu	Severa	2001	155	643	466
	Extrema	2005	107	759	631
Vila Real	Severa	2001	150	545	392
	Extrema	2005	81	611	513
Bragança	Severa	1986	142	545	406
	Extrema	1994	54	563	467
Miranda do Douro	Severa	2000	92	655	526
	Extrema	2005	33	724	645

Na Tabela 3.10 apresentam-se os resultados das alternativas de calendários de rega para todas as regiões estudadas.

Tabela 3.10. Resultados das simulações da rega do milho para diferentes localidades em condições de seca severa e extrema e várias estratégias de rega (I = 15 mm)

Local	Procura climática	Estratégia de rega	$ASW_{ini.}$ (mm)	$ASW_{fin.}$ (mm)	Precipitação (mm)	Necessidades de rega (mm)	TWU (mm)	$ET_{c\ adj}$ (mm)	Perda relativa de produção (%)
Beja	Severa	a	178	133	38	795	878	880	2
		b		131		765	850	851	6
		c		123		750	843	830	9
		d		113		705	808	794	14
		e		92		645	769	755	19
	Extrema	a	179	152	43	810	880	880	2
		b		153		780	849	849	6
		c		151		750	821	822	10
		d		133		690	779	780	16
		e		117		645	750	736	22
Évora	Severa	a	182	138	61	720	825	823	1
		b		138		690	795	793	6
		c		127		675	791	774	9
		d		124		630	749	731	15
		e		101		570	712	695	21
	Extrema	a	179	160	66	825	910	910	2
		b		150		780	875	876	6
		c		142		750	853	853	9
		d		139		705	811	811	15
		e		123		660	782	767	21
Elvas	Severa	a	179	258	175	645	741	744	1
		b		255		615	714	717	6
		c		253		600	701	700	9
		d		233		540	661	661	15
		e		220		495	629	629	20
	Extrema	a	178	153	32	735	792	794	2
		b		135		690	765	767	6
		c		131		660	739	741	10
		d		125		630	715	701	16
		e		114		585	681	668	21
Coimbra	Severa	a	181	168	153	450	616	614	1
		b		157		420	597	612	1
		c		154		405	585	606	3
		d		148		375	561	559	4
		e		124		345	555	539	16
	Extrema	a	179	166	79	525	617	617	1
		b		158		495	595	595	5
		c		155		480	583	583	8
		d		140		435	553	553	13
		e		127		405	536	521	20

$ASW_{ini.}$ e ASW_{fin} indicam a água disponível no solo à sementeira e à colheita, respectivamente
TWU indica a quantidade total de água utilizada pela cultura (rega e chuva)

(cont.)

Tabela 3.10. (continuação)

Local	Procura climática	Estratégia de rega	$ASW_{ini.}$ (mm)	$ASW_{fin.}$ (mm)	Precipitação (mm)	Necessidades de rega (mm)	TWU (mm)	$ET_{c\ adj}$ (mm)	Perda relativa de produção (%)
Viseu	Severa	a	223	207	155	465	636	637	1
		b		192		435	621	622	4
		c		187		420	611	612	6
		d		179		390	589	590	10
		e		164		360	574	575	13
	Extrema	a	179	167	107	630	749	749	2
		b		152		585	719	723	6
		c		148		570	708	704	9
		d		131		510	665	665	15
		e		121		480	645	630	21
Vila Real	Severa	a	210	177	150	390	573	543	1
		b		177		375	558	527	4
		c		170		360	550	519	6
		d		159		330	531	500	10
		e		140		300	520	489	13
	Extrema	a	179	164	81	510	606	607	1
		b		168		495	587	588	5
		c		154		465	571	572	8
		d		152		435	543	544	14
		e		138		390	512	512	20
Bragança	Severa	a	188	184	142	405	551	542	1
		b		169		375	536	527	4
		c		162		360	528	519	6
		d		153		330	507	499	11
		e		150		315	495	486	14
	Extrema	a	183	139	54	465	563	560	1
		b		125		450	562	543	4
		c		122		435	550	531	7
		d		102		390	525	506	13
		e		98		360	499	480	18
Miranda do Douro	Severa	a	179	146	92	525	650	651	1
		b		141		495	625	629	5
		c		137		480	614	610	9
		d		128		435	578	578	15
		e		113		405	563	548	20
	Extrema	a	178	172	33	645	684	719	1
		b		171		615	655	689	6
		c		159		585	637	671	9
		d		147		540	604	638	15
		e		139		495	567	601	21

Pela análise dos resultados constantes na Tabela 3.10, verifica-se que, em condições de seca severa, a cultura do milho para ser gerida sem carência hídrica requer uma dotação total de rega de 645 a 795 mm, nas localidades do Sul de Portugal; diferentemente, nas localidades do

Norte necessita de 390 a 525 mm. Numa mesma óptica de gestão, em condições de seca extrema o milho necessita de 735 a 820 mm no Sul e de 465 a 645 mm no Norte.

Se, no entanto, se optar pela utilização de rega deficitária controlada (opção c) ou seja com perdas relativa de produção (Q_y) pequenas, de 3 a 9%, verifica-se uma poupança para os anos de seca severa que varia entre 6 e 8% da água utilizada para os calendários de rega em conforto hídrico, i.e., 2 a 3 regas; se seleccionarmos a mesma estratégia nos anos de seca extrema a poupança de água de rega varia então entre 6 e 10%. As estratégias que conduzem a maior poupança de água, (d) e (e), não são viáveis para os preços actuais do milho como se analisa no estudo de Rodrigues et al. (2010), nomeadamente se os sistemas de rega tiverem baixos desempenhos e o preço da água subir.

Na Fig. 3.2 apresenta-se a aplicação das estratégias (a) e (c) no ano de seca extrema para o caso de Évora. O exemplo da Fig. 3.2 corresponde a uma poupança de água de 75 mm (5 regas) quando se opta pelo calendário de rega deficitária (Fig. 3.2b); no entanto correspondem-lhe 7% de perdas relativas de produção (Tabela 3.10).

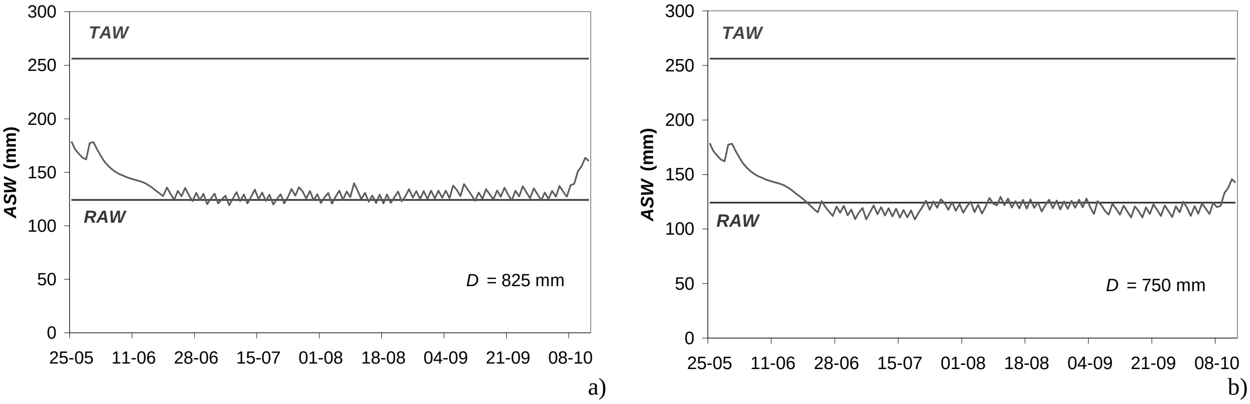

Fig. 3.2. Variação do teor de água disponível no solo (ASW) para as condições de seca extrema, Évora, para dois calendários de rega da cultura do milho: a) em conforto hídrico (estratégia a), b) em rega deficitária controlada (estratégia c).

Os resultados gráficos da aplicação das estratégias (a) e (d) para Coimbra num ano de seca severa são apresentados na Fig. 3.3. Neste exemplo, existe uma poupança de água de rega correspondente a 7 regas (105 mm) quando se opta pelo calendário de rega deficitária forte (d) ocorrem 15% de perdas relativas de produção (Tabela 3.10). Comparando as Figs. 3.2 e 3.3 percebe-se bem que as grandes diferenças entre as NIR no Sul e no Centro se devem à precipitação durante o período do ciclo da cultura. Tal ocorrência de precipitação pode viabilizar a rega deficitária, mas não é certo que isso ocorra.

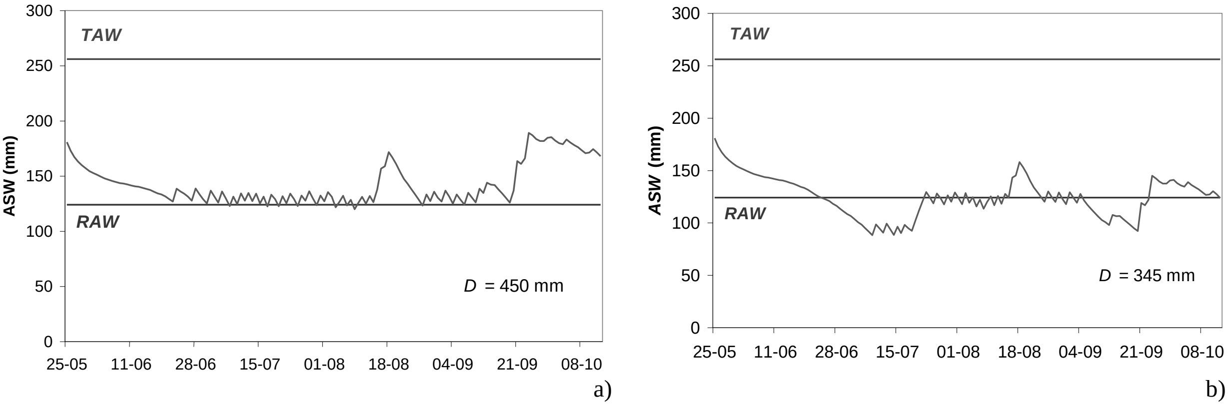

Fig. 3.3. Variação do teor de água disponível no solo (ASW) para a cultura do milho em Coimbra para condições de seca severa comparando calendários de rega: a) em conforto hídrico e b) em rega deficitária (estratégia d).

A aplicação em Vila Real da estratégia de rega deficitária (c) comparando um ano húmido com um de seca extrema é representada na Fig. 3.4. A figura ilustra as diferenças em termos de água do solo quando em Vila Real se adopta uma estratégia de rega deficitária em ano húmido (precipitação de 285 mm) e em ano de seca extrema (precipitação 81 mm); verificou-se que, apesar de existir uma diferença de 180 mm na quantidade de rega, a diferença na quantidade de água utilizada TWU (mm) é de apenas 53 mm.

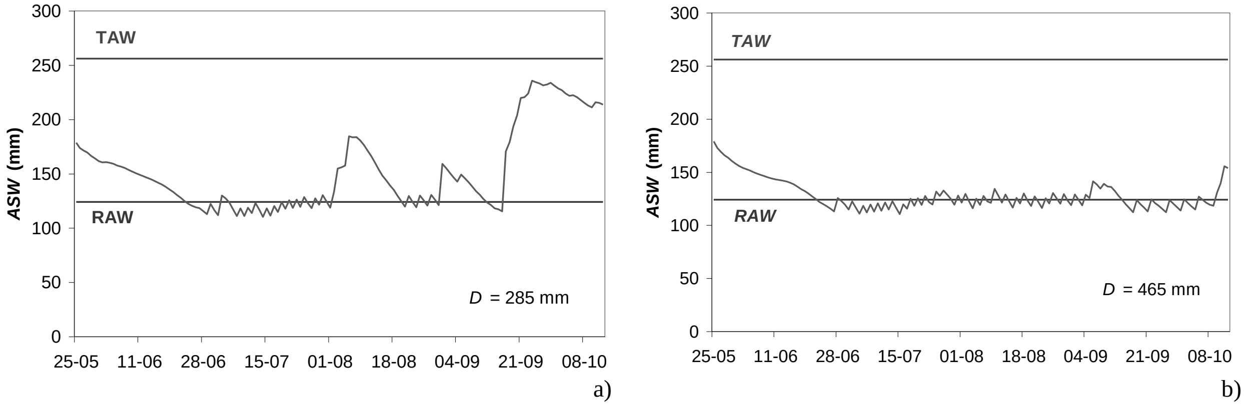

Fig. 3.4. Variação do teor de água disponível no solo (ASW) para a cultura do milho em Vila Real adoptando um calendário de rega deficitária (estratégia c) para as condições de ano húmido (a) e de seca extrema (b).

3.4. Conclusões

Para uma adequada programação e condução da rega, com o objectivo de gerir recursos hídricos escassos, devem ser utilizados modelos, como o modelo SIMDualKc, para simular o comportamento das culturas face a diferentes estratégias de rega. A aplicação daquele modelo, após se ter procedido à sua calibração e validação para a cultura do milho em Portugal, efectuou-se com o intuito de gerir eficientemente a água disponível. Procedeu-se à selecção de estratégias de rega em condições de carência hídrica, as quais se basearam na optimização das disponibilidades de água, associada a uma quebra de produção relativamente pequena que permitisse maximizar o uso da água de rega.

Verificou-se que em condições de disponibilidade limitada de água, a selecção de uma estratégia de rega que optimiza as disponibilidades de água em relação à menor quebra de produção possível depende não só da cultura e do local onde esta é praticada, mas ainda das condições de procura climática (forte e muito forte) a que aquela está sujeita. Os resultados mostram que as estratégias que conduzem a elevadas poupanças de água (19 a 24% da dotação total de rega em conforto hídrico) levam a perdas grandes de produção (16 a 22%), o que na conjuntura actual de preços do milho e custos da água torna impossível a sua adopção pelos agricultores. Assim, considera-se que em situação de seca severa e extrema, para os preços actuais do milho, a melhor opção será a adopção de défices muito pequenos ou da rega para satisfação das necessidades totais do milho mas reduzindo a área cultivada.

Verificou-se que o modelo SIMDualKc comprovou ter capacidade para apoiar eficientemente o gestor na prática da rega, tanto em conforto hídrico como na rega deficitária.

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Capítulo 4 - Partitioning evapotranspiration, yield prediction and economic returns of maize under various irrigation management strategies

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Partitioning evapotranspiration, yield prediction and economic returns of maize under various irrigation management strategies

Abstract

Several maize field experiments, including deficit and full irrigation, were used to assess irrigation impacts on yields. The SIMDualKc water balance model was first calibrated and validated to obtain the basal crop coefficients (K_{cb}) and the depletion fractions for no stress (p) relative to all crop growth stages. The values 0.15, 1.15, 0.30 were obtained for, respectively, the $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$, as well as p = 0.50. The SIMDualKc model provided the partitioning of crop ET into transpiration and soil evaporation. The estimates of the actual transpiration of the maize crop under different irrigation schedules were used with the global and multiphasic Stewart's models (S1 and S2) to assess yields. A test was performed to compare the observed yield versus the models predicted yield. Good yield prediction was achieved with both S1 and S2 models; however, the S2 model performed better since it considers the distinct water stress effects at various crop growth stages. A RMSE of 1209 kg ha^{-1} was obtained for S2 yield estimates, which represents 6.8% of the observed average yield, while the RMSE for the S1 model represents 10%. Performance indicators relative to water productivity (WP) and the economic water productivity ratio (EWPR) were used to assess irrigation scheduling scenarios. Results show that the mild deficit scenario had the better WP. However, WP indicators are more sensitive to water use than to yield, which makes them less adequate for assessing the performance of irrigation water use at farm. Differently, when analysing scenarios under an economic perspective using full cropping costs with EWPR, deficit irrigation was ranked lower than full irrigation. This indicator shows to be more suitable to analyse economic viability of different irrigation strategies.

Keywords: Dual crop coefficients, transpiration, soil evaporation, Stewarts' water-yield models, water productivity, economic water productivity ratio, deficit irrigation

4.1. Introduction

Deficit irrigation is commonly proposed by water managers; however, farmers have a different view of the problem because they need to achieve adequate economic returns that allow them to keep farming. Therefore, in addition to accurately evaluate the crop responses to irrigation, there is the need to assess the corresponding economic consequences. This research aimed to contribute responding to this challenging issue.

Numerous studies on water stress imposed on maize at various crop stages are available (Stewart et al., 1977; Stegman, 1982; Alves et al., 1991; Çakir, 2004; Igbadun et al., 2007). Based on that knowledge, deficit irrigation is often proposed without economic considerations (Farré and Faci, 2009) and aiming to increase water productivity (Geerts and Raes, 2009); however, this is not a farming objective (Payero et al., 2006). Unfortunately, the original concept of deficit irrigation (English and Raja, 1996; Pereira et al., 2002) is often not considered and only a few studies refer to economic impacts of deficit irrigation (Domínguez et al., 2012; Rodrigues et al., 2013a, b; Sampathkumar et al., 2013).

Developing irrigation schedules to cope with actual water availability requires knowledge on yield responses to water, which can be assessed through modelling. Two main approaches may be used: relating yields to evapotranspiration or transpiration (e.g., Jensen, 1968; Hanks, 1974; Stewart et al., 1977; Doorenbos and Kassam, 1979), or estimating yields from crop growth and biomass production models, e.g., CERES-Maize (DeJonge et al., 2012), EPIC (Cavero et al., 2000), or AquaCrop (Hsiao et al., 2009). These crop growth models are very demanding in terms of parameterization and data, particularly relative to soil hydraulic properties, crop characteristics and nutrients. Thus, adopting the empirical yield-water relation models may constitute a good alternative despite the present trend to adopt deterministic models.

Considering the need to better understand when maize deficit irrigation could be applied, the main objective of the present study is to combine the soil water balance model SIMDualKc with the empirical Stewart's global (S1) and multi-phasic (S2) water-yield models to predict yield and assess impacts on maize yields under full and deficit irrigation. The specific objectives, using data from appropriate observations in farmers' fields, consist of: (1) calibrating the SIMDualKc water balance model to properly estimate transpiration and soil evaporation; (2) assessing both the global and multi-phasic Stewart's models to predict maize yields, and (3) evaluating economic impacts of various irrigation management strategies.

4.2. Material and methods

4.2.1. Field experiments

Field observations were performed in farmer's fields of Quinta da Lagoalva de Cima, located in Alpiarça, Ribatejo, Portugal. The farm has a total irrigated area of near 500 ha of which 200 ha are cropped with maize. The weather data were observed with an automatic station located nearby in the farm (39.16º N, 8.33ºW and 24 m elevation). Climate has Mediterranean characteristics with mild rainy winters and dry hot summers. The average weather data relative to the maize crop season and the observations period of 2010 – 2012 are presented in Table 4.1.

Table 4.1. Average monthly weather data relative to the maize season for the period 2010-12, Alpiarça.

	Apr	May	Jun	Jul	Aug	Sep	Oct
Min. air temperature, ºC	9.7	12.1	13.6	14.7	15.1	13.2	10.6
Max. air temperature, ºC	21.7	25.7	27.9	30.6	31.9	30.3	24.5
Minimum Relative Humidity, %	48.6	44.3	43.0	39.4	38.0	36.7	43.6
Wind Speed, m s^{-1}	1.9	1.6	1.6	1.7	1.1	0.9	1.2
Solar radiation, MJ m^{-2} d^{-1}	17.5	24.2	29.0	30.3	25.6	20.0	13.4
ET_o, mm	92.8	133.9	153.8	175.1	149.8	102.2	61.8
Precipitation, mm	94	61	33	6	5	26	114

Fields were cropped with *Zea mays* L. var. PR33Y74 (FAO 600) with a density of approximately 82000 plants ha^{-1}. Management practices were the ones used by the farmer. During the irrigation seasons of 2010 and 2012, two maize fields were observed, fields 1 and 2 and fields 2 and 3 respectively; in 2011 only field 1 was observed. The observations were performed inside the fields, thus with a surrounding area of approximately 30 ha cropped with maize.

Soils in fields 1 and 2 are loamy sand soils, with total available water TAW = 171 and 149 mm m^{-1} respectively; field 3 is a silty-loam soil, with TAW = 209 mm m^{-1}. Table 4.2 presents the main soil characteristics of these fields. Groundwater is quite deep and capillary rise was not considered.

Table 4.2. Soil textural and hydraulic properties of the three observed fields.

Soil layer (m)	Sand (%)			Loam (%)			Clay (%)			θ_{FC} (m^3 m^{-3})			θ_{WP} (m^3 m^{-3})		
Fields	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
0.0-0.10	85	86	37	11	10	40	4	4	23	0.32	0.25	0.35	0.08	0.08	0.22
0.10-0.20	84	88	35	10	8	42	6	4	24	0.25	0.17	0.36	0.06	0.05	0.24
0.20-0.40	85	87	35	9	8	41	6	5	23	0.22	0.17	0.36	0.06	0.04	0.20
0.40-0.60	86	81	60	8	12	25	6	8	15	0.22	0.26	0.37	0.04	0.09	0.12
0.60-0.80	85	86	62	9	8	24	6	6	14	0.22	0.16	0.36	0.05	0.04	0.10
0.80-1.00	85	83	53	9	10	31	7	6	16	0.17	0.32	0.37	0.04	0.14	0.12

In 2010 two Sentek EnviroSCAN probes were used in each field for measuring the soil water content. One probe was placed in the plant row and the other between rows. Soil moisture sensors were placed at depths of 0.10, 0.20, 0.30 and 0.50 m and observations were performed every 15 minutes. For 2011 and 2012, a Sentek DIVINER 2000 probe was used and measurements were performed at 0.10 m intervals to the depth of 0.90 m. 4 observation points were located in the row and 4 in the inter-row. These 8 points were replicated at a distance of 5 m, thus totalling 16 observation points. The probes were previously calibrated using a wide range of soil water content data, from near the wilting point to near saturation. Observations of the soil water content were performed between irrigation events. The recommendations for accuracy by Allen et al. (2011) were considered.

All the maize fields were sprinkler irrigated with center-pivots in fields 1 and 2 and a linear moving system in field 3. The irrigation schedules were decided by the farmer. In 2010, the first irrigation event was delayed to allow a good root development, and few irrigations and small depths were applied during the period before flowering. More frequent irrigation was scheduled during 2011. In 2012 the irrigation schedule for field 2 was designed to assure full ET rates, thus more frequent irrigations were performed. In field 3, due to the good soil water storage characteristics, less frequent irrigations were practiced. Irrigation depths of 3 to 16 mm were applied with a variable frequency, from daily to 5-day intervals. Low irrigation depths were practiced during the initial and crop development stages. Table 4.3 presents the total net irrigation depths for all growth stages and the whole season. The irrigation systems performance was evaluated several times along the season in all fields and years using the methodology proposed by Merriam and Keller (1978). The net irrigation depths were determined using rain gauges placed 0.20 m above the canopy and near the access probe tubes.

Table 4.3. Net irrigation depths (mm) by growth stage and the season.

	Field	Net irrigation (mm)			Season net irrigation (mm)
		Vegetative	Flowering	Maturation	
2010	1	146	76	402	624
	2	176	82	330	588
2011	1	99	85	274	458
2012	2	209	84	292	585
	3	240	138	155	533

Field observations included the dates of each crop growth stage (Table 4.4), crop height (h, m) and the fraction of soil covered or shaded by the crop canopy near solar noon (f_c, dimensionless). f_c ranges from 0.01 to 1 (Allen et al., 1998; Allen and Pereira, 2009). Data on f_c and h are summarized in Table 4.5. Measurements of h were performed twice a week until flowering and observations of f_c were visually performed every two weeks by mid-day and with help of photographs of the ground shadow. The root depths were surveyed along the crop seasons; results show that most roots were in the first 0.30 to 0.40 m of soil, which are common when frequent and small irrigation depths are applied such as for center-pivot and linear moving systems. The actual yield was observed by harvesting samples of 10 plants near each probe access tube, corresponding to a total sampling area of 6.7 m^2. Samples were oven dried to constant weight at 65±5^{o}C. The yield was adjusted to 13% grain moisture.

Table 4.4. Maize growth stages dates for each experimental year (2010-12), Alpiarça.

Year/field		Crop growth stages				
		Planting/initiation	Crop development	Mid-season	Late season	Harvest
2010	Field 1	25/05 – 25/06	26/06 – 17/07	18/07 – 02/09	03/09 – 12/10	13/10
	Field 2					
2011	Field 1	20/04 – 17/05	18/05 – 28/06	29/06 – 17/08	18/08 – 19/09	20/09
2012	Field 2	16/04 – 08/05	09/05 – 24/06	25/06 – 20/08	21/08 – 19/09	20/09
	Field 3	30/05 – 15/06	16/06 – 16/07	17/07 – 12/09	13/09 – 11/10	12/10

Table 4.5. Crop height (h) and fraction of ground covered by the crop (fc) at the main crop growth stages.

Year	Field		Crop growth stages				
			Planting	Start of crop development	Start of mid-season	Start of late-season	Harvest
2010	1	h (m)	0	0.30	2.10	2.30	2.10
		f_c ( )	0.01	0.10	0.75	0.70	0.65
	2	h (m)	0	0.36	1.93	2.20	2.00
		f_c ( )	0.01	0.10	0.70	0.68	0.55
2011	1	h (m)	0	0.40	2.50	2.70	2.60
		f_c ( )	0.01	0.10	0.95	0.90	0.91
2012	2	h (m)	0	0.34	2.20	2.80	2.70
		f_c ( )	0.01	0.10	0.95	0.90	0.90
	3	h (m)	0	0.32	2.52	2.72	2.65
		f_c ( )	0.01	0.10	0.94	0.93	0.92

4.2.2. Water balance modelling, calibration and validation procedures

The SIMDualKc model is an irrigation scheduling simulation model that performs a daily soil water balance at the field scale (Rosa et al, 2012a) using the dual crop coefficient approach to compute crop evapotranspiration (ET) (Allen et al., 1998, 2005; Allen and Pereira, 2009). The model allows generating and assessing alternative irrigation schedules. SIMDualKc has been calibrated and validated for a variety of crops and environments (Rosa et al., 2012b; Fandiño et al., 2012) particularly for maize, with and without mulch and using soil water and eddy covariance ET observations (Martins et al., 2013; Zhang et al., 2013; Zhao et al., 2013).

The model computes the maximum crop evapotranspiration (ET_c, mm) from the reference evapotranspiration (ET_o, mm) and the basal and evaporation coefficients (K_{cb} and K_e, dimensionless) that characterize respectively crop transpiration and soil evaporation:

$$ET_c = (K_{cb} + K_e)\, ET_o \tag{4.1}$$

It results maximum transpiration $T_c = K_{cb}\, ET_o$ (mm) and soil evaporation $E_s = K_e\, ET_o$.(mm). The Ritchie's model (Ritchie, 1972) is used to compute K_e (Allen et al., 2005). This approach has been tested against observations of soil evaporation for both trees and field crops (Paço et al., 2012; Zhao et al., 2013).

The actual ET ($ET_{c\ adj}$, mm) is computed by the model as a function of the available soil water in the root zone: when soil water depletion is smaller than the depletion fraction for no stress (p) then $ET_{c\ adj} = ET_c$; otherwise $ET_{c\ adj} < ET_c$, decreasing with the available water. Thus,

$$ET_{c\ adj} = (K_s\, K_{cb} + K_e)\, ET_o \tag{4.2}$$

where K_s [0 - 1] is the water stress coefficient. The actual plant transpiration is therefore $T_a = K_s\, K_{cb}\, ET_o$. Further description of the model, including the soil water balance approach and the auxiliary equations, is given by Rosa et al. (2012a).

The SIMDualKc calibration procedure aimed at obtaining the crop parameters K_{cb} and p relative to all crop growth stages, the soil evaporation parameters TEW (total evaporable water, mm), REW (readily evaporable water, mm) and Z_e (evaporable layer depth, m), and the parameters a_D and b_D of the deep percolation parametric function. As described in the above quoted applications, the calibration was performed by minimising the differences between observed and simulated daily available soil water (ASW) relative to the entire root depth using the irrigation schedules as they were actually applied in the field. Calibration was performed using the experimental values observed in field 1 in 2011. Based on soil water observations, the initial depletion for the root zone was then set at 0% of TAW and the initial depletion of the evaporable layer was set at 0% of TEW. Validation consisted of using the parameters previously calibrated (K_{cb}, p, TEW, REW, Z_e, a_D and b_D) with data of the experiments of Alpiarça in fields 1 and 2 in 2010 and fields 2 and 3 in 2012. The initial depletion in the effective root zone was then set at 30% of TAW for both fields in 2010, 40% for field 2 in 2012 and 0% for field 3 in 2012. The initial depletion of the evaporable layer was set at 20% of TEW for fields 1 and 2 in 2010, and at 20% and 0% respectively for fields 2 and 3 in 2012.

To assess the goodness of fit of the model a linear regression between observed and simulated ASW values forced through the origin was used. The corresponding regression and determination coefficients were consequently used as indicators. A set of indicators of residual estimation errors was also computed: the root mean square error (RMSE) and the average absolute error (AAE). In addition, statistical indicators of the quality of modelling approaches were used: the Nash and Sutcliff (1970) modelling efficiency (EF, dimensionless), that is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Moriasi et al., 2007); and the Willmott (1981) index of agreement (d_{IA}, dimensionless) that represents the ratio between the mean square error and the "potential error" (Moriasi et al., 2007). All referred indicators have been used in former studies with SIMDualKc (e.g., Rosa et al., 2012b; Martins et al., 2013) where they are described.

4.2.3. Water-yield relations and water productivity

Yield losses due to water stress were estimated using the water-yield models S1 and S2 proposed by Stewart et al. (1977). In Stewart's model S1, the relationship between the seasonal relative evapotranspiration deficit and the relative yield losses is:

$$1-\frac{Y_a}{Y_m}=K_y\left(1-\frac{ET_{c\ adj}}{ET_c}\right) \tag{4.3}$$

where $ET_{c\ adj}$ and ET_c (mm) are respectively the actual and (predicted) maximum crop evapotranspiration (Eq. 4.1 and 4.2), Y_a and Y_m are the yields (kg ha^{-1}) corresponding to the actual and optimal water supply conditions, and K_y is the crop yield response factor (dimensionless) relative to the entire crop season. Following the results reported by Alves et al. (1991), crop transpiration T was adopted instead of ET because T is the component of ET directly responsible for yield formation. In addition, this approach prevents bias due to differences in E_s/ET ratios relative to different experiments or locations. Therefore, the actual yield was estimated as

$$Y_a = Y_m - \frac{Y_m K_y T_d}{T_c} \tag{4.4}$$

where, in addition to variables defined for Eq. 4.3, T_c is the seasonal maximum transpiration (mm) and T_d is the seasonal transpiration deficit (T_c - T_a).

Considering that the timing when water stress occurs is crucial, with the most sensitive growth periods being the flowering and yield formation periods, Stewart et al. (1977) developed the model S2, which considers the effect of water stress timing as:

$$1 - \frac{Y_a}{Y_m} = \frac{\sum_i [K_{yi}(ET_{ci} - ET_{c\,adji})]}{ET_c} \tag{4.5}$$

where $ET_{c\ adj\ i}$ and $ET_{c\ i}$ are the actual and maximum ET relative to each crop stage i, and $K_{y\ i}$ are the crop yield response factors for the same stages i. In the present study, for Y_a estimation the model S2 (Eq. 4.5) takes the form

$$Y_a = Y_m - \frac{Y_m(\beta_v T_{d,v} + \beta_f T_{d,f} + \beta_m T_{d,m})}{T_c} \tag{4.6}$$

where β_v, β_f and β_m (dimensionless) are the yield response factors relative to the vegetative, flowering and maturation crop stages, T_c is the seasonal maximum transpiration (mm) and $T_{d,v}$, $T_{d,f}$ and $T_{d,m}$ are the transpiration deficits (T_c- T_a, mm) for the same crop stages.

The yield response factors used in the present study were obtained from an accurate experiment performed at Sorraia Valley, near Coruche, Portugal (Alves et al. 1991). The corresponding data set has been analysed and used in a previous study (Rodrigues et al., 2013a). The experiment was performed with *Zea mays* L. var. LG18 (FAO 300) with a plant density of approximately 90000 plants ha^{-1}. Similarly to other studies (Stewart et al., 1977), several deficit and full irrigation schedules were established considering 3 crop growth stages: vegetative, flowering and maturation/ripening (Alves et al., 1991). 6 strategies with several replications were selected from the Alves et al. (1991) data set to perform the present analysis: (A) full irrigation in all crop growth stages; (B) stress imposed during the vegetative stage; (C) stress imposed during maturation/ripening; (D) stress imposed during the vegetative and flowering stages; (E) stress imposed during the vegetative growth and maturation/ripening; and (F) stress imposed along the entire crop season. Average observed yields at 13% grain moisture for irrigation strategies A to F were respectively: 12037, 10004, 12190, 7334, 6865, 6331 kg ha^{-1}.

The SIMDualKc model (section 4.2.2) was previously calibrated and validated for maize in the same Sorraia Valley research station (Rosa et al., 2012b). It was therefore applied to refine the previous water balance analysis and the partition of ET into T_c and E_s, *i.e.*, the results reported by Alves et al. (1991) were consequently refined for use in this study. Therefore, the partition of actual ET into actual E_s and T_a could be accurately performed and $ET_{c\ adj}$ and T_a data could be used for validating the yield-ET and yield-T relations. The referred application of

SIMDualKc to Alves et al. (1991) data was independent of the application to the Alpiarça case study dealt in this paper.

The value for K_y = 1.32 (Eq. 4.1) was obtained from the experimental data sets of Alves et al. (1991) and used in the present study. It is in the range of the values obtained for maize by Stewart et al. (1977) [K_y = 1.03 to 1.72] and other authors, including Howell et al. (1997) [K_y = 1.47], Popova et al. (2006) [K_y= 1.00 and 1.48], Dehghanisanij et al. (2009) [K_y= 1.03 to 1.46], and Popova and Pereira (2011) [K_y = 1.32].

Table 4.6 presents the yield response factors β_v, β_f and β_m relative to the S2 model as reported by Alves et al. (1991) that were used in the present study. β_v is for crop emergence until the start of flowering, β_f corresponds to the period from flowering until the end of pollination, and β_m refers to the period from end of pollination until harvesting. The values presented in Table 4.7 are within the ranges reported by Stewart et al. (1977): β_v ranging from 1.0 to 1.8, β_f from 0.6 to 2.8 and β_m from 0.8 to 5.7.

Table 4.6. Yield response factors (Alves et al., 1991).

Growth stage when stress is imposed	βv	βf	βm
Vegetative	2.1	-	-
Maturation	-	-	2.1
Along the crop cycle	1.2	2.8	0.9

The maximum yield of a crop (Y_m) to be used with equations 4.4 and 4.6 corresponds to the harvested yield of a high producing variety, well-adapted to the given growing environment, under conditions where water, nutrients, weeds, pests and diseases do not limit the yield (Doorenbos and Kassam, 1979). The Y_m values used in the present study were obtained both from the highest yields achieved in the full irrigation treatments, where no stress was observed, and from yield data information collected from farmers in the study area. These Y_m values were compared with those estimated with the 'Wageningen method' (Doorenbos and Kassam, 1979). Thus, following the procedure applied by Rodrigues et al. (2013a), the Y_m for the water-yield experiment for the variety LG18 (FAO 300) (Alves et al., 1991) was 14169 kg ha^{-1}. The maximum yields for the farmers' adopted maize variety PR33Y74 (FAO 600) were 21952 kg ha^{-1} for the 2010 crop season, 19779 kg ha^{-1} for 2011, and 20595 kg ha^{-1} for 2012; however, for field 3 in 2012, because planting was late and harvesting was anticipated due to rain, Y_m = 16865 kg ha^{-1} was observed.

In order to assess the experimental and alternative irrigation scenarios, water productivity indicators were used (Pereira et al., 2012): total water productivity (WP, kg m^{-3}), irrigation water productivity (WP_{Irrig}, kg m^{-3}), economic water productivity (EWP, € m^{-3}), economic irrigation water productivity (EWP_{Irrig}, € m^{-3}). These indicators represent the ratio between the yield achieved and the total water use (TWU) or the season irrigation water (IWU); the economic ones refer to the ratios between the yield values and the total or the irrigation water use. Particular attention was given to assess the economic performance of production using the economic water productivity ratio ($EWPR_{full\ cost}$) that relates the yield value with the full farming costs, *i.e.*, the full costs to achieve Y_a when the total and irrigation water use are respectively TWU and IWU:

$$EWPR_{\text{full cost}} = \frac{\text{Value}(Y_a)}{\text{Irrigation farming costs}} \tag{4.7}$$

The beneficial water use fraction (BWUF), defined as the fraction of total water use that was consumed to produce the actual yield (Pereira et al., 2012), was used as water use performance indicator. BWUF was calculated as the ratio between $ET_{c\ adj}$ and TWU.

4.3. Results and discussion

4.3.1. Calibration and validation of SIMDualKc

As reported above, the calibration of the SIMDualKc model for maize was performed by minimizing the differences between observed and simulated available soil water (ASW, mm) relative to field 1 in 2011. Validation was performed with data from the other observed fields. All calibrated values (K_{cb}, p, TEW, REW, Z_e, a_D and b_D) are presented in Table 4.7, which also includes the initial values used to start calibration. When comparing the initial and calibrated values for K_{cb} and p shown in Table 4.7, it is evident that if the model was used with the standard tabled values by Allen et al. (1998) model results would have been quite similar as previously analysed by Rosa et al. (2012b).

Results comparing the observed and simulated ASW values throughout the crop season are presented in Fig. 4.1. It shows a good adherence of simulated to the observed ASW values, thus that the model is able to predict ASW throughout the crop season and for various water management conditions with a quite small bias of estimation. Results in Fig. 4.1b and 4.1c show that the irrigation schedules adopted caused water stress to occur.

Table 4.7. Maize basal crop coefficients (K_{cb}), depletion fractions for no stress (p) soil evaporation parameters (TEW, REW and Z_e) and deep percolation parameters.

Parameter	Initial value			Calibrated		
K_{cbini}	0.15			0.15		
$K_{cb\ mid}$	1.15			1.15		
$K_{cb\ end}$	0.50			0.30		
p_{ini}	0.55			0.50		
p_{dev}	0.55			0.50		
p_{mid}	0.55			0.50		
p_{end}	0.55			0.50		
	Field 1	Field 2	Field 3	Field 1	Field 2	Field 3
REW (mm) *	11	11	11	7	7	10
TEW (mm) *	18	18	18	28	21	24
Z_e (m) *	0.10	0.10	0.10	0.10	0.10	0.10
a_D*	360	300	430	300	270	400
b_D*	-0.017	-0.017	-0.017	-0.020	-0.025	-0.015

* These parameters depend upon soil characteristics, hence are different among fields

Table 4.8 presents the goodness of fit indicators relative to the calibration and validation of the model. The indicators derived from a regression through the origin show a good agreement between observed and simulated ASW: the regression coefficients, which are close to 1.0 for all fields, and the determination coefficients, that range from 0.79 to 0.93, with $R^2 = 0.85$ for the calibration. When a regression coefficient (b) is close to 1.0 then the covariance was close to the variance of the observed values, hence indicating that predicted and observed values were statistically similar. If a coefficient of determination (R^2) is not far from 1.0 it indicates that most of the total variance of the observed values was explained by the model. The scatter plot relative to the observed and simulated ASW values (not shown) shows that the distribution of residuals is homoscedastic, thus that the spread of the residuals is about the same throughout the plot values and no systematic patterns were observed. These results demonstrate that the model is able to simulate ASW.

Table 4.8. Indicators of goodness of fit relative to SIMDualkc model testing, Alpiarça case study.

Year	Field	Goodness of fit indicators						
		b	R^2	RMSE (mm)	RMSE/TAW (%)	AAE (mm)	EF	d_{IA}
2010	1	1.01	0.92	4.8	3.1	3.9	0.91	0.98
	2	1.00	0.94	4.0	3.1	3.2	0.92	0.98
2011 (calibration)	1	0.99	0.85	6.3	4.1	5.5	0.84	0.96
2012	2	0.98	0.79	5.7	4.3	4.7	0.74	0.93
	3	0.99	0.85	6.5	3.5	5.7	0.80	0.95
All experiments		1.00	0.98	5.0	-	4.1	0.98	0.99

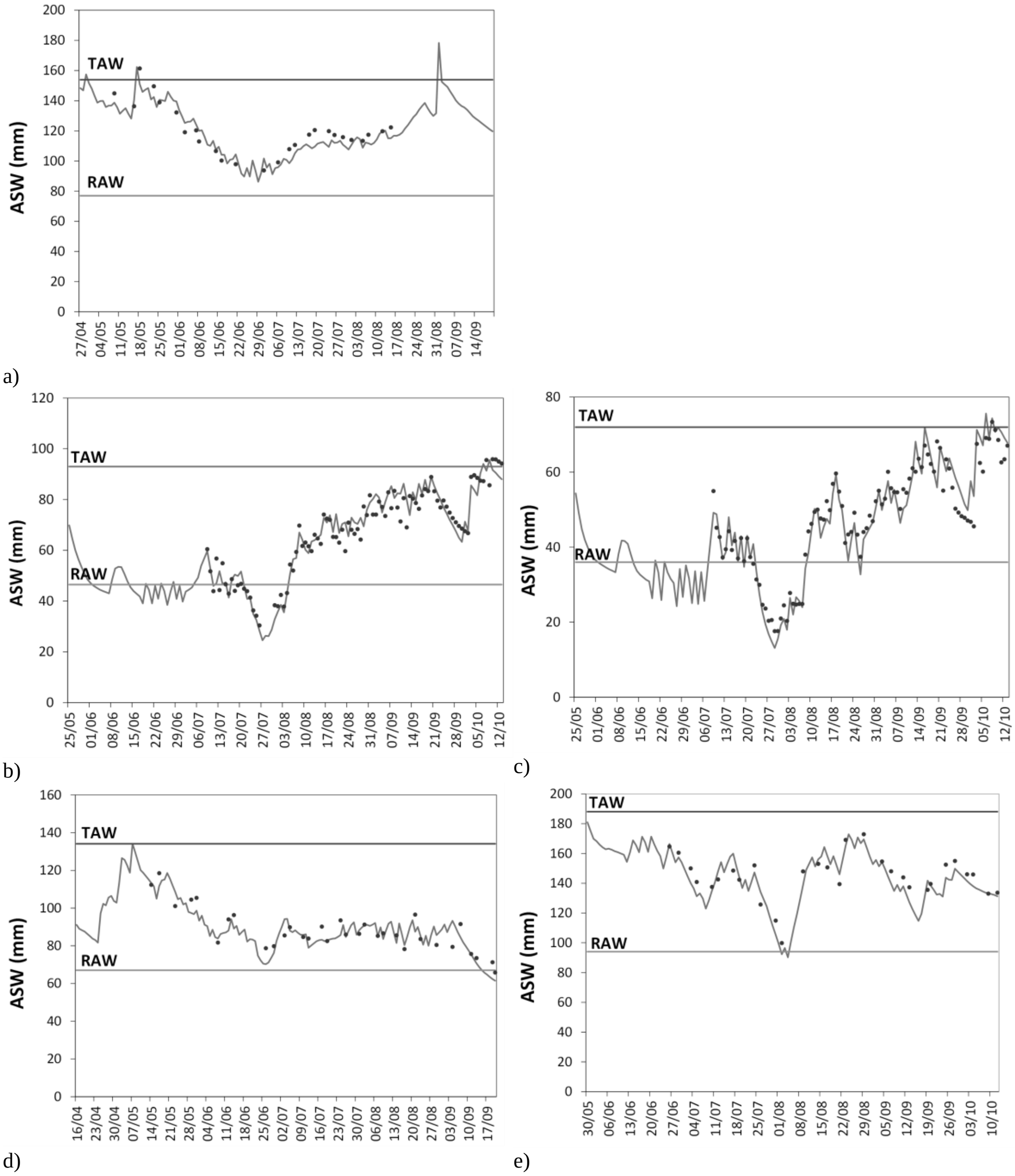


Fig. 4.1. Daily observed (•) and simulated (——) available soil water (ASW) for the Alpiarça maize experiments: a) plot 1 in 2011 (calibration), b) plot 1 in 2010, c) plot 2 in 2010; d) plot 2 in 2012; and e) plot 3 in 2012.

Estimation errors are low (Table 4.8), with RMSE ranging from 4.1 to 6.5 mm, i.e., 3.1 to 4.3% of TAW. AAE range 3.3 to 5.7 mm, thus being smaller than 4% of TAW. EF is high, ranging 0.74 to 0.91, which indicates that the relative magnitude of the residual variance is comparable to the measured data variance (Moriasi et al., 2007), hence that the model is a good predictor of the soil water dynamics. d_{IA} ranges from 0.93 to 0.98 indicating that the mean square error is close to the potential error due to modelling. Overall, the indicators of goodness of fit show that the modelling approach is appropriate, thus allowing both a good interpretation of results and the derivation of alternative solutions.

4.3.2. Basal crop coefficients and partition of crop evapotranspiration

The calibrated basal crop coefficients are presented in Table 4.7 and Fig. 4.2. The value $K_{cb\ mid} = 1.15$ is equal to that proposed by Allen et al. (1998) and by Zhao et al. (2013), and is close to that reported by Martins et al. (2013). Assuming $K_{cb\ mid} = K_{c\ mid}$-0.05 (Allen et al. 1998), the $K_{cb\ mid} = 1.15$ compares well with $K_{c\ mid}$ values reported by several other authors, e.g., Gao et al. (2009) and Piccinni et al. (2009). The calibrated $K_{cb\ ini}$= 0.15 is to be expected for climate conditions where rainfall events during the initial period of a crop are relatively infrequent (Allen et al., 1998). Differently, the $K_{cb\ end}$ values depend upon crop management options. The value found in this study, $K_{cb\ end}$ = 0.30, is in agreement with the values proposed by Allen et al. (1998), Suyker and Verma (2009), and Gao et al. (2009). It corresponds to a condition where harvesting is at low grain moisture, thus after leaves senescence. The calibrated p = 0.50 is similar to that recommended by Allen et al. (1998).

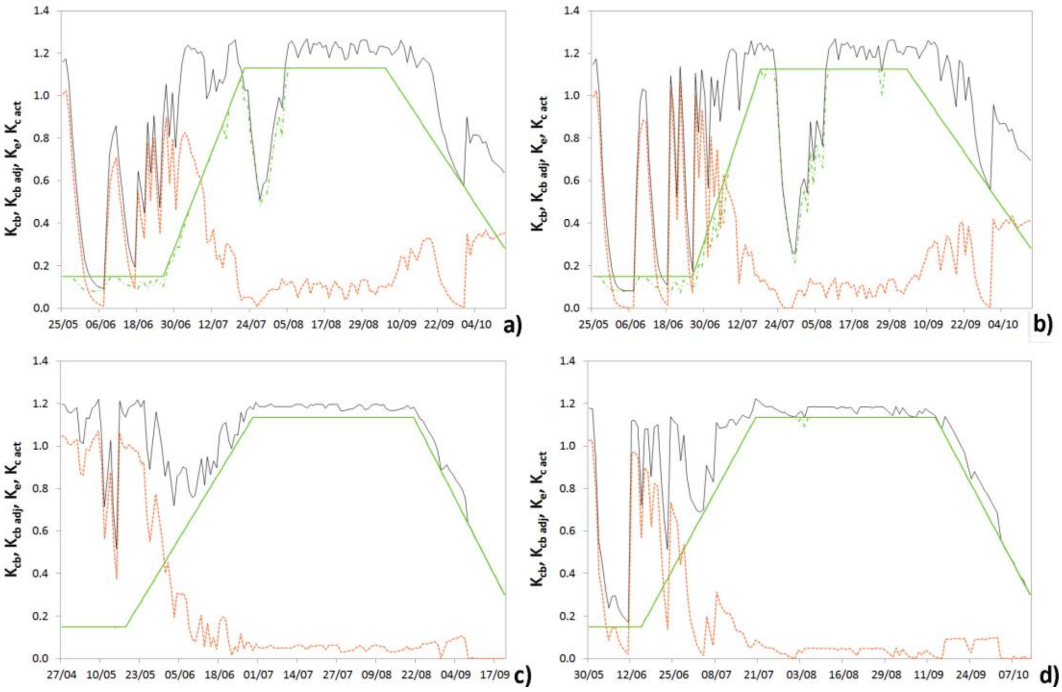


Fig. 4.2. Seasonal variation of the coefficients K_{cb} (——), $K_{cb\ adj}$ (— · -), K_e (-----) and $K_{c\ act}$ (——) for the following experimental conditions: a) 2010 (plot 1), b) 2010 (plot 2), c) 2011 (plot 1) and d) 2012 (plot 3).

Figure 4.2 presents the seasonal variation of the evaporation and basal crop coefficients for selected case studies. The $K_{cb\ adj}$ curve represents the basal crop coefficient values adjusted for stress, *i.e.*, $K_{cb\ adj} = K_s\ K_{cb}$. Fig. 4.2c and d show that $K_{cb} = K_{cb\ adj}$ for nearly the entire seasons of 2011 and 2012 since irrigation was practiced for no stress. Contrarily, for 2010, the $K_{cb\ adj}$ curve lays below the K_{cb} curve when stress periods occur (Fig. 4.2a and b). Similarly, the single $K_{c\ act}$ curve is also below the K_{cb} curve whenever water stress occurs contrarily to periods of no stress when the $K_{c\ act}$ curve is above K_{cb}. Results in Fig. 4.2 show that the soil evaporation coefficient K_e has numerous peaks due to the soil wettings by irrigation and precipitation, larger when soil evaporation is greater than transpiration during the earlier crop growth stages, and smaller when plant transpiration largely exceeds soil evaporation during the mid- and end-seasons. The differences in f_c and energy available at the soil surface causes differences in K_e, that is higher in 2010 (Fig. 4.2 a and b) than in 2011 and 2012 (Fig. 4.2c and d). Therefore, the peaks of $K_{c\ act}$ in 2010 are higher than those for 2011 and 2012 (Fig. 4.2) due to higher K_e, which relates to lower f_c (see Table 4.5) and consequent greater energy available for evaporation at the soil surface.

Results for the partition of $ET_{c\ adj}$ into soil evaporation and plant transpiration are presented in Fig. 4.3, where the seasonal variation of actual and maximum transpiration (T_a and T_c) is also included. A proper identification of the periods when crop growth and production were affected by water stress was provided by these data. Results for 2010 show that the T_a curve lays below the T_c curve during the periods when water stress was imposed, *i.e.*, the late vegetative stage and a large part of the flowering stage, respectively in Fig. 4.3a and Fig. 4.3b. Differently, $T_a = T_c$ for 2011 and 2012 (Figs. 4.3c and d) because water stress was avoided.

Results in Fig. 4.3 and Table 4.9 show that soil evaporation is the main component of ET during the initial crop growth stage, when large fractions of the soil are not shadowed by the crop, thus are exposed to radiation that provides energy for evaporation of the soil water. The ratio E_s to ET decreases as the crop develops and ground cover increases. Table 4.9 shows the results for E_s, T_c, T_a and $E_s/ET_{c\ adj}$ for the considered crop growth stages. E_s and $E_s/ET_{c\ adj}$ were higher for the 2010 experiments, where deficit irrigation was adopted. This relates with smaller f_c (see Table 4.5). The seasonal E_s ranged from 18 to 29% of the seasonal $ET_{c\ adj}$. The larger value is for the deficit irrigated fields observed in 2010. These results are similar to the ones obtained by Suyker and Verma (2009) in a center-pivot irrigated maize in Nebraska and are comparable to those reported by other authors (Klocke et al., 1996; Allen et al., 2005; Grassini et al., 2009; Katerji et al., 2010). Consequently, results show a decrease in T_a relative to T_c when deficit irrigation was applied in 2010, with T_a smaller than T_c by 8 and 14 % for fields 1 and 2, respectively. These decreases in T_a were reflected in the yield decrease that occurred during that season as analysed hereafter.

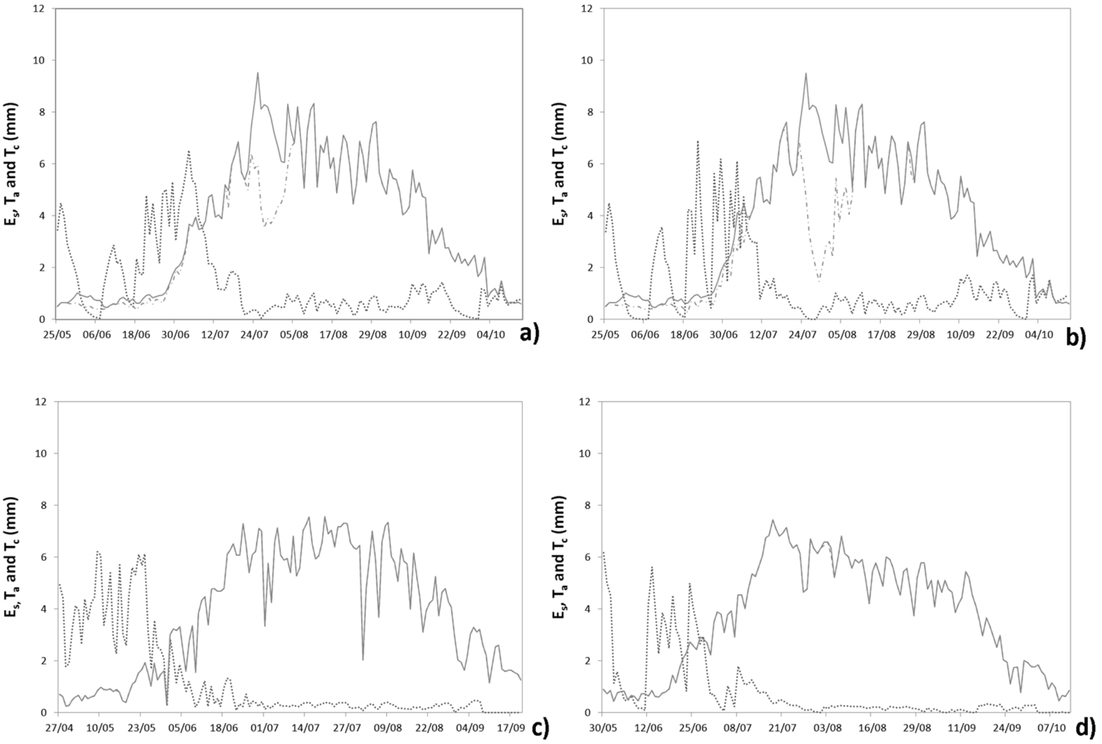


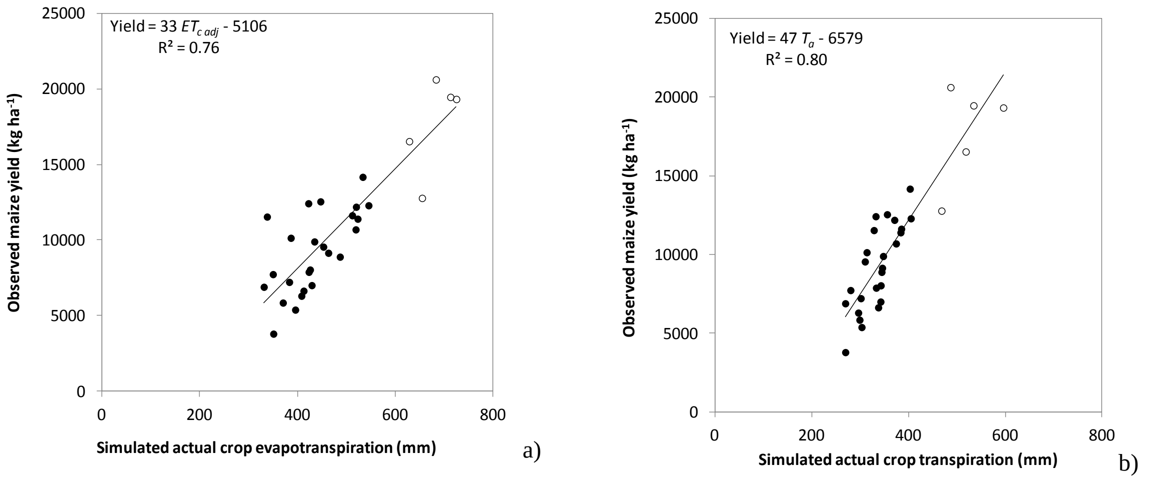
Fig. 4.3. Seasonal variation of the actual transpiration (T_a, – –), maximum transpiration (T_c,——) and soil evaporation (E_s, ...) for: a) 2010 (plot 1), b) 2010 (plot 2); c) 2011 (plot 1) and d) 2012 (plot 3).

Table 4.9. Evaporation (E_s, mm) and actual and maximum transpiration (T_c and T_a, mm) for the three crop growth stages of the maize crop, Alpiarça.

		Crop growth stages												
Year	field	Initial and vegetative				Flowering				Maturation				Seasonal
		E_s (mm)	T_a (mm)	T_c (mm)	$E_s/ET_{c\ adj}$ (%)	E_s (mm)	T_a (mm)	T_c (mm)	$E_s/ET_{c\ adj}$ (%)	E_s (mm)	T_a (mm)	T_c (mm)	$E_s/ET_{c\ adj}$ (%)	$E_s/ET_{c\ adj}$ (%)
2010	1	128	44	48	74	19	89	101	18	51	341	366	13	29
	2	123	73	88	63	9	91	139	9	53	287	296	16	29
2011	1	158	150	150	51	4	90	90	4	16	285	285	5	25
2012	2	112	193	193	37	5	86	86	5	13	317	317	4	18
	3	108	194	194	36	3	98	98	3	9	214	214	4	19

4.3.3. Water-yield relations and water productivity

$ET_{c\ adj}$ and T_a data simulated with SIMDualKc model and the observed yields from the above described experiments were added to the Alves et al. (1991) data (see Section 4.2.3). Fig. 4.4 shows the yield-$ET_{c\ adj}$ and yield-T_a linear relations for all referred experimental data and both maize varieties. These linear relations allow to assume a similar behaviour of both maize varieties and that it is possible to use the water-yield models (Eq. 4.4 and 4.6) with the parameters described in Section 4.2.3 for yields prediction for the current maize varieties. The approach adopted herein of using yield observations relative to different varieties and observation years for yield predictions was also adopted by others, e.g., Retta and Hanks (1980) and Liverman et al. (1986). Stewart et al. (1977) also used data of various locations and years when developing their models. Results in Fig 4.4 also show that the yield-T_a relationship is preferable when compared to the yield-$ET_{c\ adj}$ linear relation as observed by others (Stewart et al., 1977; Payero et al., 2006).



a) b)

Fig. 4.4. Relationship between maize seasonal: a) evapotranspiration ($ET_{c\ adj}$) and b) transpiration (T_a) with observed yield using all experiments results (○ for Alpiarça observations and ● for historical data by Alves et al., 1991, Sorraia Valley).

All transpiration-yield data pairs were subsequently used with both S1 and S2 models (Eqs. 4.4 and 4.6, parameterized as referred in Section 4.2.3) to assess their accuracy in predicting maize yields. Results are shown in Fig. 4.5 and related goodness of fit indicators are presented in Table 4.10. The linear regression through the origin comparing simulated with observed yields produced b = 1.0 for both models and $R^2 = 0.84$ and 0.92 for the S1 and S2 models, respectively (Fig. 4.5 and Table 4.10). Results indicate that the predicted yield values are statistically close to the observed ones and that a large fraction of the variation of the observed yields is explained by the models. The S1 model application leads to RMSE = 1800 kg ha^{-1} (Table 4.10), which is approximately 10% of the observed average yield of the currently used variety (17740 kg ha^{-1}). The AAE was smaller (1507 kg ha^{-1}). d_{IA} and EF were high, respectively 0.94 and 0.81. The S2 model leads to smaller estimation errors: RMSE = 1209 kg ha^{-1} and AAE = 926 kg ha^{-1}. This RMSE represents 6.8% of the same average yield of 17740 kg ha^{-1}. d_{IA} and EF were quite high, respectively 0.98 and 0.92, thus indicating that the residual variance compares well to the measured data variance. These results show that yields can be well simulated with both models, but with smaller errors when using the model S2.

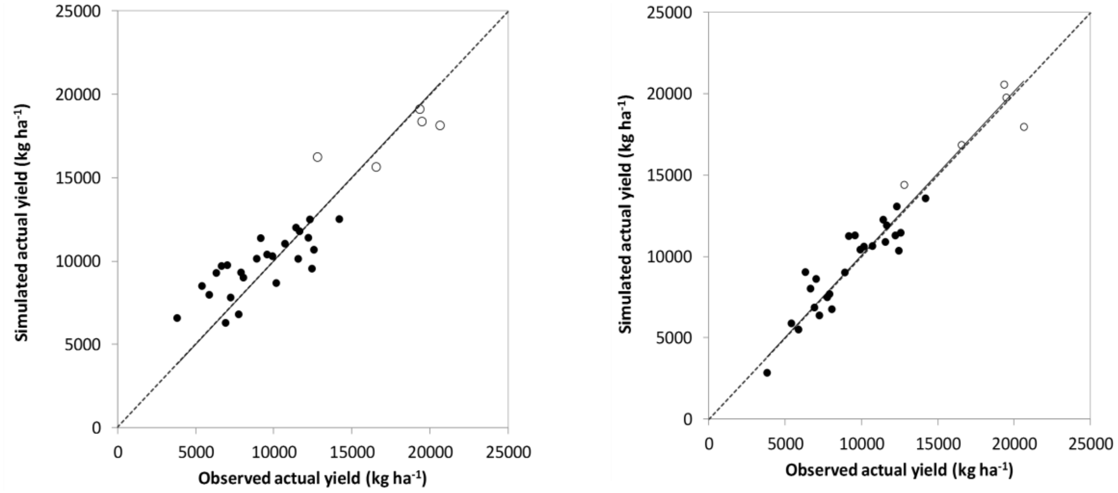


Fig. 4.5. Maize actual and simulated yield (kg ha^{-1}) using (left) S1 and (right) S2 models, (○ for Alpiarça observations and • for historical data by Alves et al., 1991, Sorraia Valley).

Table 4.10. Indicators of goodness of fit relative to Stewart's 1 and 2 models testing for both case studies.

Model	b	R^2	RMSE (kg ha^{-1})	AAE (kg ha^{-1})	EF	d_{IA}
S1	1.00	0.84	1800	1507	0.81	0.94
S2	1.00	0.92	1209	926	0.92	0.98

The RMSE = 1209 kg ha^{-1} resulting from the S2 model is smaller than errors relative to applications of other crop growth models, which are more demanding in terms of parameterization. Cavero et al. (2000) found RMSE ranging 1760 -1800 kg ha^{-1} with the EPIC model. Liu et al. (2011), using the DSSAT-CERES-Maize model for 50-years of experimental data, reported a RMSE of 1391 kg ha^{-1} for treatments with N-fertilization. DeJonge et al. (2012) applied the CERES-Maize model and found RMSE ranging 1327-1394 kg ha^{-1}. Monzon et al. (2012) reported for CropSyst and CERES-Maize models yield predictions with RMSE of 1543 and 2219 kg ha^{-1} respectively. Various applications of the AquaCrop model also led to relatively high deviations between predicted and observed yields: Hsiao et al. (2009) reported deviations up to 23.8%, Heng et al. (2009) reported RMSE from 650 to 1570 kg ha^{-1}, and Katerji et al. (2013) found deviations of 4.2 to 13.3%. Results therefore show that both S1 and S2 models are adequate for maize grain yield estimation. The S1 model should be applied when only seasonal T_c and T_a data are available while the S2 model can be used when those data are available for the three crop growth stages considered.

Results from the five observed fields were assessed in terms of water productivity (Table 4.11). When the economic WP is considered, related results refer to the commodity prices relative to each observation year and updated production costs. Table 4.11 also includes the field observed BWUF, which ranges from 0.53 to 0.81, with the smaller value being observed in 2010 (field 2) and the highest in 2012 (field 3). These results reveal that the farmer improved the irrigation systems following the field performance assessments performed along with the maize experimental observations. WP and WP_{Irrig} also changed in consequence of BWUF improvements, which impacted water use, mainly irrigation water. Nevertheless, the highest WP_{Irrig} and EWP_{Irrig} were obtained for 2011 because yield was the second highest observed (Table 4.11) and the irrigation schedule was highly appropriate.

Table 4.11. Yield, gross season irrigation, beneficial water use fraction, water productivity and economic water productivity ratio.

Year	Field	Observed yield (kg ha^{-1})	Season gross irrigation (mm)	BWUF	WP (kg m^{-3})	WP_{Irrig} (kg m^{-3})	EWP (€ m^{-3})	EWP_{Irrig} (€ m^{-3})	$EWPR_{full\text{-}cost}$ ()
2010	1	20615	1156	0.55	1.68	1.78	0.35	0.37	2.43
	2	12775	1131	0.53	1.36	1.48	0.29	0.31	1.58
2011	1	19459	619	0.80	2.08	3.15	0.46	0.69	2.58
2012	2	19322	848	0.74	1.96	2.28	0.47	0.55	2.64
	3	16530	683	0.81	2.14	2.42	0.51	0.58	2.32

Because production costs do not change proportionally to irrigation water use, as irrigation is a relatively small fraction of total costs (averaging 29%), results for $EWPR_{full\ cost}$ well reflect the influence of the yield and its value, that showed little variation during the period 2010-2012. Therefore, the highest value for field 2 in 2012 corresponds to a high yield (19322 kg ha^{-1}) and to a production cost that reflects the high BWUF (0.74) achieved. Overall this indicator allows to perform a cost/benefit analysis showing that for each euro invested the farmer will have a return of at least 2 euro for all plots and years except for the field 2 in 2010 ($EWPR_{full\ cost}$ = 1.58) due to low yield (12775 kg ha^{-1}) and relatively high production costs which were due to a low BWUF (0.53). These results led to select results of field 2 in 2010 as baseline for assessing effects of improving irrigation scheduling as described hereafter.

4.3.4. Assessing alternative irrigation scenarios: an water productivity analysis

Various irrigation scheduling scenarios were designed with SIMDualKc as alternatives to that observed in field 2 in 2010 which caused high water stress during the flowering stage and resulted in a low yield (12775 vs. 21952 kg ha^{-1}). The alternative scenarios were developed using the field data relative to field 2 in 2010 using the calibrated crop and soil parameters referred in Section 4.3.1. The economic indicators were computed with the farmers' irrigation and production costs (not shown) and the commodity prices of 2010 (0.21 € kg^{-1}). A fixed net irrigation depth of 15 mm per irrigation event was adopted. The alternative schedules correspond to various water supply restrictions applied during the vegetative, flowering and maturation stages (Table 4.12). These alternative scenarios are:

AS1, without water supply restrictions (full satisfaction of crop water requirements);

AS2, irrigation reduced by 14% relative to AS1 with moderate stress during the vegetative stage and mild stress at flowering and maturation;

AS3, irrigation reduced by 16% relative to AS1, with mild stress in all stages;

AS4, irrigation reduced by 22% relative to AS1 with moderate stress during the vegetative and maturation stages and mild stress during flowering.

Table 4.12. Alternative irrigation depths for all scenarios.

Irrigation scenario	Net water supply (mm) per crop growth stage			Total net irrigation (mm)
	Vegetative	Flowering	Maturation	
Observed	176	82	330	588
AS1	270	150	330	750
AS2	165	150	330	645
AS3	180	150	300	630
AS4	180	150	255	585

For the alternative scenarios AS2 to AS4, the water stress imposed during the vegetative stage was enough to assure the conditioning effect during flowering and maturation (Stewart et al., 1977).

Results in Table 4.13 show that the observed irrigation scenario leads to high transpiration deficit (T_d = 66 mm), in particular during flowering ($T_{d,\,f}$ = 48 mm), which highly impacts yields (RYL = 42%). This scenario and AS4 present similar net seasonal irrigation and total T_d but AS4 shows a smaller yield loss (RYL = 21%) because the water deficit during the flowering stage is much smaller ($T_{d\ f}$ of 17 vs. 48 mm).

Table 4.13. Transpiration deficits ($T_{d,i}$, mm), simulated actual yield (Y_a, kg ha^{-1}), and relative yield losses (RYL, %) and physical (WP) and economic water productivities (EWP) for the different irrigation scenarios.

	Irrigation scenario				
	Observed	AS1	AS2	AS3	AS4
Net irrigation (mm)	588	750	645	630	585
Ratio net to optimum application depth	0.78	1.00	0.86	0.84	0.78
$T_{d,v}$ (mm)	15	2	18	15	15
$T_{d,f}$ (mm)	48	2	18	9	17
$T_{d,m}$ (mm)	9	1	6	13	32
Total T_d (mm)	66	5	42	37	64
T_d/T_c (%)	12.6	0.7	8.0	7.1	12.2
Simulated Y_a (kg ha^{-1})	12775*	21650	18342	19455	17432
RYL (%)**	42	1	16	11	21
WP (kg m^{-3})	1.36	1.84	1.78	1.94	1.84
WP_{Irrig} (kg m^{-3})	1.48	1.97	1.92	2.10	2.04
EWP (€ m^{-3})	0.29	0.39	0.37	0.41	0.39
EWP_{Irrig} (€ m^{-3})	0.31	0.41	0.40	0.44	0.43
$EWPR_{full\text{-}cost}$ ()	1.58	2.59	2.23	2.39	2.18

* observed yield; ** RYL = Y_a/Y_m

The highest WP is for AS3 (Table 4.13) with a RYL of 11%. However the highest yield and lower RYL are for AS1. This scenario and AS4 have the same WP = 1.84 kg m^{-3} but the later has much higher yield losses (RYL = 21%) because less water was applied. In other words, the same WP = 1.84 kg m^{-3} was obtained for alternatives whose yield were as different as 21650 and 17432 kg ha^{-1}. These results clearly show that obtaining a higher WP cannot be considered a farmer's objective, nor WP is an appropriate farming performance indicator.

The behaviour of WP_{Irrig} is similar to that of WP. The observed scenario has the lowest WP_{Irrig} (1.48 kg m^{-3}) and AS3 has the highest (2.10 kg m^{-3}), which corresponds to a mild deficit. However, the scenario AS1, with the highest yield, ranks third, after AS3 and AS4. These rankings indicate that WP_{Irrig} is also less appropriate as a farm irrigation indicator. EWP and EWP_{Irrig} behave similarly relative to WP and WP_{Irrig}, with the smaller values for the observed scenario (EWP = 0.29 € m^{-3} and EWP_{Irrig} = 0.31 € m^{-3}), and the highest values for AS3 (EWP = 0.42 € m^{-3} and EWP_{Irrig} = 0.46 € m^{-3}), which corresponds to mild deficit irrigation. The fact that EWP and EWP_{Irrig} behave similarly to WP and WP_{Irrig} requires that their use needs caution in interpreting results, as already observed by Rodrigues et al. (2013a and b).

To assess the economic returns relative to the various scenarios, the $EWPR_{full\ cost}$ is used. $EWPR_{full\ cost}$ shows a behaviour different from WP and WP_{Irrig} (Table 4.13). Its maximum value is 2.59 for the full irrigation scenario (AS1) and the minimum value is for the observed scenario, with a high transpiration deficit resulting in the highest relative yield loss. Differently from EWP, $EWPR_{full\ cost}$ reflects the value of produced yield per unit of total farming costs, which is different from relating the yield value with the unit of water used. Because the irrigation costs represent a relatively small fraction of the total farming costs as referred above, the denominator of $EWPR_{full\ cost}$ does not change much with the water use and differences among alternatives highly reflect differences in yields. AS1 shows to be the best option (Table 4.13), having an $EWPR_{full\ cost}$ 63% larger than that of the observed scenario. That difference is mainly due to a higher yield, which results in the highest yield value per unit of farming costs. Results in Table 4.13 also show that for the 2010 commodity price all deficit irrigation strategies were economically viable ($EWPR_{full\ cost} > 1.0$) and could be adopted if water availability would be insufficient for full irrigation.

4.4. Conclusions

The SIMDualK$_c$ model was successfully calibrated and validated, confirming the appropriateness of adopting the K_{cb} and p values standardized by FAO56 (Allen et al., 1998). SIMDualKc provided for the partition of evapotranspiration into soil evaporation and plant transpiration. The respective analysis showed that the ratio E_s/ET was higher for the fields where deficit irrigation was adopted. Differences were small during the initial crop stages and large from full cover to harvesting because a stressed crop has a lower ground coverage, hence allowing higher energy available at the ground surface. These differences in E_s/ET ratios also relate to the fact that high frequency irrigation with center-pivot sprinkling kept the evaporable soil layer with high moisture.

Actual transpiration (T_a) was lower than T_c during the stages when water stress was imposed, which led to lower yield. In agreement with former studies, results showed that the timing when water stress was imposed influenced the impacts on yield, which were higher when water stress occurred during the flowering stage.

Good yield predictions were obtained when combining the SIMDualKc model with both the global and multi-phasic Stewarts' S1 and S2 models. Prediction errors represented about 10 and

6.8% of the average observed yields, respectively. Better predictions with model S2 relate to the fact that different yield impacts of water stress are considered in relation to the various crop stages. However, the application of S2 model implies that the transpiration deficits are known for each stage (vegetative, flowering and maturation) and yield response factors for each stage have to be validated. Model S1 is to be applied when only the seasonal yield response factor K_y is available. Both models may be used with an ET deficit instead of T_d but results are likely to be less good because soil evaporation then influences the yield-water relations.

When comparing several alternative irrigation scheduling scenarios to the worst field results observed it was possible to use and compare various performance indicators relative to water productivity. It was observed that WP and WP_{irrig}, as well as EWP and EWP_{irrig}, were more sensitive to water use than to yield. Hence, the same results were obtained for low and high yields when associated with, respectively, less and more water use. Since the farmer objective is to obtain high yields and related economic returns that provide for a sustained farming success, indicators that are less sensitive to yields are less adequate to assess the performance of irrigation water use at farm. Differently, $EWPR_{full\ cost}$ has shown to respond well to both the yield value and the farming costs, having the highest value for the non-stressed alternative and the lowest for the less yielding one. This indicator proved to be able for assessing the economic viability of any irrigation alternative, mainly to assess deficit irrigation strategies. However, it requires full economic data, which is often difficult to obtain.

Overall, the methodology adopted, relative to both the observations in farmer's fields and the modelling application, revealed appropriate to understand water use by the crop and related impacts on yields and on farmer's returns under diverse irrigation management strategies. In particular, it was possible to assess the economic feasibility of deficit irrigation for the specific conditions analysed. The methodology using $EWPR_{full\ cost}$ is likely appropriate for further studies relative to water saving irrigation technologies as already demonstrated in a previous study (Rodrigues et al., 2013a). Studies with other crops and applied to different environments and socio-economic conditions are desirable.

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Capítulo 5 - Assessing the performance of the FAO AquaCrop model to estimate maize yields and water use under full and deficit irrigation with focus on model parameterization

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Paredes, P., Melo-Abreu, J.P., Alves, I., Pereira, L.S., 2014. Assessing the performance of the FAO AquaCrop model to estimate maize yields and water use under full and deficit irrigation with focus on model parameterization. Agr. Water Manage. DOI: 10.1016/j.agwat.2014.06.002 (Em publicação)

Assessing the performance of the FAO AquaCrop model to estimate maize yields and water use under full and deficit irrigation with focus on model parameterization

Abstract

Several maize field experiments, including deficit and full irrigation, were performed in Ribatejo region, Portugal and were used to assess water stress impacts on yields using the AquaCrop model. The model was assessed after its parameterization using field observations relative to leaf area index (LAI), crop evapotranspiration, soil water content, biomass and final yield data and also using default parameters. LAI data were used to calibrate the canopy cover (CC) curve. Results showed that when the CC curve is properly calibrated, with root mean square errors (RMSE) smaller than 7.4%, model simulations, namely relative to crop evapotranspiration and its partition, show an improved accuracy. The model performance relative to soil water balance simulation revealed a bias in estimation but low estimation errors, with RMSE < 13% of the total available soil water. However the model tends to overestimate transpiration and underestimate soil evaporation. A good model performance was obtained relative to biomass and yield predictions, with RMSE lower than 11% and 9% of the average observed biomass and yield, respectively. Overall results show adequacy of AquaCrop for estimating maize biomass and yield under deficit irrigation conditions, mainly when an appropriate parameterization is adopted. The model showed less good performance when using the default parameters but errors are likely acceptable when field data are not available.

Keywords: crop growth model, yield-water relations, soil water simulation, canopy cover, biomass and yield predictions, SIMDualKc model, dual crop coefficients

5.1. Introduction

Selecting the best irrigation schedule is required for improved use of the available water and for achieving the best yields. That selection implies appropriate prediction of the yield response to water, which is in the origin of numerous studies on water-yield responses to a variety of water stresses imposed throughout the crop season.

Several studies have been performed on maize showing the impacts of water deficits by reducing crop growth and canopy development (NeSmith and Ritchie, 1992), changing morphological characteristics of the plants (Traore et al., 2000; Stone et al., 2001a, b; Çakir 2004), reducing the number and weight of kernels (Weerathaworn et al., 1992; Karam et al., 2003), and thus reducing yields (Stewart et al., 1977; Doorenbos and Kassam, 1979).

In the extensive work by Stewart et al. (1977) results showed different maize yield responses when water stress was imposed at different growth stages, with higher impacts when water stress occurred during the flowering period. Other sensitive periods are those of grain filling and the end of the vegetative stage. The same conclusion was reported by Denmead and Shaw (1960) and Westgate and Grant (1989). For maize, lower yield losses due to mild stress during flowering are to be expected when the crop has already been subject to stress during the vegetative stage (Stewart et al., 1977). Alves et al. (1991) also noticed this conditioning behaviour when reporting results of an extensive field work on determining impacts of water stress on maize.

Simulation models may be helpful for assessing the impacts of water stress in crop yield. There are several studies using mechanistic models that allow determining biomass and yields and that may also be used for evaluating crop and irrigation management practices. Examples of applications of these models to maize include the use of CERES-Maize (Panda et al., 2004; DeJonge et al., 2012), CropSyst (Stöckle et al., 2003), EPIC (Cavero et al., 2000; Ko et al., 2009) and STICS (Katerji et al., 2010). A combination of the water balance model SIMDualKc (Rosa et al., 2012) with the phasic Stewart's water yield model (Stewart et al., 1977) was recently tested when using maize transpiration as driving variable (Paredes et al., 2014a). The crop growth model recently proposed by FAO, AquaCrop (Steduto et al., 2012), was selected for the present study because of its novelty and yet already wide application not only to maize (Hsiao et al., 2009; Heng et al., 2009; Katerji et al., 2013), but also cotton (Farahani et al., 2009), barley (Araya et al., 2010), and wheat (Andarzian et al., 2011).

Despite the existence of a large number of publications on applications of AquaCrop, information relative to parameterization, calibration and validation provided by the model authors (Hsiao et al., 2009) and the reference manual (Raes et al., 2012), as well as by other authors, is insufficient. Users may have a hard task when trying to correctly use the model, which becomes even harder when crops have not been previously parameterized by FAO (Raes et al., 2012). In addition, available publications often do not assess the performance of the model in simulating the available soil water, or in describing the canopy cover curve. There are a few studies that discuss model limitations (Farahani et al., 2009; Andarzian et al., 2011; Katerji et al., 2013; Paredes et al., 2014b, c). Difficulties were referred by Heng et al. (2009) and Katerji et al. (2013) relative to the AquaCrop application to maize when high water stress is considered. Farahani et al. (2009) referred to limitations in estimating the water balance components in applications to cotton.

Considering that some of the studies referred above have shown the need for a better parameterization of the model, particularly for conditions of water stress, the present study aims at testing AquaCrop for biomass and yield predictions of maize under various deficit irrigation levels and timings, and to assess the performance of the model using different parameterization approaches, including the adoption of the default parameters provided by Raes et al. (2012). In addition, the parameterization is analysed relative to the canopy cover curve, the simulation of the available soil water, and the prediction of biomass and harvestable yield.

5.2. Material and methods

5.2.1. Case studies

5.2.1.1. Real farming maize production

Observations were performed in farmer's fields at "Quinta da Lagoalva de Cima", located in Alpiarça, central Portugal. This farm has a total of 200 ha cropped with maize. Daily weather data were observed in a meteorological station located nearby (39.28 ^{o} N; 8.55^{o} W and 24 m elevation) and included maximum and minimum temperatures (^{o}C), wind speed (m s^{-1}), global solar radiation (W m^{-2}), relative humidity (%) and precipitation (mm). Climate in the region has Mediterranean characteristics, with mild rainy winters and dry hot summers. Daily weather data relative to the observations period of 2010 – 2012 are shown in Fig. 5.1 including the reference evapotranspiration (ET_o, mm d^{-1}) determined with the FAO-PM method (Allen et al., 1998).

Fields were cropped with *Zea mays* L. hybrid PR33Y74 (FAO 600) with a density of approximately 82000 plants ha^{-1}. Management practices, including fertilization and irrigation, were performed according to the standard practices in the region and were decided by the farmer. Direct sowing was used. Along the three irrigation seasons several fields were followed-up: two fields in 2010 and 2012, respectively fields 1 and 2, and fields 2 and 3; in 2011 only field 1 was observed. These fields were approximately 30 ha (fields 1 and 2) and 40 ha (field 3). Further information, including crop stages, is given by Paredes et al. (2014a).

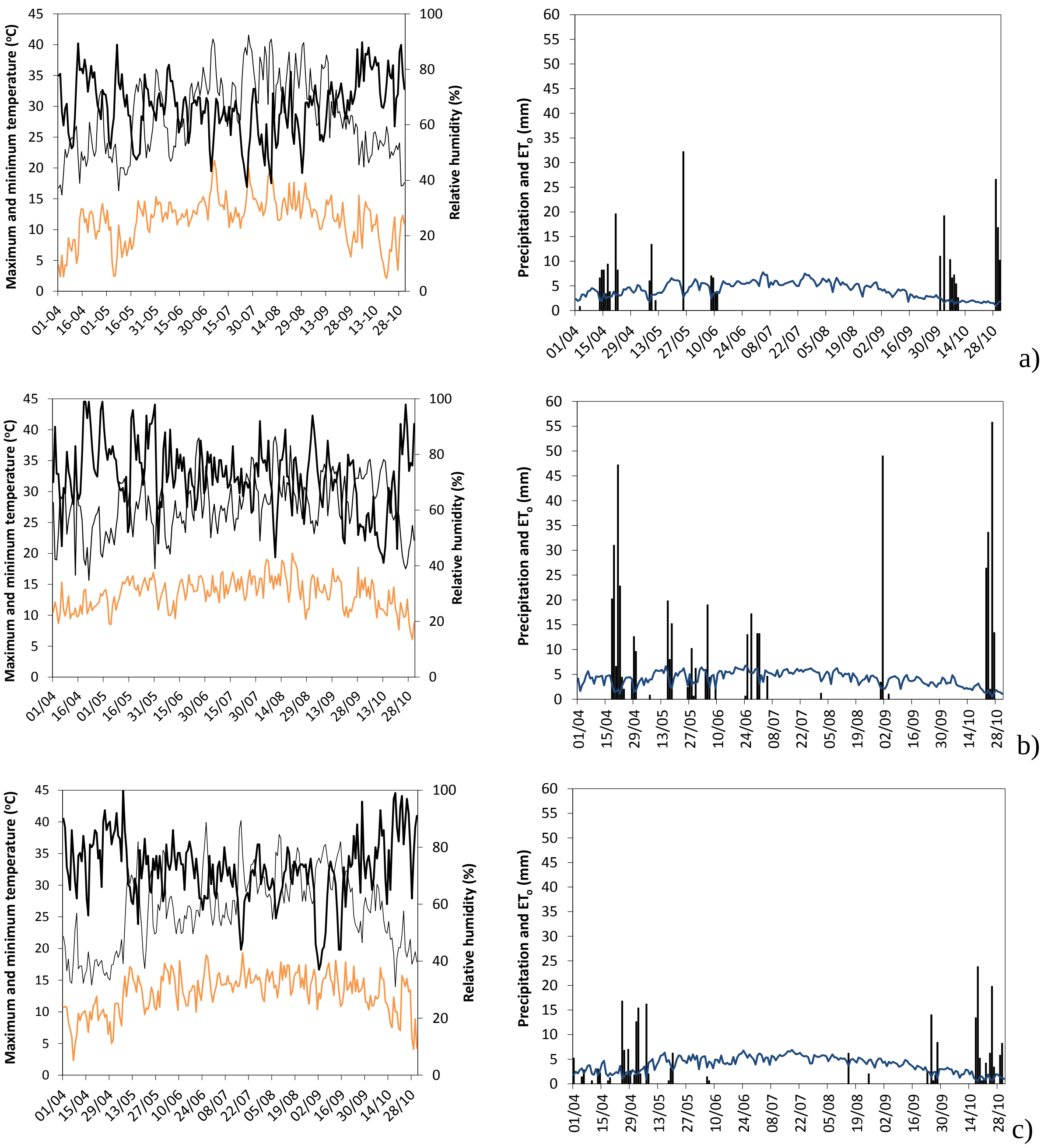


Fig. 5.1. Daily weather data of Alpiarça during the cropping seasons of 2010 (a), 2011 (b) and 2012 (c): on left maximum (—) and minimum (—) temperatures and relative humidity (▬); on right precipitation (▮) and reference evapotranspiration (ET_o) (▬).

The main soil hydraulic properties of the three fields observed are presented in Table 5.1. Three undisturbed soil samples of 100 cm^3 for each soil layer to a maximum depth of 1 m were collected prior to the beginning of the experiment to determine the soil water retention curve and the dry bulk density. The soil water retention curve for each layer was determined in the laboratory using suction tables with sand for suctions below -10 kPa, and a pressure plate apparatus for suctions of -10, -33, -100 and -1500 kPa (Ramos et al., 2011; Moreno et al., 2013). The saturated hydraulic conductivity (K_{sat}, cm d^{-1}) values were obtained using pedotransfer functions of texture and bulk density (Ramos et al., 2014). Soils are Eutric Fluvisols (FAO, 2006). In fields 1 and 2 soils have loamy sand texture and in field 3 the soil has a silt loam texture. The total available water (TAW), difference between the soil water stored at field capacity and at the wilting point to a depth of 1.0 m, is 171 and 149 mm m^{-1} for fields 1 and 2, respectively, and TAW = 209 mm m^{-1} for field 3. The saturated hydraulic conductivity (K_{sat}, cm d^{-1}) was moderate for the entire profile except for the top 0.10 m (Table 5.1) where higher values are associated with moderate to high organic matter content, averaging 25, 30 and 26 mg g^{-1} for fields 1, 2 and 3, respectively. This is due to manure additions performed two weeks prior to sowing and also to crop residues from the previous crop season because direct sowing is practiced. The K_{sat} values (Table 5.1) are near the range proposed by Rawls et al. (1998) and Raes et al. (2012) for loamy sand and silt loam soils. A full description of the soils textural properties is presented by Paredes et al. (2014a). Groundwater is below 10 meters and therefore capillary rise does not influence the moisture conditions in the maize root zone.

Table 5.1. Selected soil hydraulic properties of the Alpiarça fields

Soil layer (m)	θ_{FC} (m^3 m^{-3})			θ_{WP} (m^3 m^{-3})			θ_{sat} (m^3 m^{-3})			K_{sat} (cm d^{-1})		
	Field 1	Field 2	Field 3	Field 1	Field 2	Field 3	Field 1	Field 2	Field 3	Field 1	Field 2	Field 3
0.00-0.10	0.32	0.25	0.35	0.08	0.08	0.22	0.48	0.56	0.45	442	891	71
0.10-0.20	0.25	0.17	0.36	0.06	0.05	0.24	0.35	0.39	0.41	129	157	46
0.20-0.40	0.22	0.17	0.36	0.06	0.04	0.20	0.33	0.36	0.42	93	117	50
0.40-0.60	0.22	0.26	0.37	0.04	0.09	0.12	0.34	0.32	0.43	87	40	59
0.60-0.80	0.22	0.16	0.36	0.05	0.04	0.10	0.34	0.36	0.43	93	86	61
0.80-1.00	0.17	0.32	0.37	0.04	0.14	0.12	0.24	0.39	0.45	92	66	77

θ_{FC} is volumetric water content at field capacity; θ_{WP} is volumetric water content at wilting point; θ_{sat} is volumetric water content at saturation; K_{sat} is saturated hydraulic conductivity

Field observations included:

(i) dates of most relevant crop growth stages;

(ii) rooting depths, observed using a 1 m probe in random points between emergence and maximum canopy cover;

(iii) leaf area index (LAI, m^2 m^{-2}), measured along the crop season, usually with a 7-day interval, at three locations per field using a ceptometer (Decagon Devices Inc. USA, model AccuPAR LP-80) and following the recommendations proposed by Johnson et al. (2010). LAI measurements in 2010 were lost due to problems with the logger incorporated in the ceptometer;

(iv) biomass samples and the final actual yield observed at harvesting: samples were composed of 10 plants harvested near each soil water probe access tube (see (vi) below). Samples were placed in refrigerator containers for transporting to the lab, where they were separated into leaves, stem, cob and grains; samples were weighted to obtain fresh weight and then oven dried to constant weight at 65±5°C to obtain dry weight. The yield was adjusted to 13% grain moisture as used in other studies (Popova and Pereira, 2011).

(v) irrigation depths (D, mm), observed with rain gauges placed 0.20 m above the canopy and near the probe access tubes. All fields were sprinkler irrigated with a center-pivot in fields 1 and 2 and a linear moving system in field 3, both equipped with overhead rotator sprinklers;

(vi) volumetric soil water content, measured during 2010 using previously calibrated EnviroSCAN probes (Sentek Pty. Ltd, Stepney, South Australia) at depths of 0.10, 0.20, 0.30 and 0.50 m, and during 2011 and 2012 with a DIVINER 2000 probe (Sentek Pty. Ltd, Stepney, South Australia), with measurements at each 0.10 m until 0.90 m depth. Probes calibration followed manufacturer recommendations and procedures (Sentek, 2001) and therefore a calibration curve was obtained for each field. Observations were generally performed twice a week at 16 locations per field.

A more detailed description of the experiments is given in Paredes et al. (2014a).

5.2.1.2. Deficit irrigation trials

Experiments were performed in 1989 at the António Teixeira Experimental Station, located in the Sorraia Valley, Coruche, Central Portugal. These fields are inside a 15000 ha irrigation district. The experiments were set with the objective of assessing the impacts on maize yields at various levels of deficit irrigation at different crop growth stages. The climate is similar to that of Alpiarça, reported above. Figure 5.2 presents main climatic data of the maize crop season including ET$_o$ computed with the FAO-PM method (Allen et al., 1998).

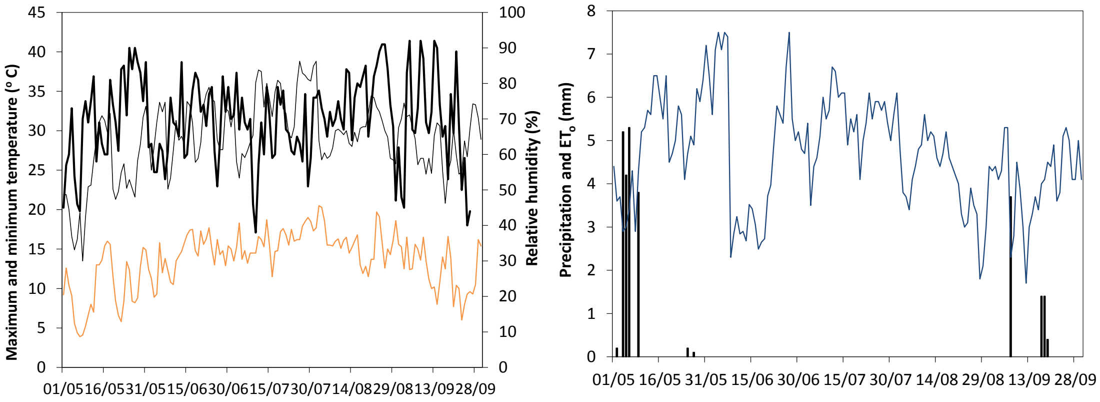


Fig. 5.2. Daily weather data observed at Sorraia Valley station during the 1989 maize crop season: on left maximum (—) and minimum (—) temperatures, and relative humidity (—); on right precipitation (▮) and reference evapotranspiration (ET$_o$) (—).

The experiments were performed with *Zea mays* L. hybrid LG18 (FAO 300) with a plant density of approximately 90000 plants ha^{-1}. The maize crop was sown on the 10th May, emergence occurred on 25th May, the maximum canopy cover was reached on 12th to 19th July depending on the irrigation treatment; the start of canopy senescence, which also depended upon the treatment, occurred from the 1st to the 28th August. Harvest was performed on 5th September for all treatments (Alves et al., 1991). The soil characterization is given in Table 5.2. These data have been analysed and used in previous studies (Rodrigues et al., 2013; Paredes et al., 2014a).

Table 5.2. Selected soil hydraulic properties of the Sorraia Valley experimental field.

Soil layer (m)	θ_{FC} (m^3 m^{-3})	θ_{WP} (m^3 m^{-3})	θ_{sat} (m^3 m^{-3})	K_{sat} (cm d^{-1})*
0.00-0.55	0.22	0.075	0.37	445

θ_{FC} is volumetric water content at field capacity; θ_{WP} is volumetric water content at wilting point; θ_{sat} is volumetric water content at saturation; K_{sat} is saturated hydraulic conductivity;
* Cameira et al. (2003)

Field observations and measurements relative to each treatment included:

(i) dates of most relevant crop growth stages;

(ii) leaf area index (LAI, m^2, m^{-2}), measured at key dates of the crop season, using a ceptometer (LI-3000 A, LI-COR, Lincoln, Nebraska, USA). Three measurements were performed during the crop development and four after flowering;

(iii) final yield at harvesting, using a sampling area of about 1.6 m^2 per treatment. Samples were separated into leaves, stem, cob and grains; samples were weighted to obtain fresh weight and then oven dried to constant weight at 65±5°C to obtain the dry weight. Yield was adjusted to 13% grain moisture.

(iv) irrigation depths (D, mm) determined using rain gauges placed above the canopy and near the probe access tubes. The irrigation treatments were set using a modified sprinkler line-source technique (Hanks et al., 1976). Irrigation was performed every 5 days during the summer months. Infra-red thermometers allowed to confirm that the plants in the well irrigated field were kept stress free (Jackson, 1982; Alves and Pereira, 2000);

(v) soil water content measured before and after each irrigation event using a previously calibrated neutron probe (DIDCOT, UK) at depths of 0.10, 0.15, 0.20, 0.30, 0.40, 0.50, 0.60, 0.80, 1.00 and 1.20 m. Calibration procedures followed Bell (1976) and Hodgnett (1986). A special calibration of the probe was performed for the surface layers (0.10, 0.15 and 0.20 m) as proposed by Bell (1976);

(vi) actual crop evapotranspiration ($ET_{c\ adj}$), determined for all periods between two successive irrigation events using a soil water balance following Doorenbos and Pruitt (1977). Deep percolation was estimated from soil water measurements performed below the root depth (0.60 to 1.20 m); runoff was null as well as capillary rise.

The irrigation treatments were set using a modified sprinkler line-source technique (Hanks et al., 1976). This technique allows a gradual transition between treatments, the grading of water applied to the crop lead also to gradual effects in the crop.

Several deficit and full irrigation schedules were established considering 3 crop growth stages: vegetative, flowering to yield formation, and maturation/ripening (Alves et al., 1991; Paredes et al., 2014a). Six strategies with several replications were selected from the Alves et al. (1991) data set to perform the present study:

(A) full irrigation in all crop growth stages;

(B) water stress imposed during the vegetative stage only;

(C) water stress imposed during maturation/ripening only;

(D) water stress imposed during the vegetative and flowering stages ;

(E) water stress imposed during vegetative growth and maturation/ripening; and

(F) water stress imposed along the entire crop season.

Further information is given by Paredes et al. (2014a).

5.2.2. The AquaCrop model

The Aquacrop model (Steduto et al., 2012; Raes et al., 2012) is a crop growth model which combines four sub-models: 1) the soil water balance; 2) the crop development, growth and yield; 3) the atmosphere sub-model, handling rainfall, evaporative demand (reference evapotranspiration, ET_o) and CO_2 concentration; 4) and the management sub-model, which includes irrigation and fertilization (Raes et al., 2012).

The model computes daily crop evapotranspiration (ET_c, mm d^{-1}) separating crop transpiration (T_c, mm d^{-1}) and soil evaporation (E_s, mm d^{-1}). T_c is given as (Raes et al., 2012)

$$T_c = CC^* K_{cTr,x}\, ET_o \qquad (5.1)$$

where ET_o is reference evapotranspiration (mm), $K_{cTr,x}$ is the maximum standard crop transpiration coefficient (non-dimensional), and CC* is the actual crop canopy cover (%) adjusted for micro-advective effects. The actual (or adjusted) transpiration (T_a) is obtained by adjusting T_c to soil water stress conditions using the water stress coefficient K_s (0 - 1), i.e., $T_a = K_s T_c$. The coefficient K_s describes the effects of soil water stress on the following crop growth processes (Raes et al., 2012): i) reduction of the canopy expansion rate; ii) acceleration of senescence; iii) closure of stomata; and iv) changes in the harvest index (HI) after the start of the reproductive growth. $K_{cTr,x}$ is adjusted by the model to take into consideration ageing effects and senescence.

The soil evaporation is also obtained from CC* and ET_o as

$$E_s = K_r (1 - CC^*) K_{ex} ET_o \tag{5.2}$$

where K_{ex} is the maximum soil evaporation coefficient (non-dimensional) and K_r is the evaporation reduction coefficient (0 - 1), with $K_r < 1$ when insufficient water is available in the top soil to respond to the evaporative demand of the atmosphere. K_{ex} can be adjusted for withered canopy, for mulches and for partial wettings following the FAO56 approach (Allen et al., 1998).

The above ground dry biomass (B, t ha^{-1}) is estimated by the model using the water transpired by the crop along the season and the normalized biomass water productivity (WP_b*, g m^{-2}). WP_b* represents the above ground biomass produced per unit of land area considering both the cumulative transpiration, after normalization for atmospheric CO_2 concentration, and ET_o (Raes et al., 2012). A semi-empiric approach is used to compute the crop yield (Y, t ha^{-1}) from B as:

$$Y = f_{HI} HI_o B \tag{5.3}$$

where HI_o is the reference harvest index, which indicates the harvestable proportion of biomass, and f_{HI} is an adjustment factor integrating five water stress factors relative to the inhibition of leaf growth, inhibition of stomata, reduction in green canopy duration due to senescence, reduction in biomass due to pre-anthesis stress, and pollination failure (Raes et al., 2012).

In the present study, HI_o was observed in all seasons in no stress conditions and averaged 0.49 and 0.48 for the Alpiarça and Sorraia Valley sites, respectively. This averaging approach follows those adopted in other AquaCrop studies (Araya et al. 2010; Zeleke et al., 2011). Our HI_o values are in the range of those reported by Di Paolo and Rinaldi (2008) [0.36-0.53], Heng et al. (2009) and Hsiao et al. (2009) [0.48], Farré and Faci (2009) [0.16-0.51] and Katerji et al. (2013) who found a value of 0.46.

The model input data (Raes et al., 2012) includes:

1) Daily weather data on maximum and minimum air temperatures (°C), precipitation, P_e (mm),

reference evapotranspiration, ET_o (mm); atmosphere data refer to annual CO_2 concentration.

2) Crop data referring to: (i) the dates of emergence, when maximum canopy cover is reached, when maximum root depth is attained, when canopy senescence starts, when maturity is reached, when flowering starts and ends; (ii) maximum value of the transpiration crop coefficient ($K_{cTr,x}$); (iii) minimum and maximum root depths Z_r (m) and roots expansion shape factor; (iv) the initial and maximum crop canopy cover (CC_o, CC_x), canopy growth coefficient (CGC) and the canopy decline coefficient (CDC); (v) normalized biomass water productivity (WP_b*); (vi) reference harvest index, (vii) water stress coefficients relative to canopy expansion, stomatal closure, early canopy senescence and aeration stress due to waterlogging.

3) Soil data for a multi-layered soil including a maximum of 5 layers. For each layer data refer to layer depth d (m), soil water content at field capacity θ_{FC} ($m^3\ m^{-3}$), at the wilting point θ_{WP} ($m^3\ m^{-3}$) and at saturation θ_{sat} ($m^3\ m^{-3}$), and the saturated hydraulic conductivity (K_{sat}). Relative to the soil profile, data refer to the readily evaporable soil water (REW, mm) and the curve number (CN).

4) Irrigation scheduling data, both dates and depths of observed irrigation events or, when the model is used to generate irrigation schedules, the soil water thresholds and irrigation depths and frequency.

5) Field management practices relative to salinity, soil fertility, mulching and runoff reduction practices.

The canopy cover (CC) is equivalent to the fraction of soil covered by the canopy (f_c, non-dimensional) in FAO56 (Allen et al., 1998); however, the model does not allow using observed data to build the CC curve but allows to calibrate the CC curves. Model computations of CC are performed through three phases (Raes et al., 2012): the first one uses an exponential function of time, which begins at crop emergence and ends when half of the maximum CC is reached, with the CC growth rate defined by the parameter CGC; the second phase uses another exponential function until the maximum CC (CC_x) is reached, with the shape given by the same CGC parameter; the last phase refers to the decline of green canopy cover after senescence starts and its shape is defined by the parameter CDC (Raes et al., 2012). To parameterize the CC curves (CC_x, CGC and CDC) observed LAI values may be used to compute the corresponding CC values with an exponential time decay function (Hsiao et al., 2009):

$$CC = 1.005\ [1 - exp(-0.6\ LAI)]^{1.2} \tag{5.4}$$

Further descriptions of the model and auxiliary equations are given by Raes et al. (2012).

5.2.3. Model parameterization, calibration and validation

The AquaCrop model uses a large number of parameters including several conservative ones that are expected to change little with time, management or location, and are described and tabled by Raes et al. (2012). These tabled values were used together with other conservative parameters obtained for maize based on field experiments reported by Hsiao et al. (2009) and Heng et al. (2009). The model was first parameterized for appropriately describing the CC curve given its great importance to model both transpiration and soil evaporation (Eqs. 1 and 2). Thus, the trial and error procedure focused first on the parameters that determine the CC curve, i.e., CC_x, CGC and CDC. Specific parameters values were searched for each year and treatment. Subsequently, the trial and error procedure focused on adjusting the K_{cTrx}, as well as REW and CN, by comparing simulated and observed field data of available soil water (ASW) or/and ET. In this application, the REW and CN for Alpiarça were those obtained in a previous study with the SIMDualKc model (Paredes et al., 2014a). The WP_b* for Alpiarça and Sorraia Valley case studies were 33.7 and 32.3 g m^{-2}, respectively, in agreement with the values proposed by Hsiao et al. (2009). The model was calibrated with the Alpiarça data of 2011 and was tested with data collected in 2010 and 2012 and data of all the Sorraia treatments.

To assess the "goodness-of-fit" of the model, various statistical approaches were used, as in previous studies (Rosa et al., 2012; Paredes et al., 2014a). The first approach refers to the linear regression forced through the origin relating observed and predicted values; the respective regression and determination coefficients are used as indicators. A regression coefficient (b) close to 1.0 indicates that the predicted values are statistically close to the observed ones; a determination coefficient (R^2) close to 1.0 indicates that most of the variance of the observed values is explained by the model.

A set of indicators of residual estimation errors was also used (Moriasi et al., 2007): the root mean square error (RMSE), which expresses the variance of errors, and the average absolute error (AAE), that expresses the average size of the estimate errors. These indicators are computed from the pairs of observed and predicted values O_i and P_i (i = 1, 2, ..., n) whose means are respectively $\overline{O}$ and $\overline{P}$, thus:

$$RMSE = \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n} \right]^{0.5} \tag{5.5}$$

and

$$AAE = \frac{1}{n} \sum_{i=1}^{n} |O_i - P_i| \tag{5.6}$$

To test the quality of the modelling approach the Nash and Sutcliffe (1970) modelling efficiency (EF, non-dimensional) was used. It is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Moriasi et al., 2007) and is defined as:

$$EF = 1.0 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \tag{5.7}$$

EF approaches 1.0 when the residual variance is much smaller than the measured data variance, while negative EF values indicate that the mean is a better estimator than the model (Moriasi et al., 2007).

5.3. Results and discussion

5.3.1. Model performance when applied to real farming maize production

5.3.1.1. Canopy cover curve

The observed maize data on crop growth stages, roots depths and LAI were presented by Paredes et al. (2014a). As previously explained, model calibration was performed by minimizing the differences between observed and simulated available soil water (ASW, mm), biomass and yield relative using data of field 1 in 2011. That calibration was performed after appropriate parameterization of the CC curve. All calibrated values (CC_x, CGC, CDC, $K_{cTr,x,}$ WP_b*, HI_o) and conservative ones (i.e., relative to parameters that change little with management or location, Raes et al., 2012) are presented in Table 5.3; the default values used to initiate the model application are also included. The calibrated $K_{cTr,x}$ = 1.18 (Table 5.3), which corresponds to the basal crop coefficient for the mid season ($K_{cb\ mid}$) (Allen et al., 1998), is similar to the one obtained by Abedinpour et al. (2012), $K_{cTr,x}$ = 1.15, but is higher than the one reported by Hsiao et al. (2009) and Heng et al. (2009), $K_{cTr,x} = 1.05$. The calibrated $K_{cTr,x}$ is similar to the $K_{cb\ mid} = 1.15$ proposed by Allen et al. (1998), which was also obtained by Paredes et al. (2014a) for the same data set, and in the studies by Zhang et al. (2013). The calibrated $K_{cTr,x}$ also compares well with the single crop coefficient values reported by Piccinni et al. (2009) and Gao et al. (2009).

Table 5.3. Conservative and calibrated crop parameters of AquaCrop model

Description	Units or symbol meaning	Value			
Conservative parameters		Default*	Adopted		
Base temperature	°C	8	8		
Cut-off temperature	°C	30	30		
Canopy cover at 90% emergence (CC_o)	cm^2 per plant	6.5	4.1		
Soil water depletion threshold for canopy expansion	Upper threshold	0.14	0.14		
Soil water depletion threshold for canopy expansion	Lower threshold	0.72	0.72		
Shape factor for water stress coefficient for canopy expansion	Curve shape moderately convex curve	2.9	2.9		
Soil water depletion threshold for stomatal control	Fraction of TAW at which stomata start to close	0.69	0.69		
Shape factor for water stress coefficient for stomatal control	Highly convex curve	6.0	6.0		
Soil water depletion threshold for failure of pollination	Fraction of TAW at which pollination starts to fail	0.80	0.80		
Calibrated parameters		Default	Calibrated		
Crop coefficient for transpiration at CC_x	Basal crop coefficient ($K_{cTr,x}$)	1.05	1.18		
WP_b*	Biomass water productivity normalized for ET_o and CO_2 ($g\ m^{-2}$)	33.7	33.7		
HI_o	Reference harvest index (%)	0.50	0.49		
Canopy cover curve parameters		Default	2010	2011	2012
Maximum canopy cover, CCx,	%	97	96	96	96
Canopy growth coefficient, CGC	% GDD^{-1}	1.30	1.49	1.49	1.56
Canopy decline coefficient, CDC	% GDD^{-1}	1.06	0.40	0.35	0.43

* default parameters are tabled by Raes et al. (2012)

As referred before, an appropriate parameterization of the CC curve is a major requisite for the model to produce good estimates of soil evaporation, crop transpiration and biomass (Eqs. 1 to 3) and, hence, good yield predictions. However, this requirement is not properly identified by the model developers (e.g., Hsiao et al., 2009; Heng et al., 2009; Raes et al., 2012) or other authors. As previously referred, observed LAI values were used to compute the CC values (Eq. 5.4) that were used for that parameterization. Specific CC_x, CGC and CDC were obtained for each treatment (Table 5.3). Results of the fitted CC curves are shown in Fig. 5.3 for 2011 and 2012.

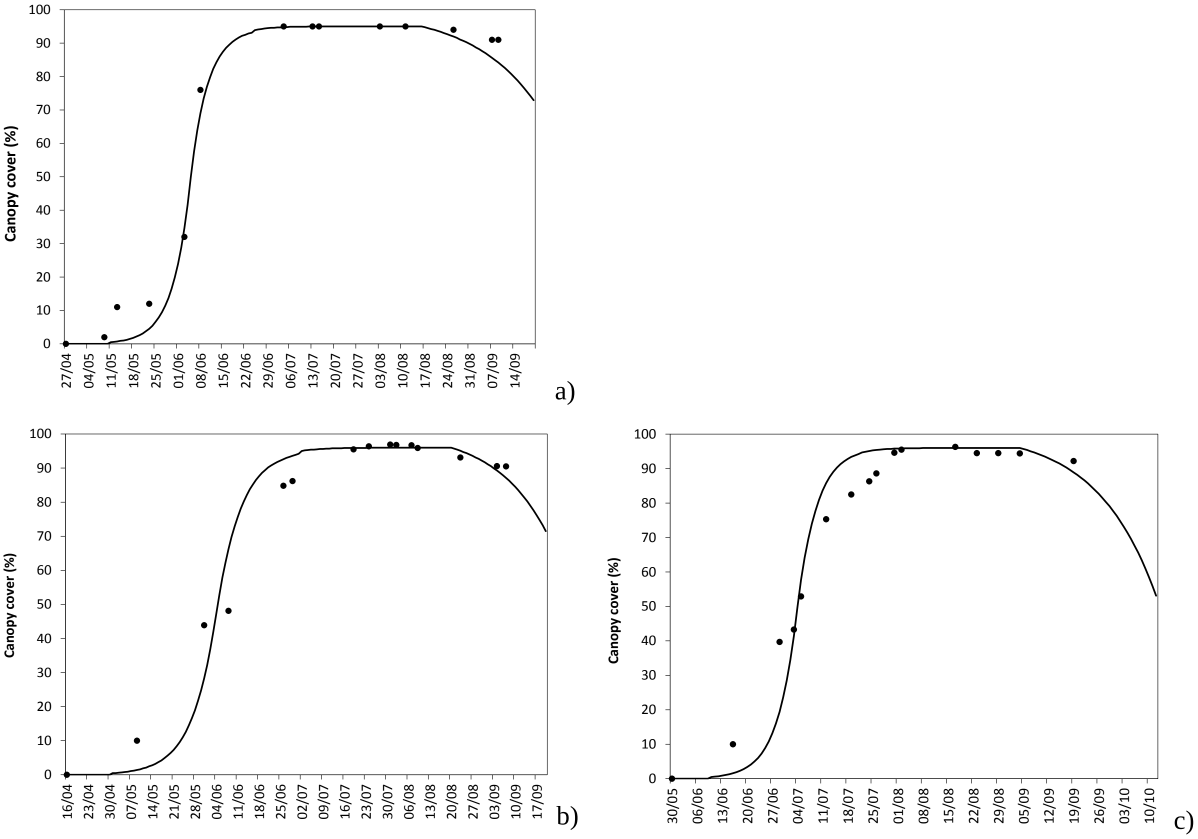


Fig. 5.3. Maize canopy cover (CC) simulated (—) and observed (●) for Alpiarça: (a) field 1 in 2011, (b) field 2 in 2012 and (c) field 3 in 2012.

The "goodness-of-fit" indicators relative to the CC curves when using default and calibrated parameters are presented in Table 5.4. Simulation results using default values show a clear tendency for under-estimation of the observed CC values, with the regression coefficient $b<0.95$ for all cases, high estimation errors (RMSE>16.6% and AAE >10.5%) and low to medium model efficiency (EF ranging 0.18 to 0.71). Differently, when a proper calibration of the CC curve parameters (CC_o, CC_x, CGC and CDC) was performed, results do not show any tendency to over or under-estimation (b ranging from 0.97 to 1.03) and the determination coefficients are higher ($R^2 > 0.96$), thus indicating that the CC model highly explains the variance of observed CC values. Estimation errors are then small, with RMSE ranging 4.6 to

7.9% and AAE varying between 3.1 to 5.3%. These RMSE values obtained with calibration are in the range or smaller than those reported by Hsiao et al. (2009), with RMSE ranging from 4.8 to 13.6%. García-Vila and Fereres (2012) reported a larger RMSE of approximately 13% and higher values were reported by Heng et al. (2009) for rainfed maize (7.2 to 34.5%). High EF values were also obtained (> 0.94) which indicate that the residual variance was much smaller than the measured data variance. These results (Table 5.4) clearly show the need for a careful calibration of the CC curve when searching for accurate results.

Table 5.4. "Goodness-of-fit" indicators relative to canopy cover using default and calibrated parameters, Alpiarça case study

	Field and year	***Goodness of fit indicators***				
		b	*R^2*	*RMSE* (%)	*AAE* (%)	*EF*
Using default parameters	Field 1, 2011	0.75	0.52	35.7	18.7	0.18
	Field 2, 2012	0.95	0.77	18.0	10.5	0.68
	Field 3, 2012	0.93	0.87	16.6	11.0	0.71
	All data	0.88	0.69	24.5	13.2	0.49
Using calibrated parameters	Field 1, 2011	0.97	0.99	4.6	3.1	0.99
	Field 2, 2012	1.01	0.96	7.2	4.5	0.95
	Field 3, 2012	1.03	0.96	7.4	5.1	0.94
	All data	1.01	0.97	6.6	4.3	0.96

5.3.1.2. Simulation of the available soil water

Results of model simulation of the available soil water (ASW) throughout all crop seasons are presented in Fig. 5.4 when using calibrated, not default parameters. Observations show that stress only occurred during the 2010 season, with the observed ASW falling below the readily available soil water (RAW) threshold during mid-season (Fig. 5.4b and c). Despite adopting a careful parameterization (Section 5.2.3), the model did not properly simulate ASW. Results in Fig. 5.4a show a trend for overestimation, which is more important for the lower values of ASW. The same trend for overestimation of lower ASW values is observed for the other simulation results. Contrarily, when ASW are closer to field capacity no trend is observed. These results are somewhat different from those obtained with SIMDualKc model for the same data sets, which are reported by Paredes et al. (2014a) and show a better fit without bias. This indicates that the AquaCrop model does not simulate properly, in particular when soil water deficits occur.

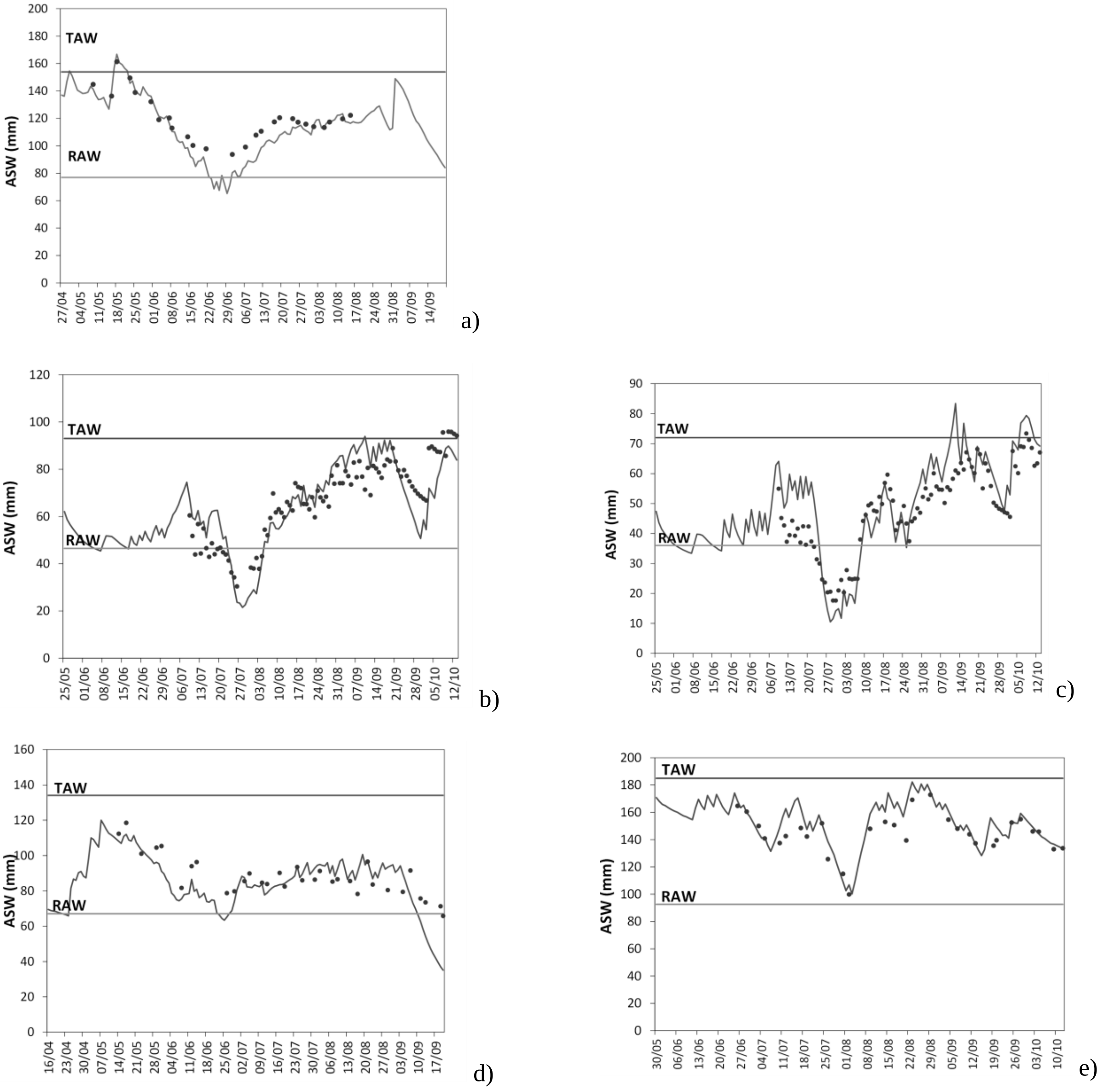


Fig. 5.4. Observed (•) and simulated (——) available soil water (ASW) for the Alpiarça maize fields: a) field 1 in 2011 (calibration), b) field 1 in 2010, c) field 2 in 2010; d) field 2 in 2012; and e) field 3 in 2012.

The "goodness-of-fit" indicators relative to the simulation of ASW using the calibrated parameters (Table 5.3) and represented in Fig. 5.4 are given in Table 5.5. Results show regression coefficients ranging from 0.96 to 1.09 and determination coefficients ranging from 0.59 to 0.88, with $R^2 = 0.88$ for the calibration (field 1, 2011). These results indicate that a bias of estimation occurred for all experiments. Differently, SIMDualKc results (Table 5.5) have shown b values ranging from 0.98 to 1.01 and R^2 ranging from 0.79 to 0.94. Estimation errors with AquaCrop are relatively low, with RMSE ranging from 8.4 to 11.7 mm, which correspond to a variation of 5.1 to 13.5% of the total available soil water (TAW), and the AAE values are also small, less than 8.8 mm. However, smaller errors were obtained with SIMDualKc, with RMSE from 4.0 to 6.5 mm. The modelling efficiency with AquaCrop is generally acceptable, with EF from 0.57 to 0.72, except for field 2 in 2012 where EF = 0.03. This value indicates that the residuals variance is close to the measured data variance; contrarily, results for the other data sets indicate that the residuals variance is lower than the measured data variance. However, overall, the indicators of "goodness-of-fit" failed the limits for R^2 and EF, respectively 0.80 and 0.70, proposed by Ma et al. (2011) for crop models. Using SIMDualKc (Table 5.5), EF varied from 0.74 to 0.92, thus above the limits suggested by Ma et al. (2011). Thus, results indicate that AquaCrop does not accurately simulate ASW.

Table 5.5. "Goodness-of-fit" indicators relative to AquaCrop simulations of ASW (mm) when using default and calibrated parameters for all Alpiarça fields and years.

				Goodness of fit indicators					
Model		***Year***	***Field***	*b*	*R^2*	*RMSE* (mm)	*RMSE/TAW* (%)	*AAE* (mm)	*EF*
AquaCrop	Using default parameters	2010	Field 1	1.20	0.78	16.6	17.8	14.7	0.00
			Field 2	1.26	0.71	16.3	22.6	13.7	-0.36
		2011	Field 1	1.10	0.53	17.9	11.6	13.0	-0.26
		2012	Field 2	1.30	0.03	34.5	25.7	29.9	-8.40
			Field 3	1.22	0.37	36.3	19.6	33.1	-5.30
		All data		1.21	0.89	22.3	-	18.0	0.59
	Using calibrated parameters	2010	Field 1	1.00	0.71	9.5	10.2	8.1	0.66
			Field 2	1.09	0.80	9.1	12.6	7.4	0.58
		2011	Field 1	0.96	0.88	8.4	5.5	6.7	0.72
		2012	Field 2	0.96	0.59	11.7	8.7	8.8	0.03
			Field 3	1.04	0.79	9.5	5.1	7.1	0.57
		All data		1.02	0.93	9.5	-	7.7	0.93
SIMDualKc (Paredes et al., 2014a)		2010	Field 1	1.01	0.92	4.8	3.1	3.9	0.91
			Field 2	1.00	0.94	4.0	3.1	3.2	0.92
		2011	Field 1	0.99	0.85	6.3	4.1	5.5	0.84
		2012	Field 2	0.98	0.79	5.7	4.3	4.7	0.74
			Field 3	0.99	0.85	6.5	3.5	5.7	0.80
		All data		1.00	0.98	5.0	-	4.1	0.98

When using the default parameters given by Raes et al. (2012) and the CC curve is also simulated with default parameters, the "goodness-of-fit" indicators (Table 5.5) show a clear trend for over-estimation of ASW ($1.10 < b < 1.30$) and the estimation errors are high, with RMSE ranging from 11.6 to 25.7% of TAW. EF is then generally negative, which indicates that the mean is a better predictor than the simulated values. It can be concluded that a careful parameterization of the CC curve is definitely required when soil water is simulated, and that it is advisable to parameterize the model using accurate soil water observations throughout the crop season.

The poor fitting of the observed ASW when using AquaCrop after model calibration is likely related to the less good estimations of transpiration (Eq. 5.1) and soil evaporation (Eq. 5.2). Fig. 5.5 compares T_a and E_s simulated by AquaCrop and the SIMDualKc model (Paredes et al., 2014a) along the crop seasons of 2010, 2011 and 2012 using the same data sets. Results show that AquaCrop tends to over-estimate T_a and to under-estimate E_s, thus resulting in a bias of estimates of ASW as indicated by the less good EF values in Table 5.5. Over-estimation of T_a is greater when water stress occurs as evidenced when comparing Figs. 5a and 5b. Similar differences were also observed and discussed for AquaCrop applications to maize by Katerji et al. (2013), peas (Paredes et al., 2014b) and barley (Paredes et al., 2014c).

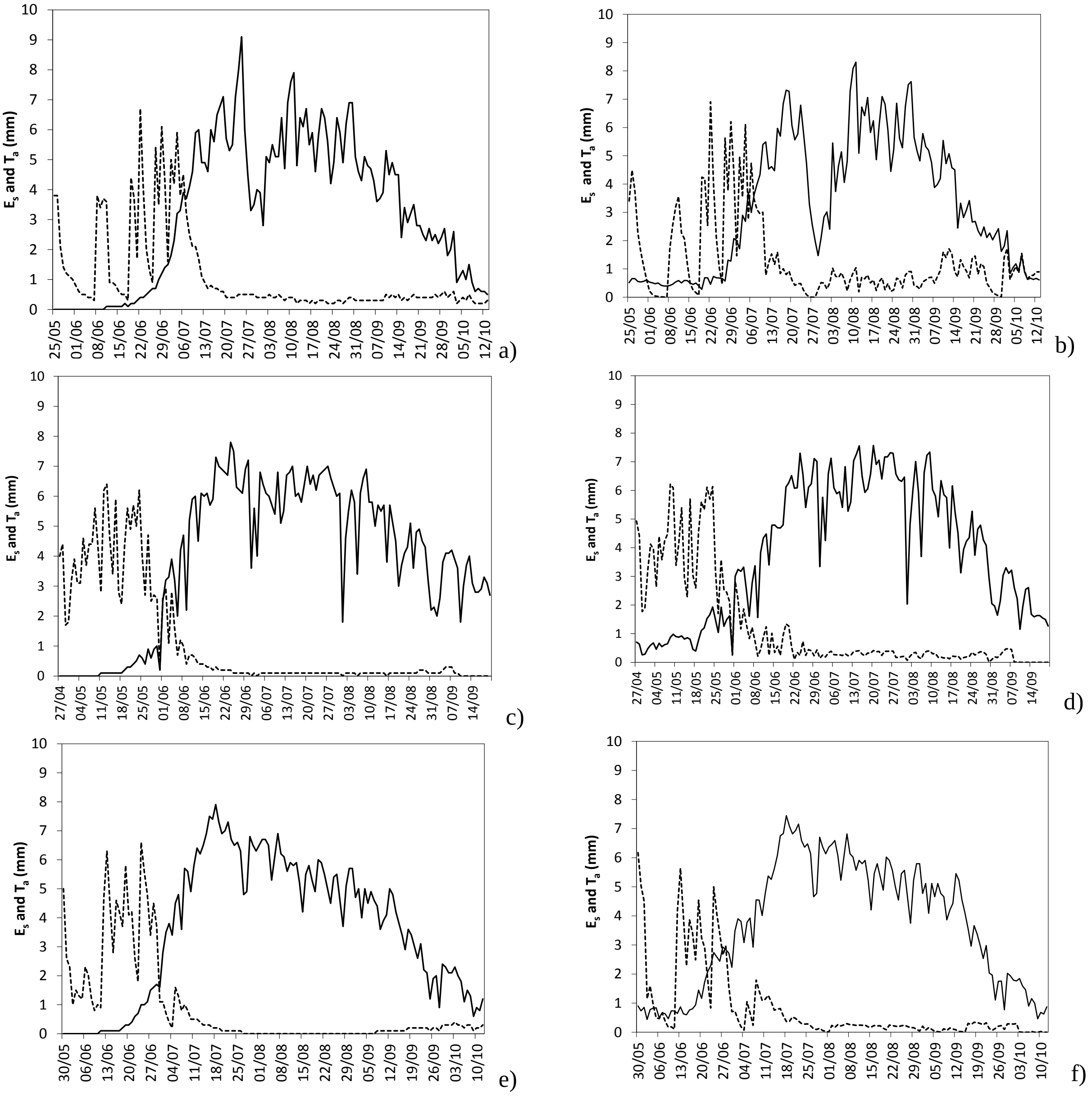
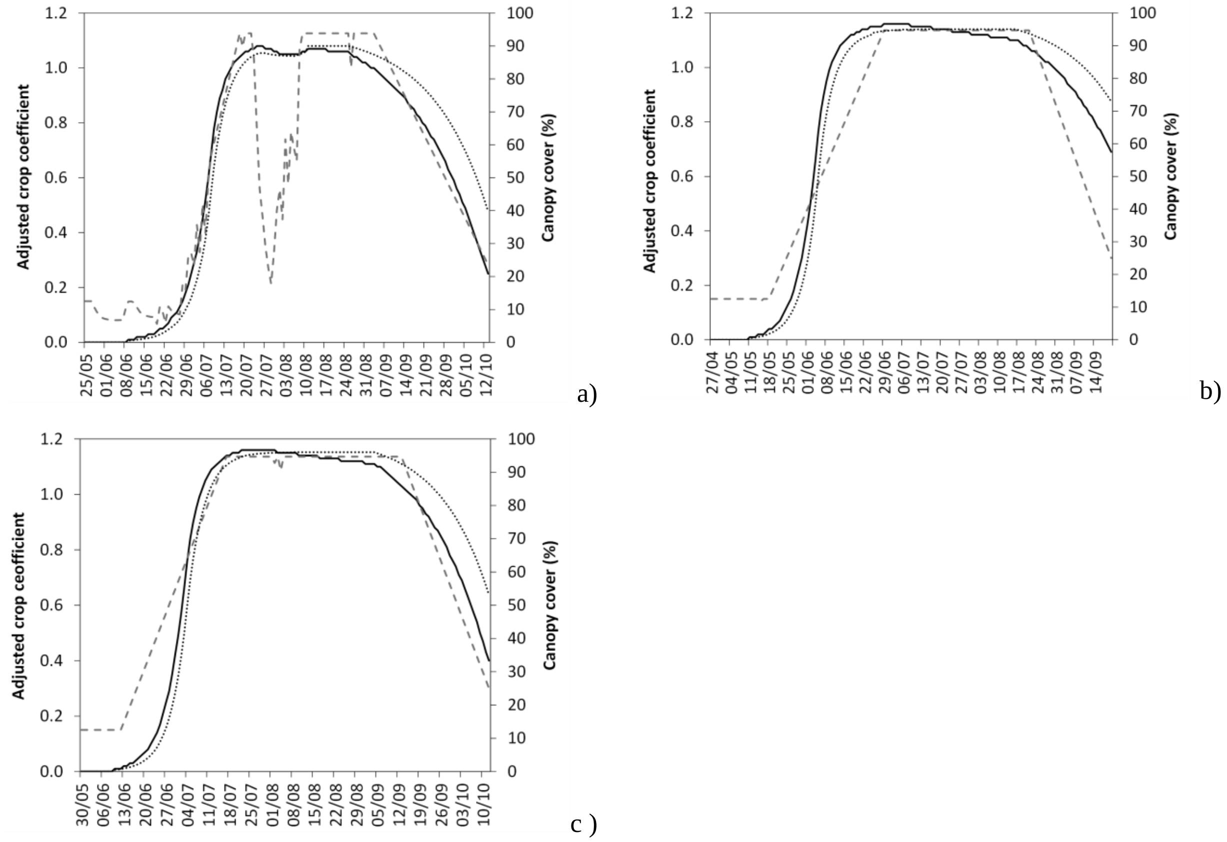


Fig. 5.5. Seasonal variation of the actual transpiration (T_a, ——) and soil evaporation (E_s, - -) in field 2 in 2010 (a, b), field 1 in 2011 (c, d), and field 3 in 2012 (e, f): on left when using AquaCrop and, on right, with the SIMDualKc model.

The over-estimations of T_a are due to problems in estimating the adjusted basal crop coefficients in T_a computations (Eq. 5.1). To verify this assumption, the seasonal variation of the adjusted K_{cb} calculated with AquaCrop and SIMDualKc are compared in Fig. 5.6 together with the canopy cover curve simulated by AquaCrop. It can be observed that while $K_{cb\ adj}$ estimated with SIMDualKc follows the classical crop coefficients curve (Allen et al., 1998, 2005; Rosa et al., 2012), the K_{cbTr} computed with AquaCrop follow the CC curve (Raes et al., 2012), thus becoming different than the common crop coefficient curves (Fig. 5.6). Therefore, since the two models follow different conceptual approaches, the adjusted K_{cb} curves are different, resulting in the AquaCrop K_{cTr} not being impacted by water stress if the CC curve itself is not affected by water stress. This is well evident in Fig. 5.6b where $K_{cb\ adj}$ is highly impacted by water stress early in midseason but K_{cTr} is not. Differences among both models, or between AquaCrop and the FAO56 approach, also exist in soil evaporation estimation: while in FAO56 and SIMDualKc E_s is daily estimated with a water balance of the evaporative layer (Allen et al., 1998, 2005; Rosa et al., 2012), in AquaCrop E_s varies with the CC curve (Eq. 5.2). This approach justifies why E_s is underestimated when the canopy cover is high, i.e., during mid- and late season. It is also likely a reason for overestimation of low ASW values as referred above. Problems reported for T_a and E_s estimation are likely to explain the less good "goodness of fit" indicators in Table 5.5. Therefore, the K_{cTr} and CC curve proportionality should be revised since the latter is not sensitive to daily water stress throughout the season but only to water stress during the vegetative stage. An approach similar to that adopted in FAO56 (Allen et al., 1998, 2005) could be considered for estimation of both transpiration and soil evaporation.

5.3.2. Model performance for deficit irrigation experiments

The parameterization of the CC curve was the first focus of the calibration procedure using LAI observations to get observed CC values using Eq. (5.4). The CC_o value used in the simulation was higher (0.045) than for the Alpiarça studies (section 5.3.1) because the plant density was higher in these experiments (see section 5.2.1.2). The CC_x was set as the maximum observed for the full irrigation treatment (0.97); CGC and CDC were set as 2.53% GDD^{-1} and 0.72% GDD^{-1} respectively. The CGC value is higher than that used for Alpiarça given the hybrid used, of FAO 300 type, that developed faster than the hybrid PR33Y74, of FAO 600 type used at Alpiarça, i.e., requiring 200 GDD less, approximately.



a)

b)

c)

Fig. 5.6. Seasonal variation of the adjusted basal crop coefficient when using SIMDualKc, $K_{cb\ adj}$ (— —), and using AquaCrop, K_{cTr} (——), compared with the canopy cover curves (·····) relative to Alpiarça fields: (a) field 2 in 2010, field 1 in 2011 (b), and field 3 in 2012 (c).

Fig. 5.7 presents examples of CC curves simulated by AquaCrop relative to each treatment. These results clearly show some discrepancies between simulated and observed CC values during the vegetative development and the mid-season stages, particularly when water stress was imposed during the vegetative stage, i.e., treatments B, D, E and F.

Table 5.6 presents the “goodness-of-fit” indicators relative to the adjustment of CC curve for every treatment when using both default and calibrated parameters. The model performance is good when using the calibrated CC parameters, with b ranging from 0.96 to 1.03 and R^2 ranging from 0.80 to 0.96. The estimation errors are small, with RMSE < 7% and AAE < 6%. EF are high, ranging from 0.75 to 0.96, hence indicating that the residuals variance is much smaller than the measured data variance.

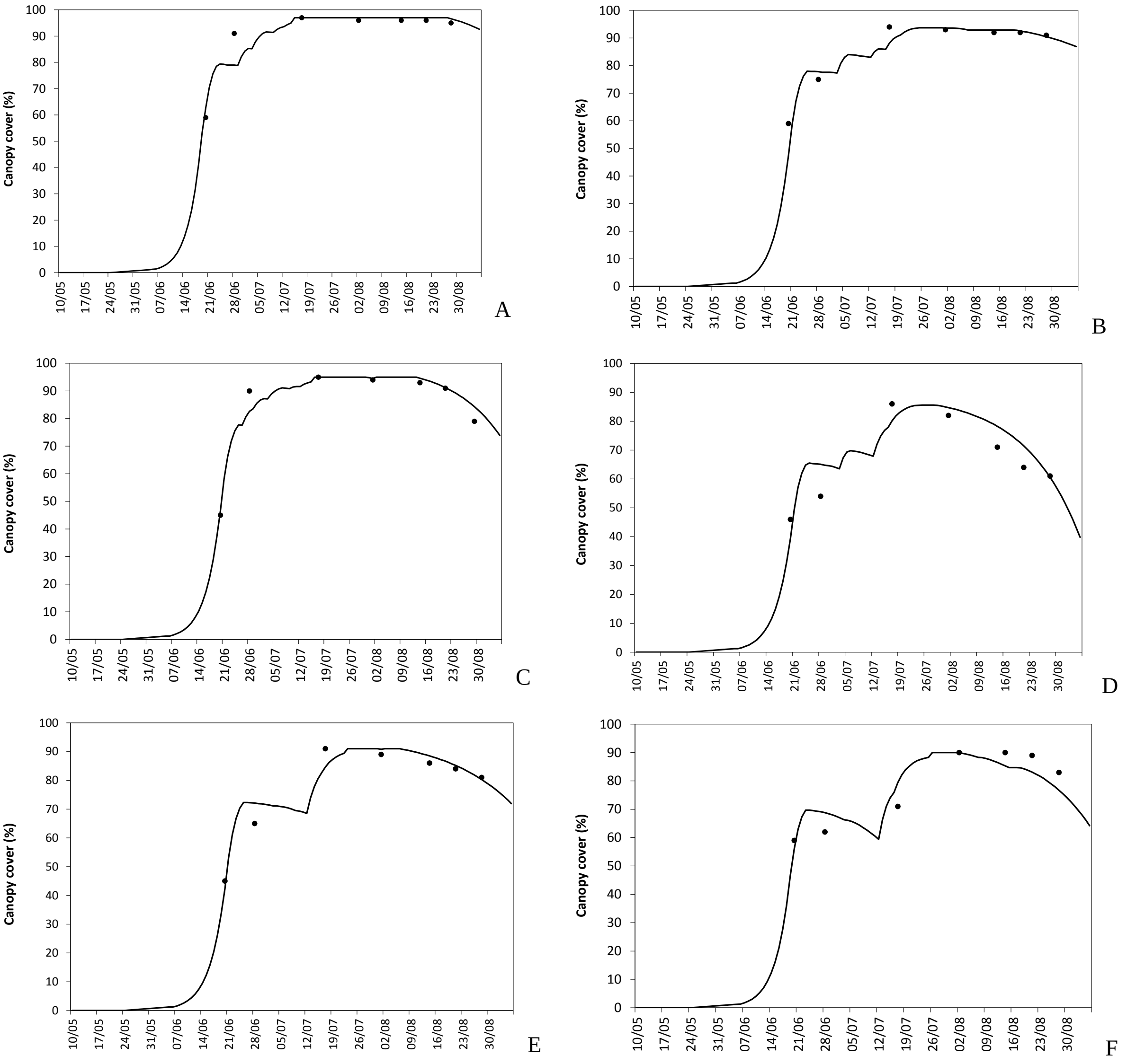


Fig. 5.7. Selected examples of maize canopy cover (CC) simulated (—) and observed (●) for Sorraia Valley experiments, treatments A, B, C, D, E and F.

Contrarily, when using the default parameters, results show a poor model performance, with b < 0.86 and R^2 <0.78. High estimation errors were found, with RMSE ranging 23.9 to 40.7% and AAE ranging from 15.3 to 32.2%. Moreover, EF is negative for all treatments, which indicates that the residuals variance is larger than the measured data variance and the modelled values are not appropriate estimators. Overall results show that the model appropriately simulates the CC curve when the parameters are properly calibrated and that, contrarily, the simulations are very inaccurate when using the default parameters.

Table 5.6. "Goodness-of-fit" indicators relative to AquaCrop adjustment of CC curve for all treatments when using the default and calibrated parameters, Sorraia Valley

	Treatment	***Goodness of fit indicators***				
		b	*R²*	*RMSE* (%)	*AAE* (%)	*EF*
Using default parameters	A	0.86	0.75	27.1	16.2	-2.1
	B	0.82	0.78	26.7	18.9	-2.2
	C	0.79	0.63	30.4	20.6	-2.3
	D	0.61	0.71	38.8	31.9	-7.4
	E	0.64	0.47	40.7	32.2	-5.8
	F	0.84	0.73	23.9	15.3	-0.4
	All data	0.81	0.71	28.9	19.4	-1.7
Using calibrated parameters	A	1.00	0.96	3.1	2.0	0.96
	B	0.99	0.88	5.3	3.8	0.87
	C	1.00	0.95	3.6	2.4	0.95
	D	1.03	0.80	6.7	5.9	0.75
	E	0.99	0.86	5.9	4.3	0.86
	F	0.96	0.91	6.6	5.0	0.90
	All data	0.99	0.92	5.1	3.6	0.91

The AquaCrop was tested for seasonal evapotranspiration calculations comparing, throughout the season, the field estimated ET (mm) with model simulations for all treatments. Fig. 5.8 shows that comparison for selected examples of full irrigation (treatment A), mild deficit irrigation (treatment B) and heavy deficit irrigation (treatment F). Results (Fig. 5.8 and Table 5.7) show that the heavy stress treatments present higher RMSE (6.5 mm vs. 5.1 mm) but no trends of over- or underestimation of ET were detected (b ranging from 0.98 to 1.02). Contrarily, there is a trend of underestimation of ET when default parameters are used (b from 0.87 to 0.97). EF values are acceptable, ranging 0.70 to 0.87 when calibrated parameters are used. EF values for the case of stressed experiments D to F highly decrease when default parameters are used (Table 5.7).

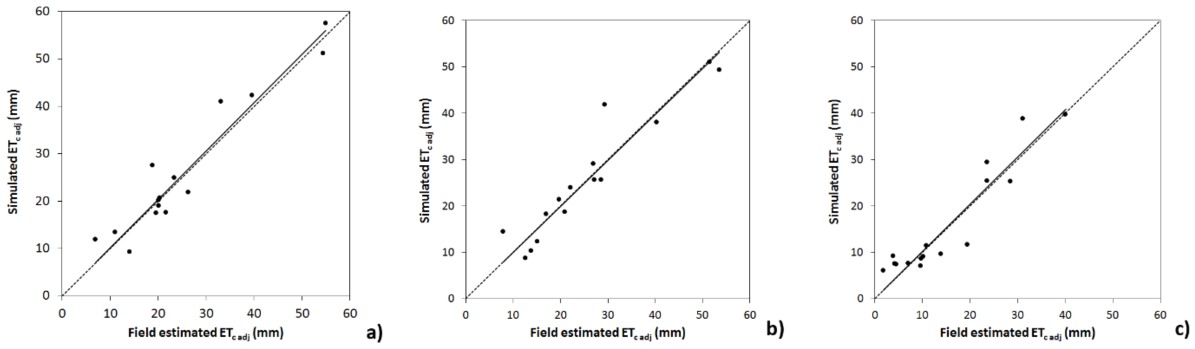


Fig. 5.8. Selected examples of field estimated vs. AquaCrop simulated crop evapotranspiration ($ET_{c\ adj}$) for selected Sorraia Valley treatments: a) full irrigation (treatment A); b) mild deficit irrigation (treatment B); and c) heavy deficit irrigation (treatment F)

Table 5.7. "Goodness-of-fit" indicators relative to ET simulations for all treatments when using default and calibrated parameters, Sorraia Valley experiments

	Treatment	*Goodness of fit indicators*				
		b	R^2	*RMSE* (mm)	*AAE* (mm)	*EF*
Using default parameters	A	0.91	0.89	5.0	4.0	0.87
	B	0.93	0.75	6.6	5.0	0.72
	C	0.91	0.87	5.7	4.9	0.85
	D	0.87	0.59	9.7	7.8	0.47
	E	0.88	0.60	8.6	6.4	0.49
	F	0.97	0.71	6.9	5.2	0.67
	All treatments	0.92	0.77	6.6	5.0	0.74
Using calibrated parameters	A	1.02	0.88	5.1	4.0	0.86
	B	1.02	0.83	5.4	3.9	0.82
	C	1.02	0.89	5.2	4.4	0.87
	D	0.98	0.76	6.7	5.3	0.75
	E	1.00	0.74	6.4	4.9	0.72
	F	1.01	0.74	6.5	4.9	0.70
	All treatments	1.02	0.81	5.7	4.3	0.81

Fig. 5.9 shows examples of the different responses of the adjusted crop coefficient - K_{cTr} in case of Aquacrop and $K_{cb\ adj}$ in case of SIMDualKc – to water stress, thus identifying a much larger dependency in case of $K_{cb\ adj}$ than for K_{cTr} because the latter is very much tied to the CC curve. Results show that in AquaCrop the impacts of water stress on transpiration are minimized due to the dependency of K_{cTr} and T_a upon CC, as discussed before. Contrarily, when adopting the approach by FAO56 that is considered in SIMDualKc (Allen et al., 1998, 2005; Rosa et al., 2012), $K_{cb\ adj}$ is sensitive to water stress. Following discussions in section 5.3.1, it can also be concluded that the K_{cTr} and CC curve proportionality should be revised and an approach similar to that adopted in FAO56 could be considered. These results indicate that model computations of the actual ET are less sensitive to the CC curve than soil water computations because the over-estimations of T_a partly compensates for the underestimation of E_s, thus resulting in small differences between estimated and observed ET.

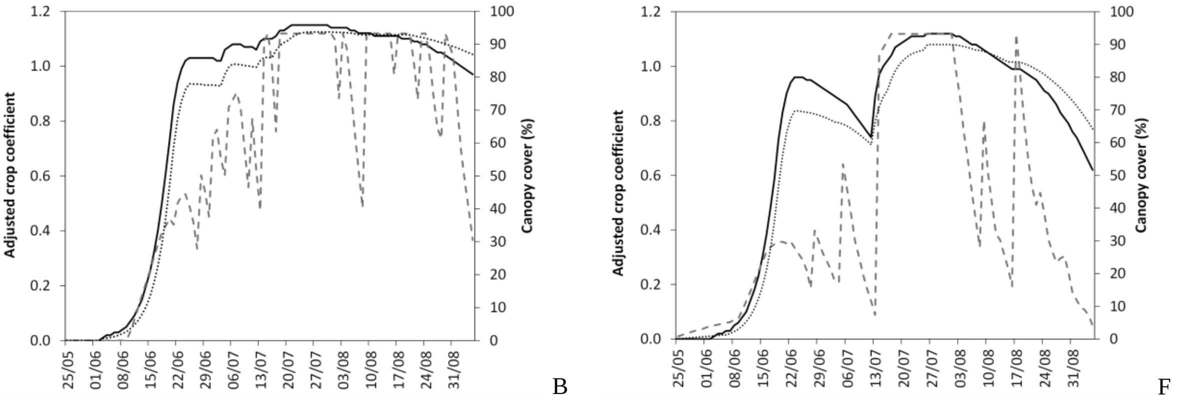


Fig. 5.9. Seasonal variation of the adjusted basal crop coefficient when using SIMDualKc, $K_{cb\ adj}$ (— —), and AquaCrop, K_{cTr} (——) compared with the canopy cover curve (·····) relative to selected examples of B and F treatments.

5.3.3. Evapotranspiration-yield relations, and biomass and yield predictions

The observed final harvested biomass, yield and the harvest index for the Alpiarça case study are presented in Table 5.8; these data was used to test AquaCrop predictions. Higher yields were obtained in field 1 in 2010 and 2011. The lowest yields were obtained in field 2 in 2010 due to poor irrigation management that did not avoid stress during flowering. The variation of yields observed was discussed by Paredes et al. (2014a) aiming at developing more appropriate management scenarios.

Table 5.8. Sowing and harvesting dates, dry final above ground biomass, yield and harvest index for all maize seasons and fields in Alpiarça

Field, year	Crop season dates		Harvested dry total above ground biomass (t ha^{-1})	Dry total yield (t ha^{-1})	Harvest index ()
	Sowing	Harvest			
Field 1, 2010	25/05	13/10	41.86(±8.37)	20.62(±4.14)	0.49(±0.04)
Field 2, 2010	25/05	13/10	26.27(±5.25)	12.78(±2.56)	0.49(±0.03)
Field 1, 2011	20/04	20/09	40.02(±5.86)	19.46(±2.97)	0.49 (±0.01)
Field 2, 2012	16/04	20/09	38.70(±7.09)	19.32(±2.63)	0.50(±0.05)
Field 3, 2012	30/05	12/10	33.62(±7.64)	16.53(±3.72)	0.49(±0.04)

*Standard deviation of observations between brackets

The observed average final harvested biomass and yield and the harvest index for all treatments in the Sorraia Valley are presented in Table 5.9. Results show that higher biomass and yield was attained for the full irrigation treatment (A) followed by the treatment where stress was imposed later in the season (C). Treatment F, where stress was imposed along the crop season, produced the lowest total biomass and yield.

Table 5.9. Dry final above ground biomass, yield and harvest index for all maize treatments (Alves et al., 1991)

Treatment	Dry total above ground biomass (t ha^{-1})	Dry total yield (t ha^{-1})	Harvest index ()
A	26.57(±3.42)	12.15(±1.20)	0.48(±0.02)
B	21.61(±2.19)	10.03(±1.27)	0.46(±0.05)
C	25.02(±0.96)	12.23(±0.40)	0.45(±0.08)
D	17.59(±0.88)	6.65(±0.26)	0.38(±0.01)
E	19.06(±0.27)	7.11(±1.13)	0.38(±0.07)
F	14.02(±0.39)	6.66(±0.98)	0.47(±0.06)

*Standard deviation of observations between brackets

A linear relationship between yield (Tables 5.8 and 5.9) and $ET_{c\ adj}$ and with T_a was observed. Fig. 5.10 presents these relationships using all experimental data relative to both maize hybrids LG18 (FAO 300) and PR33Y74 (FAO 600). The approach adopted herein of using field observations relative to different hybrids and observation years for yield predictions was also adopted by others, e.g., Retta and Hanks (1980), Liverman et al. (1986) and Paredes et al. (2014a). Results in Fig. 5.10 indicate a similar behaviour of these hybrids. They also indicate that using the yield-T_a relationship is preferable to the one between yield and $ET_{c\ adj}$. Not only R^2 is higher but, as observed by other authors (Stewart et al., 1977; Payero et al., 2006; Raes et al., 2012; Paredes et al., 2014a), using the yield-T_a relationship avoids the variability due to the soil evaporation component, which depends upon crop and irrigation management, and refers only to transpiration that is directly responsible for yield.

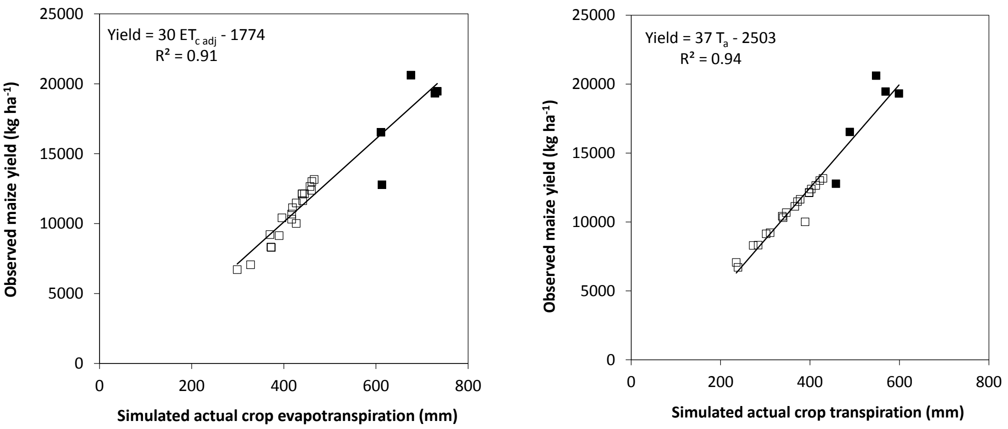


Fig. 5.10. Relationship between maize seasonal evapotranspiration ($ET_{c\ adj}$) and yield (on left), and between transpiration (T_a) and yield (on right) using observed yield using data from all fields of Alpiarça (■) and from all experiments of Sorraia Valley (□).

All data relative to biomass and yield from all the above described case studies (Tables 5.8 and 5.9) were used to assess the model accuracy in predicting maize biomass and yield (Fig. 5.11). When calibrated parameters were used, there was no trend in biomass estimation (Fig. 5.11a) but just a slight trend for over-estimation of yield (Table 5.10). The b value is close to 1.0 for biomass predictions and b = 1.05 for final yield estimation. If default parameters are used then under-estimations occur, with $b \leq 0.84$ and RMSE doubling those observed when calibrated parameters are used. With default parameters, EF is relatively low (<0.70) but is higher when using calibrated parameters ($EF \geq 0.81$), thus indicating that the residuals variance is much smaller than the observed data variance. Results for biomass and yield predictions therefore evidence the advantage in using appropriately calibrated parameters. The yield over-estimation by AquaCrop is likely related to the above referred insufficiencies in the partition of $ET_{c\ adj}$ into E_s and T_a, the latter being over-estimated.

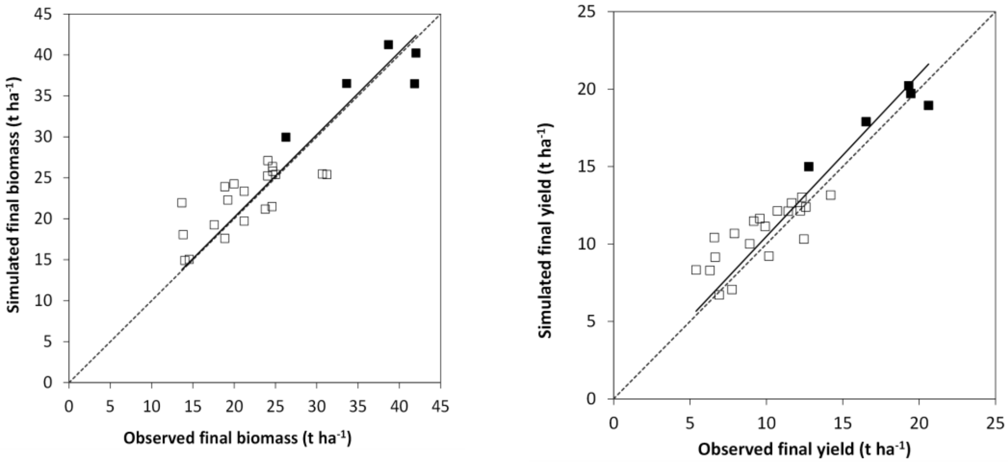


Fig. 5.11. Maize actual and simulated final biomass (t ha^{-1}), on left, and yield (t ha^{-1}), on right, using data from all fields of Alpiarça (■) and from all experiments of Sorraia Valley (□).

Table 5.10. "Goodness-of-fit" indicators relative to model prediction of biomass along the crop season, and yield using data from both case studies, when using default and calibrated parameters

		Goodness of fit indicators				
		b	*R^2*	*RMSE* (t ha^{-1})	*AAE* (t ha^{-1})	*EF*
Biomass along crop season	Default	0.75	0.91	7.21	5.71	0.70
	Calibrated	0.97	0.92	3.83	2.83	0.92
Final dry biomass	Default	0.84	0.77	6.14	4.71	0.41
	Calibrated	1.01	0.82	3.49	2.93	0.81
Final yield	Default	0.84	0.82	2.51	1.77	0.63
	Calibrated	1.05	0.87	1.73	1.45	0.82

Hsiao et al. (2009), Heng et al. (2009) and García-Vila and Fereres (2012) used AquaCrop for predicting maize final dry biomass and reported RMSE values similar to the bulk value given in Table 5.10. However, the RMSE reported by Heng et al. (2009) for deficit irrigation are larger. Applications of different models led to comparable results, e.g., López-Cedrón et al. (2005) using CERES-Maize, and Ma et al. (2006) with DSAAT-Ceres and RZWQ-CERES. The RMSE results for yield prediction (Table 5.10) are also comparable with other AquaCrop maize applications, e.g., Heng et al. (2009) and García-Vila and Fereres (2012), as well as with RMSE obtained with different models such as Ma et al. (2006) with the DSAAT-Ceres and RZWQ-CERES models, López-Cedrón et al. (2005), Liu et al. (2011) and DeJonge et al. (2012) with CERES-Maize, Monzon et al. (2012) with CropSyst and CERES-Maize, Cavero et al. (2000) with the EPIC model. In a previous study, using the same case studies data, Paredes et al. (2014a) combined the soil water balance model SIMDualKc with both the global and multi-phasic Stewarts' models and obtained RMSE of 1.80 and 1.21 t ha^{-1}, respectively, i.e., achieved better results with that simplified approach than with AquaCrop.

4. Conclusions

The AquaCrop model was tested using a set of calibrated parameters describing the canopy cover, ET, soil water content, and biomass and yield observed in large farm fields at Alpiarça and in experimental fields at the Sorraia Valley. It was further tested for the same locations using the default parameters provided by Raes et al. (2012). Results showed that a correct calibration of the canopy cover curve parameters highly improved the models' performance because the CC curve is used by the model for daily computations of crop transpiration and soil evaporation. Naturally, if the CC curve adheres to field canopy data it is likely that the resulting transpiration and evaporation estimates are better than those obtained using default parameters.

Results showed an insufficient accuracy of the model in simulating the soil water content dynamics along a crop season particularly if default parameters are used. Therefore, AquaCrop is not suitable for irrigation scheduling purposes. Problems were also identified relative to daily ET calculation and its partition. The adjusted basal crop coefficient is extremely tied to the CC curve, thus less influenced by water stress and leading to over-estimation of plant transpiration. Similarly, soil evaporation is underestimated because it is also made dependent on the CC curve. Nevertheless, the cumulative ET throughout the season could be simulated quite well since the over-estimation of T_a is compensated by the under-estimation of E_s. It is therefore advisable to revise the ET partition, using the approaches proposed in FAO56.

Good prediction results were obtained for biomass and crop yield when using properly calibrated parameters. Results showed a slight under-estimation of biomass along the crop season but relatively small errors of estimates were obtained for the final harvested biomass. Differently, the estimations of the final yield have shown a tendency for over-estimation (b = 1.05) but with low estimation errors. The referred over-estimations are likely related to the model trend of overestimating transpiration, which is the main driving variable used for yield estimation. When default parameters are used, final biomass and yield estimation have a larger error, nevertheless acceptable for most applications when field data are not available. Summarizing, overall results show adequacy of AquaCrop for estimating biomass and yield.

Results evidence that when using the model for research purposes, thus when high accuracy is desired, it is required to calibrate the canopy cover curve using field data. If the model is to be used for management purposes, it is also necessary to calibrate the model for soil water or ET simulation. Calibration/parameterization is also advisable when accuracy in biomass and yield predictions are desired. However, it is desirable that model developers improve the estimations relative to the components of the water balance, mainly aiming at improving the estimation of transpiration, which has major influence on yield estimation.

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Capítulo 6 - Comparing sprinkler and drip irrigation systems for full and deficit irrigated maize using multicriteria analysis and simulation modeling: ranking for water saving vs. farm economic returns

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Comparing sprinkler and drip irrigation systems for full and deficit irrigated maize using multicriteria analysis and simulation modeling: ranking for water saving vs. farm economic returns

Abstract

This study aims to assess the economic feasibility of full and deficit irrigated maize using center pivot, set sprinkler systems and drip tape systems through multicriteria analysis. Different irrigation treatments were evaluated and compared in terms of beneficial water use and physical and economical water productivity for two commodity prices and three irrigation systems scenarios applied to a medium and a large field of 5 and 32 ha respectively. Results show that deficit treatments may lead to better water productivity indicators but deficit irrigation (DI) feasibility is highly dependent on the commodity prices. Various well-designed and managed pressurized irrigation systems' scenarios - center pivot, set sprinkler systems and drip tape systems - were compared and ranked using multicriteria analysis. For this, three different prioritization schemes were considered, one referring to water savings, another relative to economic results, and a third one representing a balanced situation between the first two. The rankings of alternative solutions were very sensitive to the decision-maker priorities, mainly when comparing water saving and economic results because the selected alternatives were generally not common to both priority schemes. However, some of the best alternatives for the balanced priorities scheme are common to the other two, thus suggesting a possible trade-off when selecting the best alternatives. Deficit irrigation strategies also rank differently for the various scenarios considered. The study shows that deficit irrigation with exception of mild DI is generally not economically feasible. The adoption of well designed and managed irrigation systems requires consideration of priorities of farm management in terms of water saving and economic results since that some water saving solutions do not allow appropriate recover of the investment costs, particularly with DI. Basing decisions upon multicriteria analysis allows farmers and decision-makers to better select irrigation systems and related management decisions. Results also indicate that appropriate support must be given to farmers when adopting high performance but expensive irrigation systems aimed at sustainable crop profitability.

Keywords: Economic water productivity, irrigation and production costs, deficit irrigation, multicriteria analysis, alternative irrigation systems.

6.1. Introduction

Maize is one of the main crops in Portugal. It is the fourth most produced commodity in the country, averaging more than 760 thousand tonnes from 1992 to 2010 (FAO, 2012a). The percentage of the cultivated area equipped for irrigation increased from 28.87 to 30.75% from 1990 to 2007 (FAO, 2012b) and the agricultural sector is responsible for more than 73% of the country total water withdrawal. With the increasing water scarcity, there is the need to optimize water use, mainly for irrigation purposes (Pereira et al., 2009). Thus, farmers are forced to adopt improved irrigation managements in order to optimize water use, including the adoption of deficit irrigation and enhancing irrigation performance, thus leading to higher water productivities (WP). The pathway to achieve an efficient irrigation water use imposes the need to systematically optimise the soil and water management practices and the irrigation equipment (Knox et al., 2012).

The optimization of water use and productivity, whose indicators are defined by Pereira et al. (2012), may be achieved through the adoption of deficit irrigation (DI). DI consists of deliberately applying irrigation depths smaller than those required to fully satisfy the crop water requirements but keeping a positive economic return. Many authors assessed the impacts of DI on maize yields (Cabelguenne et al., 1999; Farré and Faci, 2009; Popova and Pereira, 2011; Ma et al., 2012), water productivity (Payero et al., 2009; Katerji et al., 2010) and economic returns (Rodrigues and Pereira, 2009; Abd El-Wahedand and Ali, 2012; Dominguez et al., 2012). Consequently, authors searched irrigation schedules that could achieve the feasibility of DI because this technique highly depends upon the adopted management, i.e., when those deficits are applied (Bergez et al., 2004), as well as on irrigation and water costs (Kampas et al., 2012; Montero el al., 2012). Modelling can play a main role in determining rational deficit irrigation schedules (Mailhol et al., 2011; DeJonge et al., 2012; Ma et al., 2012).

Higher WP may be achieved by adopting high performance irrigation systems, having high distribution uniformity (Pereira et al., 2002; 2009). Numerous studies show that there is great potential to achieve a more efficient water use, mainly through an enhanced distribution uniformity when improving surface irrigation (Raghuwanshi and Wallender, 1998; Horst et al., 2007; Gonçalves et al., 2011) or pressurized sprinkler and drip irrigation (Namara et al., 2007; Pedras et al., 2009; López-Mata et al., 2010; Ørum et al., 2010; Mailhol et al., 2011;

Abd El-Wahed and Ali, 2012; van Donk et al., 2012). Choosing the most suitable irrigation system involves numerous factors, such as irrigation scheduling, soils, system performance, irrigation costs, and the performance of the off farm systems. The latter are particularly important because adopting an optimized irrigation scheduling in collective irrigation systems requires that off farm systems are dependable and reliable in terms of discharges and time of deliveries in surface irrigation systems (Gonçalves et al., 2007; Zaccaria et al., 2010), and in terms of timing, discharge and pressure in case of pressurized systems (Lamaddalena and Pereira, 2007; Lamaddalena et al., 2007; Calejo et al., 2008). The adoption of more uniform systems involves a trade off between increased capital expenditure on equipment and the benefits associated with reduced water application when it is uniformly distributed (Bernnan, 2007).

When modelling to rank the best irrigation management alternatives, simulation outputs may be difficult to handle and the selection of the most feasible alternatives may be hard to achieve. However, a variety of design and management alternatives can be created and then ranked by adopting multicriteria analysis (MCA) (Roy and Bouyssou, 1993; Pomerol and Romero, 2000), multi-attribute modelling (Bartolini et al., 2007), or multi-objective optimization (Groot et al., 2012). When aiming at combining different actors in decision-making, e.g., farmers and stakeholders, instead of ranking solutions, fuzzy cognitive mapping may be used; however, few studies have been applied to irrigation (Giordano et al., 2007; Mouratiadoua and Moranb, 2007; Kafetzis et al., 2010). MCA proves to be a useful approach that can incorporate a mixture of quantitative and qualitative information and take into account the preferences of users. Various applications of MCA to irrigation are reported in the literature (Tecle and Yitayew, 1990; Bazzani, 2005; Manos et al., 2006; Riesgo and Gómez-Limón, 2006; Bartolini et al., 2010) and are applied to irrigation systems design (Gonçalves et al., 2007, 2011; Pedras et al., 2009; Darouich et al., 2012).

Considering the aspects analysed above and previous developments by Rodrigues and Pereira (2009), the main goal of this study is to assess the economic impacts of water deficits, commodity prices and enhanced irrigation systems performance on the physical and economic water productivity of irrigated maize in the Vigia Irrigation District, Southern Portugal. Multicriteria analysis is adopted to rank alternative solutions and help understanding contradictory results due to assigning priorities to water saving *vs.* farm economic results.

6.2. Material and methods

6.2.1. Yield responses to irrigation

The maize yield response to water was derived using several field treatments that were designed to determine the impacts of deficit irrigation in different stages of the maize crop season on yield. These experiments were performed at the António Teixeira Experimental Station, located in the Sorraia Valley, near Coruche, Portugal. A description of the experiments is given by Alves et al. (1991). The SIMDualKc model adopted in this study was calibrated/validated for maize in the same area, with the description of the experimental area, soils and climate being given by Rosa et al. (2012b).

Field experiments were performed with maize (*Zea mays* L.) var. LG18 (FAO 300) with a plant density of around 90,000 plants ha^{-1} during 1989 (Alves et al., 1991). Maize was sown by 10 May and maturation, depending on the irrigation treatment, was reached during the period 29 August to 5 September. Harvest was performed for all treatments by 5 September. Using a line-source system, seven different irrigation schedules, with various replications, were adopted, including full and deficit irrigation treatments and considering three crop development stages: vegetative, flowering and maturation (Alves et al., 1991).

Due to heavy yield losses associated with stress at the mid season stage, from flowering to maturation, imposing stress during that period have been shown to be economically unfeasible as observed by several authors (Stewart and Hagan, 1973; Stewart et al., 1977; NeSmith and Ritchie, 1992; Karam et al., 2003; Farré and Faci, 2009); thus the corresponding treatments are not considered in the present study. The four treatments analysed herein differ in the timing that the stress was implemented:

- A – full irrigation with application of the required irrigation water depth in all the selected crop development stages;
- B – stress imposed during the vegetative stage;
- C – stress imposed during maturation and;
- D – stress imposed during the vegetative and maturation stages.

The irrigation timing was assessed using infra-red thermometers (Jackson, 1982; Alves and Pereira, 2000). This experiment allowed verifying that the transpiration rate did not decrease during the 5 to 6 days following an irrigation event, with this irrigation interval being adopted thereafter to meet evapotranspiration demand (Alves et al., 1991).

The actual yield was assessed by harvesting 7 plants for each replication treatment. The yield was evaluated at 13% grain moisture (Popova et al., 2006; Popova and Pereira, 2011).

To estimate the impacts of water on yield the Stewart et al. (1977) single (S1) and multiphasic (S2) models were used. The model S1 gives an average yield reduction factor for the entire crop growth season (K_y), with

$$Y_a = Y_m - Y_m K_y (T_d/T_m) \tag{6.1}$$

where Y_m and Y_a are, respectively, the maximum (expected) yield of the crop in absence of environmental or water stresses and the actual yield obtained under stress conditions, both expressed in kg ha^{-1}; T_d is the transpiration deficit defined as the difference between maximal (T_m) and adjusted transpiration (T_{adj}), all expressed in mm. In the field studies described above, Alves et al. (1991) obtained $K_y = 1.32$ when Y_m was the highest yield achieved in the full irrigation Treatment A, where no stress was observed.

Since the maize crop exhibits different sensitivities to water stress throughout the growing cycle, the experiments allowed to use and parameterize the S2 model

$$Y_a = Y_m - Y_m (\beta_v T_{d,v} + \beta_f T_{d,f} + \beta_m T_{d,m})/T_m \tag{6.2}$$

where β_v, β_f and β_m are the yield reduction factors for each crop growth stage (vegetative, flowering and maturation) and $T_{d,v}$, $T_{d,f}$ and $T_{d,m}$ are the transpiration deficits for the same crop stages. The yield response factors for the S2 model were $\beta_v = 1.2$ and $\beta_m = 2.1$; β_f, was not considered in the current study.

6.2.2. Water Productivity and Water Use Indicators

The water productivity concepts used are those defined by Pereira et al. (2012). The total water productivity (WP, kg m^{-3}) is:

$$WP = \frac{Y_a}{TWU} \tag{6.3}$$

where Y_a is the adjusted (actual) yield achieved (kg) and TWU is the total water use (m^3). Y_a varied with the DI management adopted and TWU varied with the performance of the irrigation systems (referred in the next Section) and with the DI management considered. Replacing the numerator of equation (3) by the monetary value of the achieved yield, it results the economic water productivity (EWP, € m^{-3}):

$$EWP = \frac{\text{Value }(Y_a)}{TWU} \tag{6.4}$$

In addition, to better consider the economics of production, a ratio expressing both the numerator and the denominator in monetary terms is used. This ratio is named economic water productivity ratio (EWPR) and relates the yield value with the full farming costs when TWU is the amount of water used to achieve Y_a, i.e., also depending on the farm irrigation system considered:

$$EWPR_{\text{full-cost}} = \frac{\text{Value}\left(Y_a\right)}{\text{Cost}\left(TWU\right)} \tag{6.5}$$

Pereira et al. (2012) also proposed new water use indicators aimed at distinguishing between beneficial and non-beneficial water use, which is important from the water economy perspective. The beneficial water use fraction (BWUF) is defined as the fraction of total water use that is used to produce the actual yield, i.e., it corresponds to the ratio between the actual crop ET and the TWU as computed with the SIMDualKc model as described in Section 6.2.4.

6.2.3. Scenario characterization

Two different approaches were conducted in this study to assess the feasibility of full and deficit irrigated maize. The first consists in comparing the results relative to selected irrigation treatments when considering different scenarios on DI management and commodity prices. The second compares different well-designed and managed pressurized irrigation systems – center pivot and set sprinkler systems and drip tape systems - when used with base data relative to various full and deficit irrigation treatments. Two field sizes are considered, 5 and 32 ha, representing small to medium and large to medium size farms at Vigia Irrigation System, southern Portugal. Vigia has been object of previous studies (Calejo, 2003; Rodrigues and Pereira, 2009; Rodrigues et al., 2010a).

Two commodity prices scenarios were considered to assess the feasibility of farming maize under different deficit irrigation management. The commodity prices refer to the grain yield prices of 154 and 264 € t^{-1}, referred herein as "low" and "high" prices, respectively. The low price corresponds to a pessimist scenario that occurred in 2008. Contrarily, the second price refers to 2011, which is the reference year for all costs and prices.

Weather and soils data

Meteorological data for Vigia are those relative to the nearby station of Évora (38.77ºN, 7.71ºW, and 472 m elevation), which are reported in Table 6.1, both for the last decade and the maize season of 2011 used for simulation. Data refers to the reference evapotranspiration (ET_o), the climatic variables used to compute ET_o, and rainfall. ET_o was computed daily with the FAO-PM method (Allen et al., 1998).

Table 6.1. Monthly average climatic data, Évora, maize season of 2011 and average for 2002-2012

	May		Jun		Jul		Aug		Sep	
	2002-12	2011	2002-12	2011	2002-12	2011	2002-12	2011	2002-12	2011
Max. air temperature, ºC	25.4	27.7	30.5	30.2	32.7	32.0	33.9	32.3	30.4	30.9
Min. air temperature, ºC	10.1	12.7	13.3	12.3	14.4	13.7	15.0	14.7	13.4	12.9
Min. Relative Humidity, %	37.2	40.1	32.9	32.5	28.5	29.6	27.8	30.6	33.5	31.9
Max. Relative Humidity, %	93.7	94.6	91.4	91.2	89.1	89.7	88.3	90.5	90.6	91.8
Wind Speed, m s^{-1}	2.2	1.5	2.2	2.1	2.5	2.9	2.2	2.2	1.9	1.7
Solar radiation, MJ m^{-2} d^{-1}	22.0	21.7	24.6	25.7	25.9	26.2	22.5	21.7	17.3	17.9
ET_o, mm d^{-1}	4.2	4.1	5.3	5.3	5.9	6.0	5.4	5.1	3.8	3.8
Precipitation, mm	38.2	26.8	15.1	15.8	0.9	0.6	3.1	7.6	40.6	33.2

Note: All climatic variables were obtained averaging daily data except for precipitation that represents the monthly accumulation

Soil data are summarized in Table 6.2. They consist of textural and basic soil hydraulic properties of the Vigia fields. The total available soil water (TAW, mm) was computed from field capacity θ_{FC} (m^3 m^{-3}) and wilting point θ_{WP} (m^3 m^{-3}) as defined by Allen et al. (1998). Following the model test by Rosa et al. (2012b) and the soil properties in Table 6.2, the following soil evaporation characteristics were adopted: total evaporable water TEW = 38 mm, readily evaporable water REW = 9 mm, and thickness of the evaporation soil layer Z_e = 0.15 m. The definitions proposed by Allen et al. (1998) were adopted for all soil variables.

Table 6.2. Soil physical and hydraulic properties and total available water (TAW)

Soil layer depth (m)	Coarse sand (%)	Fine sand (%)	Loam (%)	Clay (%)	θ_{FC} (m^3 m^{-3})	θ_{WP} (m^3 m^{-3})	TAW (mm)
0.00-0.20	38.4	39.4	12.2	10.0	0.33	0.11	44.0
0.20-0.50	23.0	33.0	15.8	28.2	0.34	0.18	48.0
0.50-1.00	34.4	40.9	10.3	14.4	0.33	0.15	90.0

θ_{FC} is for field capacity, θ_{WP} for wilting point and TAW for total available soil water

Crop data

A FAO 600 maize variety (NK Famoso) with a planting density of approximately 90,000 plants ha^{-1} was used in the simulations. Y_m was obtained using the modified approach of the 'Wageningen' method (Doorenbos and Kassam, 1979) and taking into account the average yield values observed in the Vigia area; Y_m was set at 16,860 kg ha^{-1}. The dates of crop growth stages, basal crop coefficients (K_{cb}), soil water depletion fractions for no stress (p), root depths (Z_r, m), crop heights (h, m), and fractions of soil cover by vegetation (f_c) are given in Table 6.3. h and f_c vary with treatments and management. The fraction wetted by rain and sprinkler irrigation was f_w = 1.0; for drip irrigation f_w was 0.6. K_{cb} values were obtained from the SIMDualKc model when using observations of the soil water balance (Alves et al., 1991), whose global results are shown in Section 6.3.1. The adjusted crop evapotranspiration ($ET_{c\ adj}$) was then obtained from SIMDualKc simulations.

Table 6.3. Crop growth stages and related crop parameters for maize

	Treatments	Initial	Crop development	Mid season	End season
Period lengths	A	10 May – 16 Jun	17 Jun – 15 Jul	16 Jul – 28 Aug	28Aug – 20 Sep
	B	10 May – 16 Jun	17 Jun – 22 Jul	23 Jul – 30 Aug	01 Sep – 20 Sep
	C	10 May – 16 Jun	17 Jun – 16 Jul	17 Jul – 28 Aug	29 Aug – 20 Sep
	D	10 May – 16 Jun	17 Jun – 19 Jul	20 Jul – 02 Sep	03 Sep – 20 Sep
K_{cb}		0.15	0.15 - 1.15	1.15	1.15 – 0.40
p		0.65	0.65	0.65	0.65
Z_r (m)		0.20	0.40	1.00	1.00
h (m)	A	0.10	0.50 - 1.00	2.85	
	B	0.10	0.50 - 1.00	2.50	2.50
	C	0.10	0.50 - 1.00	2.50	2.50
	D	0.10	0.50 – 1.00	2.00	2.00
f_c	A	0.1	0.59	0.97	0.92
	B	0.1	0.45	0.91	0.88
	C	0.1	0.45	0.95	0.80
	D	0.1	0.45	0.91	0.79

K_{cb} = basal crop coefficients; p = depletion fraction for non-stress; Z_r = root depth; h = crop height; f_c = fraction of ground cover by the canopy

6.2.4. Models

The simulation scenarios relative to the various farm irrigation systems were developed considering the actual characteristics of systems operating in Vigia. The considered farm irrigation systems were designed with the support of three different models: DEPIVOT (Valín et al., 2012) for center-pivot irrigation, MIRRIG (Pedras et al., 2009) for drip irrigation, and PROASPER (Rodrigues et al., 2010b) for set sprinkler systems. The irrigation management scenarios were simulated with the SIMDualKc model (Rosa et al., 2012a).

DEPIVOT consists of a simulation model allowing the development and evaluation of sprinkler packages for center-pivots. The model performs various computations including: (1) sizing of the lateral pipe spans; (2) selection of the sprinklers package; (3) estimation of potential runoff; and (4) estimation of the expected performance indicators when in operation, mainly the distribution uniformity. To size the lateral pipes, both the friction losses and the effects of topography are considered. This allows estimating the pressure and discharge at each outlet, recognizing when pressure regulators are required. Once the sprinkler package is known, the model compares the application and infiltration rates at various locations along the lateral to estimate the runoff potential. The computations can be reinitiated as many times as necessary until the user verifies that the expected performance is within target values (Valín et al., 2012). Main input data consisted of: net applied depth, D = 12 mm; percentage of area adequately irrigated, pa = 95%; system pressure not exceeding 150 and 300 kPa for the 5 ha and 32 ha fields, respectively; sprayers on drop to limit wind and interception losses. The infiltration rate curve applied was

$$I = k_p\, t^a \tag{6.6}$$

were I is the infiltration rate (mm h^{-1}), t is time (h), k_p and α are empirical parameters. For the Vigia soil and after a field experiment, k_p = 6.070 mm h^{-a} and a =-0.891. Main characteristics of the center-pivot systems are included in Table 6.4. The terrain is nearly flat with a slope ranging from 0.5 to 2%; runoff was null for the small field and about 9% of D for the 32 ha field. As discussed by Pereira et al. (2002) and previously adopted by Rodrigues and Pereira (2009), it was assumed that the potential application efficiency relative to the lower quarter (PELQ) could be estimated by the distribution uniformity (DU); actual efficiency may be lower depending upon farmer’s management.

Table 6.4. Main characteristics and costs of farm irrigation systems

System scenario	Irrigated area (ha)	Discharge (l h^{-1})	System pressure (kPa)	Emitter spacing (m)	DU (%)	Potential application efficiency (%)	Investment annuity (€ ha^{-1})	Maintenance annual cost (€ ha^{-1})
Center-Pivot	5	80 to 270	150	variable	83.5	83.5	345	35
	32	80 to 750	290		90.8	87.3	152	21
Set Sprinkler	5	890	214	14 x 14	84.1	84.1	289	75
	32						270	70
Drip	5	1.10	118	0.2 x 1.4	93.8	93.8	867	120
	32						815	112

The PROASPER model was developed to support farmers in decision-making on set sprinkler systems design and evaluation. The model includes modules for design, simulation and performance analysis. Design is performed either through indirect control by the user (optimized simulation) or direct interactive calculations as selected by the user. Opting for indirect control, the simulation is performed to optimize the design, with automatic search in the database of the characteristics of the pipes and sprinklers that meet the user's previous choices in terms of spacing, length and performance. When the user directly controls the simulation, messages are displayed that indicate if design conditions are not being met prompting the user to search for appropriate solutions. The model allows obtaining a set of results related to pipes' system sizes, hydraulic pressure and discharge of each sprinkler and their variation across the system, as well as performance indicators (Rodrigues et al., 2010b). Main input data were D = 12 mm; pa = 95%; system pressure limited to 250 kPa; infiltration rate given by Equation 6. PELQ was assumed equal to DU as in a former application to Vigia (Rodrigues and Pereira, 2009). Main characteristics of the set system are also in Table 6.4.

MIRRIG is aimed at designing microirrigation systems, i.e., drip and microsprinkling set systems. MIRRIG is composed by design and simulation models, a multicriteria analysis model and a database. Various alternative design solutions are created and then ranked based upon an integration of technical, economic and environmental criteria. Design alternatives refer to the layout of the pipe system, the pipe characteristics and the emitters, either drippers or microsprinklers. The model components include: (1) a design module to iteratively size the pipe and emitters system; and (2) a performance analysis module that simulates the functioning of the system and computes various indicators used as attributes of the alternatives relative to the design criteria adopted for MCA (Pedras et al., 2009).Main input data consisted of: drip tape on the surface and double row irrigation; D = 8 mm; fw = 0.6; pressure not exceeding 120 kPa; target DU >90%; infiltration as for other cases. Relevant system characteristics are included in Table 6.4 with PELQ also assumed equal to DU following field observations (Pereira, 2007).

The model SIMDualKc adopts the dual crop coefficient approach as proposed by Allen et al. (1998, 2005) to calculate ET_c considering the E and T components separately. The model is described in detail by Rosa et al. (2012a) and its test with field data on maize is presented by Rosa et al. (2012b). Weather, soils, crop and irrigation data used in this application are described above (Tables 6.1, 6.2 and 6.3). Simulations with SIMDualKc were performed for various scenarios relative to the allowed soil water depletion (ASWD) thresholds as described in Table 6.5, which are defined in relation to the soil water depletion fractions for no stress (p). Treatments are those defined in Section 6.2.1.

Table 6.5. Allowed soil water depletion fractions (ASWD) relative to each treatment and crop stage.

Treatments	Imposed stress during maize development stages			
	Initial	Development	Mid	End
A	ASWD=p × TAW	ASWD=p × TAW	ASWD=p × TAW	ASWD=p × TAW
B	ASWD=1.2p × TAW	ASWD=p × TAW	ASWD=p × TAW	ASWD=p × TAW
C	ASWD=p × TAW	ASWD=p × TAW	ASWD=p × TAW	ASWD=1.2p× TAW
D	ASWD=1.2p × TAW	ASWD=1.05p × TAW	ASWD=p × TAW	ASWD=1.2p × TAW

6.2.5. Investment, operation and production costs

Data for labour, machinery, seeds, fertilizers and irrigation costs were obtained from regional data for 2008. These data were adjusted to 2011 considering the average annual inflation rate, resulting in the values presented in Table 6.6.

Investment costs (C_{inv}, €) were computed for each system scenario. They comprise the pump, the pipe system, and the chosen emitter package for all irrigation system scenarios defined in Table 6.4. The investment annuity A_{inv} (€ $year^{-1}$) relative to the investment cost C_{inv} is

$$A_{inv} = CRF\ C_{inv} \tag{6.7}$$

where CRF is the capital recovery factor. A_{inv} was computed for center-pivot equipment (including pump, pump pipe, distribution pipe and center-pivot) considering a life-time of n = 24 years and n = 12 years for the sprinklers. For the set sprinkler irrigation system, the life-time for all system components was n = 15 years. For the drip irrigation system, different life-times were considered: n = 15 years for the PVC pipes, n= 10 years for the PE pipes, and n = 2 years for the drip tape.

Table 6.6. Production costs.

Category	Cost
Seeds (€ ha^{-1})	243.5
Labour (€ ha^{-1})	
Farm	101.0
Irrigation	25.8
Fertilizers (€ ha^{-1})	1013.7
Machinery (€ ha^{-1})	527.2
Grain Drying (€ t^{-1})	15.6
Electricity (€ kWh^{-1})	0.13
Water Cost	
Fixed (€ ha^{-1})	52.0
Variable (€ m^{-3})	0.03

Computations were performed assuming an interest rate i = 5%. CRF was then calculated from the life-time n (years) and the interest rate i as:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{6.8}$$

The investment annuity per unit of irrigated area is C_a (€ ha^{-1} $year^{-1}$), which is the ratio of A_{inv} by the irrigated area.

The operation costs were obtained from the sum of the annual energy costs (C_{en}), the energy demand tax (C_d), and the annual maintenance costs (C_m). C_{en} is calculated as:

$$C_{en} = P_p \, E_r \, T_i \tag{6.9}$$

where P_p is the power of the pumping station (kW), E_r is the energy rate (€ kWh^{-1}), and T_i is the total operation time (h) of the pump required annually. The energy cost per unit irrigated area (€ $year^{-1}$ ha^{-1}) is calculated by dividing C_{en} by the irrigated area. Calculations are based in energy prices presented in Table 6.6. The annual maintenance costs (C_m) are considered to be an additional 1%, 2.5% and 5% of the investment cost for center-pivot, set sprinkler and drip irrigation systems, respectively.

The scenarios considered for the irrigation systems designed through application of the above referred models are characterized in Table 6.4, which includes the chosen emitter package-discharge, system working pressure, spacing, distribution uniformity (DU) and seasonal application efficiency, as well as the investment annuity and annual maintenance costs for each farm irrigation system scenario.

6.2.6. Criteria, attributes and priorities

In order to characterize the irrigation system scenarios, performance indicators were defined including the economic land productivity, irrigation costs, total production costs, BWUF, TWU, WP and EWPR. The adopted criteria to perform MCA were represented by attributes and scaled according to measures of utility using utility functions that enable variables having different units to be compared. The utilities U_j relating to any criterion j were normalized into the [0-1] interval, with zero for the more adverse and 1 for the most advantageous result. Linear utility functions were applied:

$$U_j(x_j) = \alpha . x_j + \beta \tag{6.10}$$

where x_j is the attribute, α is the graph slope and β is the utility value $U_j(x_j)$ for a null value of the attribute. The slope, α, is negative for criteria like costs and water use, whose highest values are the worst, and positive for other criteria like WP and EWPR, where higher values are the best. Criteria attributes and utility functions are presented in Table 6.7. This approach is similar to the one described by Gonçalves et al. (2011) and Darouich et al. (2012).

Table 6.7. Criteria attributes, utility functions and criteria weights.

Attributes (x)	Units	Utility function	Weights (%) for the attributes in condition of		
			Balance among economics and water saving	Priority to water saving	Priority to economic results
Economic					
Economic land productivity	€ ha^{-1}	$U(x) = 0.22 \times 10^{-3}\, x$	14	5	22
Irrigation costs	€ m^{-3}	$U(x) = 1 - 1.47x$	14	6	22
Total production costs	€ m^{-3}		14	6	22
Economic water productivity ratio	–	$U(x) = 0.60x$	14	5	22
Water Saving					
Beneficial water use fraction	–	$U(x) = 1.02x$	14	26	4
Total water use	$m^3\ ha^{-1}$	$U(x) = 5.41 - 0.82 \times 10^{-3}\, x$	15	26	4
Water productivity	kg m^{-3}	$U(x) = 0.35x$	15	26	4

The MCA method applied is the linear weighted summation (Pomerol and Romero, 2000), a full compensatory and aggregative method, which has the major advantage of its high simplicity, allowing an easier understanding of the procedure and results. However, this method has the disadvantage of full compensatory assumption, which means that any criterion with lower result can be compensated by another one with a better result, which is a trade-off that may not be well accepted by the decision makers. For each alternative, adopting user defined weights (λ_j) for every criterion j, a global utility U, that represents its integrative score performance, was computed as:

$$U = \sum_{j=1}^{7} \lambda_j \times U_j \qquad (6.11)$$

The different irrigation systems scenarios were ranked according to the global utility values. In this study, different sets of weights were adopted to characterize assigning priorities to water saving, economic results and a balance between the former (Table 6.7).

6.3. Results

6.3.1. Irrigation treatments and yield

The SIMDualKc model was validated for the various treatments referred in Section 6.2.1 (4 treatments and a total of 16 replications). Results are shown in Fig. 6.1 comparing field measured and simulated ET values cumulated for the periods between successive irrigation events. The regression coefficient is 0.98, indicating a good model fit, and R^2 is 0.86 showing that most of the variance is explained by the model. The estimated RMSE is 4.8 mm, *i.e.*, 7.7% of maximum cumulated ET observed. Results of using ET computed from observations of the soil water balance for model calibration/validation in maize are reported by Cameira et al. (2005), Popova et al. (2006) and Hong et al. (2013). The respective indicators of model fit are similar to those presented above.

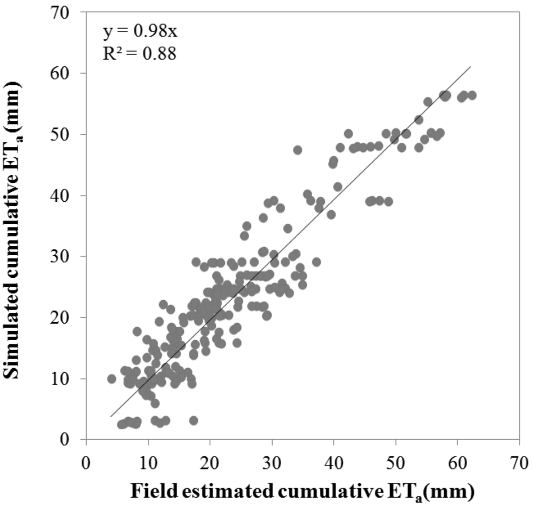

Fig 6.1. Comparison between field estimated and simulated crop evapotranspiration ($ET_{c\ adj}$) cumulated between successive irrigation events for all treatments and replications.

The referred four irrigation treatments (A, B, C and D) were adopted in this study, applied to the Vigia Irrigation System. The irrigation management scenarios simulated were built adopting different ASWD thresholds at various crop stages as given in Table 6.5. The exception was the flowering stage because maize is particularly sensitive to water stress at midseason (Alves et al., 1991; Çakir, 2004; Farré and Faci, 2009).

Table 6.8 presents the net irrigation depths, adjusted crop evapotranspiration ($ET_{c\ adj}$), adjusted transpiration (T_a), transpiration deficit (T_d), and simulated actual yield (Y_a) for all treatments obtained with the SIMDualKc model for the Vigia fields in 2011 considering sprinkler and drip irrigation methods. Results refer to the S2 model (Eq. 6.2). The maximum transpiration for the entire season was 480 mm for a non-stressed drip Treatment A.

Table 6.8. Adjusted crop evapotranspiration ($ET_{c\ adj}$), adjusted transpiration (T_a), transpiration deficit (T_d), net irrigation and simulated actual grain yield (Y_a) relative to each treatment

Irrigation method	Treatments	$ET_{c\ adj}$ (mm)	T_a (mm)	T_d (mm)	Net irrigation (mm)	Y_a (kg ha^{-1})
Sprinkler	A	568	471	4	372	16554
	B	521	438	19	360	16074
	C	569	441	28	336	14784
	D	492	413	47	300	14279
Drip	A	579	480	0	432	16858
	B	579	434	17	440	16161
	C	536	429	17	320	15614
	D	546	409	41	384	14468

Results in Table 6.8 show that greater DI (Treatment D) leads to considerable yield losses due to a reduction of $ET_{c\ adj}$, mainly transpiration, T_a, and thus an increase of the transpiration deficit, with T_d = 47 and 41 mm respectively for sprinkler and drip irrigation methods. The drip irrigation Treatment C presents a lower yield than Treatment B despite having the same T_d due to stress imposed during the late season, which produces an increased yield impact.

Yields for drip irrigation are higher than for sprinkler because when adopting smaller and more frequent irrigation events stress is more easily avoided. This is apparent in transpiration deficits reported in Table 6.8, which are higher for the sprinkler irrigation systems. However, the net irrigation depths are greater than for sprinkler systems due to higher soil evaporation that results from the higher frequency of soil wettings. As for sprinkler, yield tends to decrease for the drip system when adopting a DI schedule. Contrarily to sprinkling, Treatment C under drip irrigation has a lower T_a and higher T_d when compared with Treatment B; this is due to differences in irrigation timing.

6.3.2. Water productivity as influenced by commodity prices and irrigation systems

Results comparing the beneficial water use fraction (BWUF) and physical and economic water productivity (WP and EWP) for all treatments and irrigation systems as well as for both field sizes of 5 and 32 ha and commodity prices of 154 and 264 € t^{-1} are presented in Table 6.9. Results show that drip systems lead to higher BWUF than set sprinkler and center-pivot systems. This is due to lower soil evaporation since the wetted fraction of the soil is $f_w = 0.6$, less than for sprinkler irrigation, where all area is wetted; therefore, soil evaporation is less for drip than for sprinkling. Adopting Treatments A and C lead to higher BWUF than Treatments

B and D for all irrigation systems and all cases analyzed. Since BWUF is herein defined as the ratio of $ET_{c\ adj}$ to TWU, that situation is due to the fact that $ET_{c\ adj}$ is smaller for B and D, thus decreasing that ratio. Treatment B presents the lowest BWUF among all cases analyzed, which results from the decrease of $ET_{c\ adj}$ caused by the stress imposed during the vegetative stage. Comparing the small and the larger field, BWUF are similar for drip and set sprinkler systems but are smaller for the center-pivot systems in case of the 5 ha field comparatively to the 32 ha field.

Table 6.9. Comparison of BWUF, WP and EWP for all treatments, irrigation systems and management precision, and field sizes.

Field	Irrigation system	Irrigation treatment	BWUF	WP ($kg\ m^{-3}$)	EWP (€ m^{-3})	
					Low price	High price
5 ha	Drip	A	0.96	2.80	0.43	0.74
		B	0.88	2.47	0.38	0.65
		C	0.96	2.79	0.43	0.74
		D	0.90	2.37	0.37	0.63
	Set Sprinkler	A	0.90	2.62	0.40	0.69
		B	0.85	2.62	0.40	0.69
		C	0.91	2.36	0.36	0.62
		D	0.86	2.49	0.38	0.66
	Center-pivot	A	0.89	2.60	0.40	0.69
		B	0.85	2.61	0.40	0.69
		C	0.90	2.35	0.36	0.62
		D	0.86	2.48	0.38	0.66
32 ha	Drip	A	0.96	2.80	0.43	0.74
		B	0.88	2.47	0.38	0.65
		C	0.96	2.79	0.43	0.74
		D	0.90	2.37	0.37	0.63
	Set Sprinkler	A	0.90	2.62	0.40	0.69
		B	0.85	2.62	0.40	0.69
		C	0.91	2.36	0.36	0.62
		D	0.86	2.49	0.38	0.66
	Center-pivot	A	0.92	2.69	0.41	0.71
		B	0.87	2.69	0.41	0.71
		C	0.93	2.42	0.37	0.64
		D	0.88	2.55	0.39	0.67

BWUF = beneficial water use function; WP = water productivity; EWP = economic water productivity

When adopting full irrigation (Treatment A) a higher WP than for other treatments is generally obtained. Similar results are obtained for the C treatment, where stress is induced only during the late season. Because BWUF is also high for both treatments, yield losses are null or minimized. For B and D treatments TWU also decreases but proportionally less than for C, thus resulting in lower WP. The highest values for WP correspond to the non stressed Treatment A, varying between 2.60 to 2.80 kg m^{-3} for all systems and management conditions. The lower WP values are obtained for Treatment D under drip irrigation and Treatment C for center-pivot. This occurs because the water savings that are attained with the stress imposed during the different crop stages are not enough to overcome the correspondent yield losses. WP does not change from the 5 ha to the 32 ha field in case of drip and set sprinkler systems but WP are larger for the 32 ha field under center-pivot due to higher BWUF. This is due to higher distribution uniformity for center-pivot in a larger field (Table 6.4), that leads to a lower TWU.

EWP varies in accordance with WP. Both indicators have a similar behaviour, with EWP depending only upon the commodity prices though this indicator varies linearly with them. The highest value is achieved when adopting Treatment A under a drip system. As for WP, Treatment C has the lowest EWP value among all sprinkler treatments, but the lowest value for drip refers to Treatment D. This different behaviour, also observed for WP, results from the fact that the smaller and frequent net irrigation depths applied with drip irrigation lead to overcome stress produced with Treatment C better than sprinkler irrigation. Various studies compared drip and sprinkler irrigation and found higher yields and WP for drip irrigation, e.g., Tognetti et al. (2003) for sugar beet, Colaizzi et al. (2004) for sorghum, and Almarshadi and Ismail (2011) for alfalfa. The greater advantage of drip systems was found when deficit irrigation was applied. However, Albaji et al. (2010) found contradictory results because the relative advantages of drip or sprinkler systems depended upon various factors including soil characteristics, salinity and water quality.

EWPR was used to compare the yield values per unit of farming costs considering both scenarios of commodity prices. This approach allows assessing the feasibility of different irrigation treatments in order to define the economical return threshold for which farming becomes profitable. For this purpose, Fig. 6.2 shows the variation of EWPR for all the irrigation treatments and both commodity prices. EWPR for all treatments, all irrigation systems and both field sizes ranged from 0.64 to 0.97, thus indicating that no treatment would be feasible with that low commodity price, irrespective of the adopted irrigation system. Treatment A, corresponding to full irrigation, was the one approaching feasibility for center-pivot in case of the large field, and set sprinkler for the small one. Drip systems were far from economic viability for low commodity prices, with EWPR values lower than 0.80 in all cases. Treatments C and D had EWPR smaller than Treatments A and B, thus indicating that stress imposed during the late season led to non-negligible impacts.

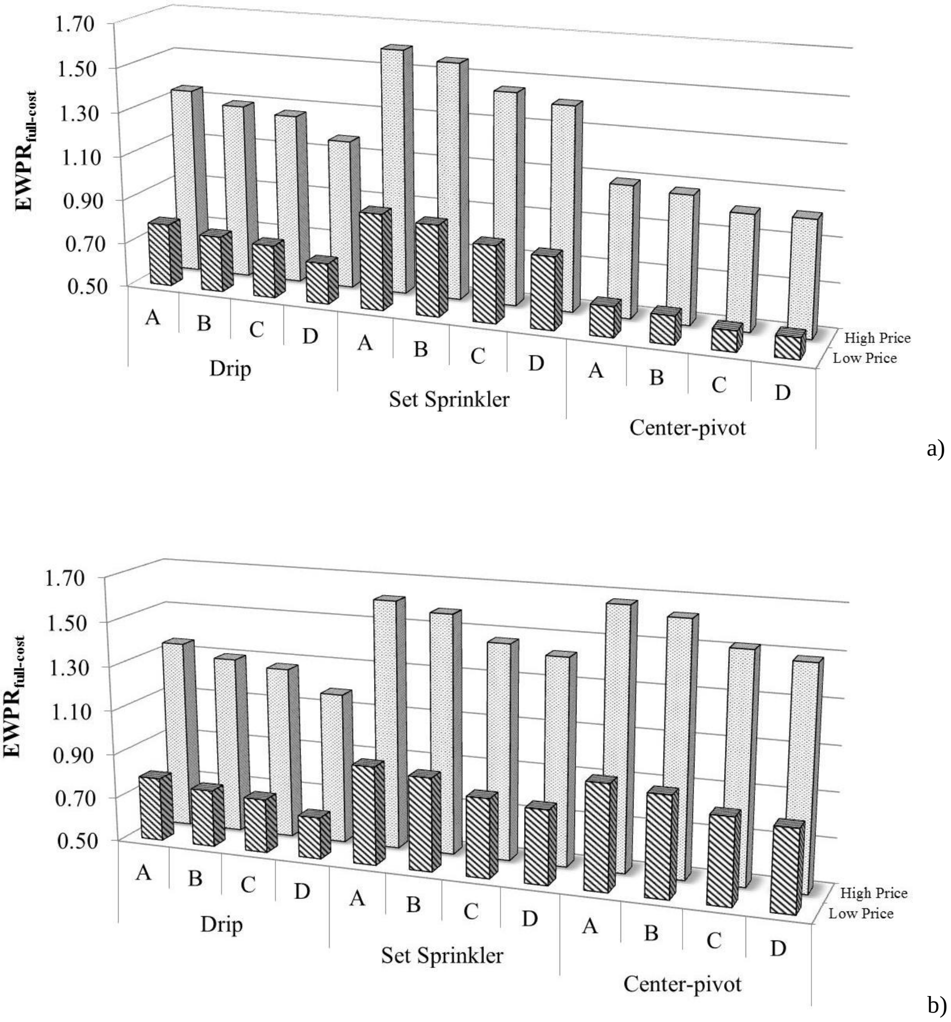

Fig. 6.2. Economic water productivity ratio (EWPRfull-cost) for all deficit irrigation treatments and irrigation systems applied to small (a) and large (b) farm sizes when adopting low (▨) and high(░),commodity prices

For high commodity prices (Fig. 6.2), most scenarios lead to positive incomes, i.e., EWPR > 1.0. A negative income was only observed when adopting Treatment D under a center-pivot system in a 5 ha field, thus confirming the non-appropriateness of this combination treatment/system in small fields. When farming maize in a 32 ha field, the adoption of deficit irrigation would lead to a positive income in all cases, with EWPR values ranging from 1.18 to 1.67. For this field size, irrigating with a center-pivot system would produce a farm income 1.40 to 1.67 times greater than the annual production costs. For 5 ha fields the best EWPR values correspond to a sprinkler set system, ranging from 1.42 to 1.61 (Fig. 6.2). Positive values were obtained for drip systems (1.18 to 1.35) but lower than for set or center-pivot sprinkler systems. However, EWPR values change with the prices of water as analyzed for Brazilian conditions (Rodrigues et al., 2013). One can conclude that the adoption of deficit irrigation is well supported for this high price scenario and that adopting drip irrigation for maize would not be selected by a farmer unless he would assign high priority for water saving, as analysed in the following chapter. Results by Heumesser et al. (2012) also found that sprinkler irrigation was more profitable than drip in case of maize. They also found that drip irrigation adoption would require subsidies for equipment investing.

6.3.3. Ranking of different alternatives

The global utilities of all the alternatives combining irrigation treatments and irrigation systems are shown in Fig. 6.3. Computations refer to the high commodity price only because when considering the low price scenario a negative farm income was obtained for all the alternatives as shown in Fig. 6.2. The three prioritization schemes defined in Table 6.7 are herein considered. Results show that the global utilities are very different for the various prioritization schemes considered, showing a disagreement between water saving and economic criteria. Changing the weights assigned to each criterion would change the utilities values. Using the weights referred in Table 6.7 it is noticeable that higher utility values correspond to the C treatment (water stress during the late season) under drip irrigation if water saving is prioritized. Differently, when the priority refers to the economic returns, the highest values of the utilities correspond to the A treatment (full irrigation) for set sprinkler systems in case of the small field and for center-pivot in case of the large field (Fig. 6.3). These results are largely explained by the costs associated with the irrigation systems, higher for drip than for sprinkler and, when considering the size of the field, because of the higher investment cost of center-pivot systems versus set systems for small fields. Differences between small and larger fields were already referred by O’Brien et al. (1998) and Lamm (2002), reporting that center-pivot irrigation was more advantageous for large fields.

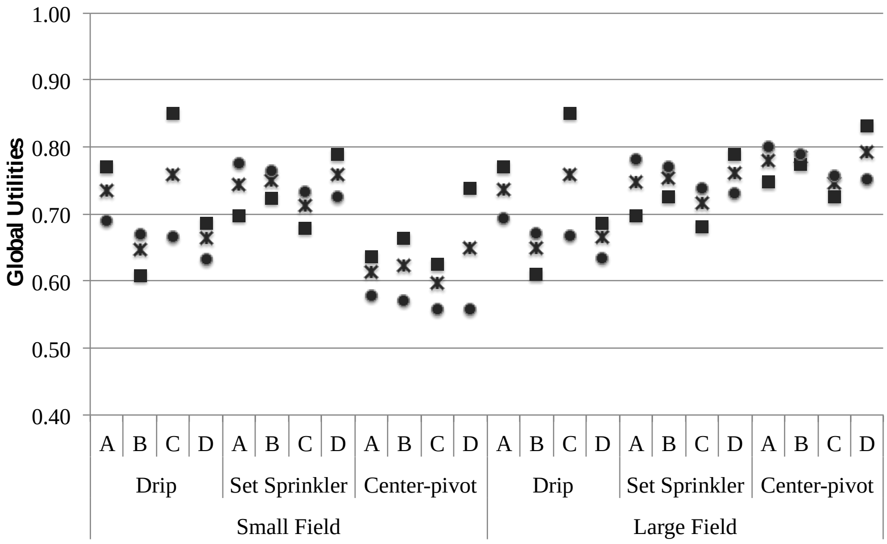

Fig. 6.3. Global utilities relative to the prioritization schemes adopted: water saving (■), farm economic returns (●), or a balance between both (✱), when considering various deficit irrigation treatments A through D, drip and sprinkler systems as well as small and large fields.

High utilities when prioritizing for water savings are also assigned to D treatments (DI during all stages except midseason) for center-pivot systems in the case of the large field, and set sprinkler systems for the small one. Differently, other high utility values when prioritizing for economic returns refer to the B treatment (stressed during the vegetative stage only) for set sprinklers and the small field or center-pivots in large fields. The advantage in using MCA for ranking is evidenced by these differences in results.

The top five alternatives relative to the three prioritization schemes defined in Table 6.7 are shown in Table 6.10 for both field sizes (5 and 32 ha). Rankings are definitely different when considering the various prioritization schemes. They also change with field sizes. For the 32 ha field, there are differences in rankings for all priority schemes but differences in utility values are small.

For all cases and water saving priorities the first rank is assigned for drip irrigation and the C treatment (stressed during the late season only), given the water saving effects linked to the irrigation method and the adoption of DI. The second place goes to Treatment D (DI during all stages but midseason) with set or center pivot sprinklers for the small and large fields, respectively. Full irrigation (Treatment A) with drip is third for the 5 ha field but is fifth for the 32 ha field. Differently, when priority is given to economic returns, set sprinkler systems with scheduling Treatments A, B, C, D are in the first four ranks; in case of large fields, the center-pivot systems A, B and C rank first, second and fifth. These rankings clearly identify the impact of systems costs combined with yield values. In the case of balanced prioritization, drip C comes in second place while drip A comes in fifth place for the small field. The other ranking positions are given to the set sprinkling systems. For the 32 ha field, center-pivot systems comes in the first 3 ranking positions, while drip C comes in the fifth position.

Table 6.10. The five best alternatives relatives to the considered prioritization scheme for both irrigation managements, field sizes and commodity price.

		5 ha			32 ha		
Priorities	Rank	Treatment	Irrigation system	Utility	Treatment	Irrigation system	Utility
Water saving	1	C	Drip	0.85	C	Drip	0.85
	2	D	Set Sprinkler	0.79	D	Center-pivot	0.83
	3	A	Drip	0.77	D	Set Sprinkler	0.79
	4	D	Center-pivot	0.74	B	Center-pivot	0.77
	5	B	Set Sprinkler	0.72	A	Drip	0.77
Economic results	1	A	Set Sprinkler	0.78	A	Center-pivot	0.80
	2	B	Set Sprinkler	0.77	B	Center-pivot	0.79
	3	C	Set Sprinkler	0.74	A	Set Sprinkler	0.78
	4	D	Set Sprinkler	0.73	B	Set Sprinkler	0.77
	5	A	Drip	0.69	C	Center-pivot	0.76
Balance between water saving and economic results	1	D	Set Sprinkler	0.76	D	Center-pivot	0.79
	2	C	Drip	0.76	B	Center-pivot	0.79
	3	B	Set Sprinkler	0.75	A	Center-pivot	0.78
	4	A	Set Sprinkler	0.75	D	Set Sprinkler	0.76
	5	A	Drip	0.74	C	Drip	0.76

These results clearly show the importance of investment costs in relation to the water saving potential. Comparisons were made for well designed and managed systems which are, all of them, able to produce high BWUF and support high WP. Therefore, the preferences evidenced by the rankings identify the possible use of various alternatives, both in terms of water saving and economic returns depending upon the decision-maker preferences.

Results show that the variation of the production costs, mainly due to the investment annuity and the maintenance annual costs, largely interfere in the economic ranking of the best alternatives when comparing different farm sizes. For a larger area, a center-pivot system proves to be the most economically feasible; however, for a smaller field, the best option is the adoption of set sprinkler systems. One can also conclude that the investment and maintenance costs play an important role when comparing different field sizes, since it widely interferes in the choosing of the best alternatives to be adopted. Marques et al. (2005) and O'Brien et al. (2010) also referred that various factors influencing production and irrigation costs and yield level and value play a major role in determining which irrigation systems should be selected. Thus, rankings shown above may deeply change when these factors are modified.

Overall results show that the selection of the best design alternatives highly depends upon the decision maker, mainly on the prioritization scheme and weights adopted. The weights and priority given to criteria must therefore involve the end user in order to choose the scenario that suits him/her the best. Adopting a decision support system with MCA requires the definition of the main purpose, choosing the most appropriate prioritization schemes and related criteria weights. For supporting the definition of the adopted priorities and weights and the analysis of results by users, one needs to take into account some additional factors such as the water availability, which is more important in case of more water demanding alternatives, the commodity prices, which could have a greater impact on the alternatives having lower land productivity; or the production costs, that affect the alternatives that require higher investment. Results also show that it is necessary to search for solutions that assure compatibility among water saving, irrigation performance and economic viability for farmers, i.e., assuring conditions for sustainable irrigation, which is in agreement with findings by Wichelns and Oster (2006). Furthermore, adopting water saving approaches requires adequate measures to support farmers on the selection of the most appropriate irrigation systems and management options since just using a MCA decision support tool requires good knowledge of factors influencing rankings. Results also indicate that appropriate support must be given to farmers when adopting high performance irrigation systems, which represent a high investment, as well as to adopt mild deficit irrigation management strategies that allow for sustainable crop profitability.

6.4. Conclusions

This study shows that economic water productivity indicators may be an appropriate approach for assessing the impacts of deficit irrigation, mainly considering commodity prices.

Comparing different scenarios of economic water productivities may help to assess when deficit irrigation is or is not feasible. The economic water productivity ratio EWPR, relating the yield values per unit of farming costs, reveals to be adequate to assess the feasibility of deficit irrigation as influenced by commodity prices and irrigation systems. Results show that viability of deficit irrigation strategies is extremely dependent on the commodity prices. If low commodity prices are considered all the treatments for all the irrigation systems and field sizes lead to a negative income. Contrarily, for higher commodity prices, most scenarios lead to positive incomes.

Drip irrigation systems were found to lead to higher water use performance in terms of beneficial water use and water productivity when compared with sprinkler systems. However, the EWPR were lower for drip than for both set and center-pivot sprinkler systems due to respective investment costs. Results were also different when comparing a 5 ha with a 32 ha field: best results for all treatments were for set sprinkler in case of the smaller field and for center-pivot in case of the large one, thus evidencing the influence of higher costs of center-pivot systems when a small field is considered. This study demonstrates that the adoption of well designed and managed irrigation systems may lead to contradictory results when the achieved water saving does not allow the desired recovery of the investment costs, also depending on the farm size. This may help policy makers to understand the contradictions between water saving and farm economic results.

Ranking irrigation system alternatives for water saving leads to the selection of drip and deficit irrigation for both types of fields. Contrarily, relative to economic results, sprinkler and full irrigation treatments are first ranked. Center-pivot rank above set sprinklers when a large field is considered. First ranking positions for water saving are not common to those obtained when the priority is assigned to farm economic results. Nevertheless, when adopting a prioritization scheme that balances water saving and economic results, it is possible to have a ranking that represents a trade-off between water saving and economic returns. This study shows the need to appropriately selecting the weights to be assigned to each criterion, which requires appropriate support to farmers when they want to select a new irrigation system allowing sustainable crop profitability. Results of this research may be useful for farmers, managers and policy makers when aiming at improving water management at field scale, particularly for understanding the economic limits of deficit irrigation, as well as economic and water saving issues when comparing drip and sprinkler systems.

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6.5. References

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Capítulo 7 - Evapotranspiration partitioning and yield prediction of peas (*Pisum sativum* L. cv. Azarro) in a Mediterranean environment

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Evapotranspiration partitioning and yield prediction of peas (*Pisum sativum* L. cv. Azarro) in a Mediterranean environment

Abstract

The soil water balance model SIMDualKc, which applies the dual crop coefficient approach for computing and partitioning crop evapotranspiration (ET_c, mm), was calibrated and validated using data two peas fields located in the Ribatejo region, Portugal. Data refers to 2011 and 2012, respectively a wet and a dry year. Results of model calibration show a good agreement between available soil water observations and predictions, with low errors of estimate - RMSE < 4% of the total available soil water - and high modelling efficiency (> 0.76). Results include calibrated basal crop coefficients for the initial, mid season and at harvesting, respectively 0.15, 1.10 and 1.05. The ET simulations were used to test the Stewart's model for assessing its accuracy to predict yields and compared with the crop growth model AquaCrop. The AquaCrop model was parameterized and tested for the same ASW data, as well as for biomass and yield observations. Water use and evapotranspiration partition by both models were different, with less good results for AquaCrop, particularly due to underestimation of soil evaporation and overestimation of deep percolation. Differences are due to adopting in SIMDualKc the well proved FAO56 assumptions for evapotranspiration partition. Both model approaches led to good prediction of peas yields, with deviations ranging 0.3 to 6.4% when combining the SIMDualKc and the Stewart's models, and 1.7 to 6.9% with AquaCrop. However, the first one requires less parameterization and may be more easily used for farmers' irrigation scheduling advising.

Keywords: crop evapotranspiration, crop coefficients, SIMDualKc water balance model, Stewarts water-yield model, AquaCrop model

7.1. Introduction

Peas (*Pisum sativum* L.) are an indeterminate plant and flowering, pod filling, and vegetative growth can occur simultaneously (Martin and Jamieson, 1996). This may cause problems when harvesting the crop. Therefore, in vining peas, which are harvested at once, irrigation is used to both satisfy crop water requirements (CWR) and achieve uniform flowering, maturation and size at harvest, i.e., to favour high commercial yields (Anderson and White, 1974; Ashraf et al., 2011). In Portugal, peas are usually cropped during the Winter-Spring season, requiring only supplemental irrigation, with more frequent irrigation and larger water applications in dry years. However, there are few studies on peas irrigation and there is the need to better know the factors influencing water use components and water-yield relations that may lead to improved irrigation of peas for industry during different growth stages.

Experimental studies relative to CWR and irrigation of peas show some controversy about water requirements during the vegetative stage, with some studies showing that irrigation during this period increases vegetative growth with limited impacts on yields (Salter, 1962; Maurer et al., 1968; Doorenbos and Kassam, 1979), while others, such as Ashraf et al. (2011), reported that peas yields are often increased by irrigation during the vegetative stage. Water stress during flowering and pod filling causes a significant reduction in peas biomass and seed yield (Maurer et al., 1968; Stoker, 1977; Martin and Jamieson, 1996; Baigorri et al., 1999; Rasaei et al., 2012) as well as in N accumulation (Mahieu et al., 2009). Moreover, water stress during flowering highly affects seeds quality (Mahieu et al., 2009; Ashraf et al., 2011). Research has shown that yield responses to irrigation during flowering are mainly due to the increase of the number of pods per plant, with smaller impacts on the number of peas per pod and on the peas weight (Stoker, 1973; Martin and Tabley, 1981).

Few model applications have been made to estimate peas yields. Berntsen et al (2004) used the FASSET model, which simulates the above ground biomass relative to a pea - spring barley intercrop. Beaudoin et al. (2008) calibrated the STICS model to predict biomass and yield of spring peas but predictions underestimated observations. Differently, Corre-Hellou et al. (2007) also applied STICS to a pea-barley intercrop and reported a good agreement between observed and simulated above ground biomass of peas. Mathe-Gaspar et al. (2005) applied the PEAGRO model to estimate the effects of solar radiation and soil water on peas biomass and yield. The FAO crop growth model AquaCrop (Steduto et al., 2009), that is presently used for a variety of crops, has not yet been used for peas. Hence, that model may be assessed for predicting biomass and yield and compared for peas yields predict with a simpler approach that combines the water balance model SIMDualKc (Rosa et al., 2012a) with the Stewart's water-yield model (Stewart et al., 1977).

The objectives of the present study consisted in exploring field experiments data on vining peas for (1) calibration and validation of the SIMDualKc model, including the derivation of basal crop coefficients (K_{cb}) and depletion fractions for no stress (p) adapted to the local conditions; (2) assessing the accuracy of the global Stewarts' model to predict vining peas yields, (3) parameterization and test of the AquaCrop model for peas and assessing its accuracy to predict crop yields; and (4) analysing water use components derived from both models to further develop farmers irrigation advising aimed at achieving higher yields.

7.2. Material and methods

7.2.1. Field experiments

Field observations in a farmer's field were performed at Quinta da Lagoalva de Cima, located in Alpiarça, and at the Sociedade Agrícola do Barracão do Duque, Golegã, both located in the Ribatejo region, Central Portugal. The farms are approximately 20 km apart. Climate is of Mediterranean type with mild rainy winters and dry hot summers. The daily weather data were observed with an automatic station (iMetos®) located nearby (39.16^{o} N, 8.33^{o}W and 24 m elevation) and included maximum and minimum temperatures (^{o}C), relative humidity (%), wind speed at 2 m (m s^{-1}) and solar radiation (W m^{-2}). The daily reference evapotranspiration ET_o was computed with the methodology proposed by Allen et al. (1998). Monthly cumulated values of precipitation and ET_o relative to the peas seasons of 2011 and 2012 are presented in Fig. 7.1. It shows that 2012 was a very dry year.

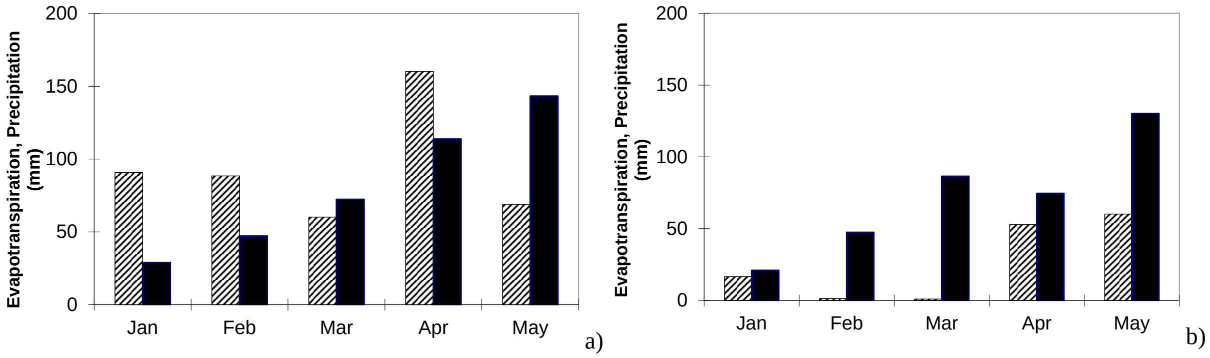

Fig. 7.1. Monthly cumulated precipitation (▨) and reference evapotranspiration (■) at Alpiarça during the peas seasons of 2011 (a) and 2012 (b).

Farms' fields were cropped with vining peas (*Pisum sativum* L. cv. Azarro) with a plant density of approximately 900000 plants ha^{-1}. An average germination rate of 90% was observed. Management practices were the ones used by the farmer. During the 2011 irrigation season two peas plots were used for field observations, plot 1 and 2; in 2012 only plot 1 was sown. The observations were performed inside the field plots, which had a surrounding area cropped with peas of approximately 30 and 47 ha in plots 1 and 2, respectively.

Soils in both plots are silty-loam. Table 7.1 presents the main soil textural and water holding characteristics of both plots. Groundwater is quite deep in both areas and capillary rise was not considered. The total available soil water (TAW), which represents the difference between the water content at field capacity and wilting point in the root zone, is 209 and 225 mm m^{-1}, in plots 1 and 2, respectively.

Table 7.1. Soil textural and hydraulic properties of the two plots of Alpiarça and Golegã fields.

Soil layer depths (m)	Sand (%)		Loam (%)		Clay (%)		θ_s (m^3 m^{-3})		θ_{FC} (m^3 m^{-3})		θ_{WP} (m^3 m^{-3})		K_{sat} (cm d^{-1})	
	Plot 1	Plot 2	Plot 1	Plot 2	Plot 1	Plot 2	Plot 1	Plot 2	Plot 1	Plot 2	Plot 1	Plot 2	Plot 1	Plot 2
0.0-0.10	37	42	40	41	23	17	0.46	0.43	0.35	0.32	0.22	0.15	71	75
0.10-0.20	35	33	41	47	24	22	0.41	0.41	0.36	0.36	0.24	0.18	46	47
0.20-0.40	35	47	41	42	24	11	0.43	0.41	0.36	0.37	0.20	0.13	53	55
0.40-0.60	60	61	25	28	15	11	0.44	0.44	0.37	0.38	0.12	0.13	59	54
0.60-0.80	62	55	24	30	14	15	0.42	0.43	0.36	0.37	0.10	0.11	61	58
0.80-1.00	50	43	34	36	16	21	0.45	0.44	0.37	0.34	0.12	0.14	77	78

θ_s, θ_{FC} and θ_{WP} are the soil water contents at respectively the saturation, field capacity and the wilting point; K_{sat} is the saturated hydraulic conductivity

Field observations included the dates of each crop growth stage (Table 7.2), crop height (h, m), fraction of soil covered by the canopy (f_c, dimensionless) and leaf area index (LAI, cm^2 cm^{-2}). LAI was measured at four locations per plot along the crop season using a non-destructive method with a Decagon Devices AccuPAR LP-80 device following the methodology by Johnson et al. (2010). LAI measurements in 2011 were lost due to hardware problems in the AccuPAR logger.

Table 7.2. Peas growth stages dates for each experimental years.

		Crop growth stages				
Year/plot		Initial	Crop development	Mid-season	Late season	Harvest
2011	Plot 1	22-01 to 11-02	12-02 to 14-03	15-03 to 23-04	24-04 to 08-05	09-05
	Plot 2	22-01 to 14-02	15-02 to 19-03	20-03 to 25-04	26-04 to 02-05	03-05
2012	Plot 1	19-01 to 22-02	23-02 to 26-02	27-03 to 08-05	09-05 to 15-05	16-05

The actual yield was observed by harvesting samples of 0.4 x 0.4 m^2 near the probe access tube, with a total of 4 samples collected. Samples were placed in a plastic, sealable bag and the bags placed in refrigerated containers for transport from the field. 3 hours after collecting the samples they were separated into leaflets, stem, flowers, pods and grains; they were weight with a 0.1 g precision and then oven dried to constant weight at 65±5ºC. Samples were collected along crop season for biomass and yield assessments; for 2011 in plot 1 samples were collected by 20 and 29 April and 9 May; plot 2 samples were collected by 8 April and 3 May; in 2012 samples were collected by 28 March, 18 April, and 9 and 14 May.

The root depths were surveyed along both crop seasons in both plots, until the maximum canopy cover, showing that most roots were concentrated in the first 0.30 m of soil but a few were found at 0.75 m. These observations are in agreement with those by Hamblin and Hamblin (1985) and Benjamin and Nielsen (2006). However, Armstrong et al. (1994) found some peas genotype that could extend roots deeper and extract soil water down from2 m.

Both plots were sprinkler irrigated. Plot 1 was irrigated with a linear moving system equipped with rotator sprinklers installed on drops and plot 2 was irrigated with a center-pivot system equipped with overhead rotator sprinklers. The irrigation systems performance was evaluated several times along the seasons in both plots and years using the methodology proposed by Merriam and Keller (1978) and Martin et al. (2007). It resulted an average distribution uniformity of 79% for plot 1 and 81% for plot 2. The application depths were observed using rain gauges placed within the crop near the access probe tubes; their averages were D= 6 mm in plot 1 and D = 4.5 mm in plot 2. The net irrigation depths cumulated to the crop growth stages and to the season were obtained by cumulating these D values. Table 7.3 presents net irrigation depths and precipitation (mm) cumulated to every growth stage and the season.

Table 7.3. Net irrigation depths (mm) and precipitation (mm) during each growth stage

	2011				2012	
	Plot 1		Plot 2		Plot 1	
Crop growth stages	Precipitation (mm)	Irrigation (mm)	Precipitation (mm)	Irrigation (mm)	Precipitation (mm)	Irrigation (mm)
Initial	17	0	50	0	4	48
Crop development	146	0	113	0	1	104
Mid-season	136	71	148	75	101	58
Late season	38	0	26	0	22	0
Total	337	71	337	75	128	210

A Sentek DIVINER 2000 probe was used to monitor the soil water content in both years and measurements were performed at each 0.10 m layer until the depth of 0.90 m. 8 soil water observation points were used and a replication was made at a distance of 5 m, totaling 16 observation points. Observations were performed once a week with three readings for each observation depth. The probe was previously calibrated for the soils in both plots using a high range of soil water content data, from near wilting point to near saturation. Observations of the soil water content were performed taking into consideration the recommendations for accuracy proposed by Allen et al. (2011).

7.2.2. The SIMDualKc water balance model and water-yield relations

The SIMDualKc model (Rosa et al., 2012a) is a daily soil water balance simulation model that uses the dual crop coefficient approach to compute crop ET (Allen et al., 1998, 2005; Allen and Pereira, 2009). The FAO dual crop coefficient approach to compute ET has been applied by several other researchers using soil water observations (Bodner et al., 2007; Yang et al., 2009; Zhang et al., 2011; Sánchez et al., 2012) or with combined soil water, sap flow and micro-lysimeters data (Ding et al., 2013).

The SIMDualKc model has been calibrated and validated in a peach orchard with separately observed T_c and E_s (Paço et al., 2012), in a vineyard considering the effects of an active ground cover (Fandiño et al., 2012), in mulched deficit and full irrigated maize (Martins et al., 2013). Furthermore, the model was also calibrated using ET data from eddy covariance observations (Zhang et al., 2013). The validation of the Ritchie's soil evaporation approach (Ritchie, 1972) adopted for the dual K_c approach (Allen et al., 1998; 2005) and in SIMDualKc was performed for a peach orchard (Paço et al., 2012), an intensive olives orchard (Pôças et al., 2013), maize and wheat (Zhao et al., 2013) and soybeans (Wei et al., 2013). Ding et al. (2013) validated this approach for maize with plastic mulch and bare soil.

The model computes the crop evapotranspiration (ET_c) as

$$ET_c = (K_{cb} + K_e)\, ET_o \qquad (7.1)$$

where ET_o is the reference evapotranspiration (mm) and K_{cb} and K_e are respectively the basal and evaporation coefficients (dimensionless) that characterize respectively crop transpiration (T_c) and soil evaporation (E_s). Therefore, the model provides for computing maximum transpiration $T_c = K_{cb}\, ET_o$ (mm) and soil evaporation $E_s = K_e\, ET_o$.(mm). The actual ET ($ET_{c\ adj}$, mm) is computed by the model as a function of the available soil water in the root zone: when soil water extraction is smaller than the depletion fraction for no stress (p) then $ET_{c\ adj} = ET_c$, otherwise $ET_{c\ adj} < ET_c$ and decreases with the available water stored in the root zone as

$$ET_{c\ adj} = (K_s\, K_{cb} + K_e)\, ET_o \tag{7.2}$$

where K_s (0 - 1) is the water stress coefficient that describes the effects of soil water stress on plant transpiration; then, the actual crop transpiration is $T_a = K_s\, K_{cb}\, ET_o$. Both crop related parameters (K_{cb} and p) should be calibrated together when using the model with a different crop and a different environment. Rosa et al. (2012a) give further descriptions of the soil water balance and auxiliary equations used by the SIMDualKc model. The input data include:

1) *daily meteorological data* on precipitation, P_e (mm) and reference evapotranspiration, ET_o (mm), or weather data to compute ET_o with the FAO-PM methodology (Allen et al., 1998);

2) *crop data* referring to the dates of crop growth stages (Table 7.2), basal crop coefficient (K_{cb}); soil water depletion fractions for no-stress (p); root zone depths Z_r (m); crop height h (m); the fraction of groundcover by vegetation (f_c), the fraction of soil wetted by irrigation and rain (f_w), and the fraction of soil wetted and exposed to radiation (f_{ew});

3) *soil data for a multi-layered soil* including the number of layers and layer depths d (m) and the respective soil water content at field capacity θ_{FC} ($m^3\ m^{-3}$) and at the wilting point θ_{WP} ($m^3\ m^{-3}$), or the total available water (TAW, mm); soil evaporation layer depth Z_e (m); the total evaporable water (TEW, mm), i.e., the maximum depth of water that can be evaporated from the evaporation layer when it has been completely wetted (mm); the readily evaporable soil water (REW, mm), which is the maximum depth of water that can be evaporated from the evaporable layer without restrictions; and the soil water content at planting in both the root zone (% TAW) and in the evaporable layer (% TEW);

4) *groundwater contribution and deep percolation parameters* relative to capillary rise from the groundwater table (CR, mm) and deep percolation through the bottom of the root zone (DP, mm), whose parametric equations are described by Liu et al. (2006); as explained before, groundwater contribution is not considered in the observed fields;

5) *runoff computation data* relative to the curve number method as described by Allen et al. (2007);

6) *irrigation scheduling data*, either dates and depths of observed irrigation when the model is being calibrated and validated, or when an observed scheduled is assessed, or soil water thresholds and irrigation depths and frequency when the model is used to generate irrigation schedules for field practice.

A simple approach was used in association with SIMDualKc to assess the impacts of water deficits on yields by applying the water-yield model proposed by Stewart et al. (1977), which assumes a linear variation of the relative yield losses with the relative evapotranspiration deficits at the season scale:

$$1 - \frac{Y_a}{Y_m} = K_y\left(1 - \frac{ET_{c\ adj}}{ET_c}\right) \tag{7.3}$$

where ET_c and $ET_{c\ adj}$ are respectively crop evapotranspiration and crop adjusted ET (mm), Y_a and Y_m are the maximum and the actual yield (kg ha^{-1}) obtained respectively under full and deficit irrigation, and K_y is the crop yield response factor (dimensionless). For peas, Doorenbos and Kassam (1979) proposed K_y= 1.15, that was adopted in the present study.

The estimated yield ($\widehat{Y_a}$) is obtained from Eq. 7.3 as:

$$\widehat{Y_a} = Y_m - \frac{Y_m\,K_y\,ET_d}{ET_c} \tag{7.4}$$

where ET_d is the ET deficit, i.e., $ET_d = ET_c - ET_{c\ adj}$. $ET_{c\ adj}$ and ET_c were computed with the SIMDualKc model after its calibration. Y_a were the dry yields observed at each plot and year. Y_m were obtained for both years using information on the highest yields achieved by farmers in the study area; these Y_m values were then compared with Y_m values estimated using the 'Wageningen method' (Doorenbos and Kassam, 1979). Thus, the dry maximum yields were set for the 2011 experiments at 3289 and 3202 kg ha^{-1} respectively for plot 1 and 2, and at 2205 kg ha^{-1} for 2012. Values for 2011 are slightly different due to different harvesting dates, and values for 2012 were lower due to differences in climatic data, mainly radiation and temperature.

7.2.3. The crop growth model AquaCrop

The AquaCrop model (Steduto et al., 2009; Raes et al., 2012) also allows computing and separating T_c from E_s using a daily time step. To estimate T_c the model includes a simple canopy growth and senescence model, which are related with canopy ground cover (CC, %) instead of leaf area index (LAI). The model applies Eq. 7.3 using T_c instead of ET because it is the component directly responsible for yield formation and thus avoiding the effect of the nonproductive consumptive use of water.

The AquaCrop model is the combination of four sub-models: 1) the soil water balance; 2) the crop development, growth and yield; 3) the atmosphere sub-model, handling rainfall, evaporative demand (reference evapotranspiration, ET_o) and CO_2 concentration; 4) and the management sub-model, which includes irrigation and fertilization (Raes et al., 2012).

The crop growth and development along the season is obtained by expanding its canopy and deepening its rooting system. The model simulates the crop responses to water deficits using stress coefficients (K_s). Water stress is assumed to impact on the following crop growth processes (Raes et al., 2012): i) reduction of the canopy expansion rate; ii) acceleration of senescence; iii) closure of stomata; and iv) changes in the harvest index (HI) after the start of the reproductive growth. The model allows using calendar or Growing Degree Days (GDD) for defining the crop development stages.

The above ground dry biomass (B, kg ha^{-1}) is estimated by the model using the biomass water productivity, which requires parameterization, and the water transpired by the crop along the season, that is computed by the model. The crop yield is obtained from B through the harvest index (HI), which indicates the proportion of biomass that is harvestable. HI is adjusted using five water stress coefficients relative to inhibition of leaf growth, inhibition of stomata, reduction in green canopy duration due to senescence, and for reduction in biomass due to pre-anthesis stress and pollination failure (Raes et al., 2012). HI relative to dry yields was observed at all plots; since all treatments were full irrigated the average of observed HI was used in simulations (HI = 0.30). This approach follows those for other crops as used with AquaCrop (Araya et al., 2010b; Zeleke et al., 2011; Yuan et al., 2013). That HI value is similar to values reported for peas by White et al. (1982) [0.25-0.28], Uzun and Açkgöz (1998) [0.29-0.35] and Rasaei et al. (2012) [0.28 - 0.47], whose lower values are for high peas density as for the current study.

The model input data include climatic data concerning daily values for minimum and maximum air temperatures, precipitation, reference evapotranspiration (ET_o) and mean annual carbon dioxide concentration in the atmosphere. Contrarily to SIMDualKc, the AquaCrop model does not compute ET_o. The soil input data refer to a maximum of five layers and, for each layer, include the hydraulic conductivity at saturation and the water content at saturation, field capacity and wilting point. Input data include the readily evaporable water (REW) and the curve number (CN) characterizing surface runoff of the field which are further calibrated. The 4.0 version of the model (Raes et al., 2012) includes the computation of capillary rise using the saturated hydraulic conductivity of each layer. However, as referred above for SIMDualKc, this computation was not considered.

The field management practices include soil fertility levels and soil management practices that affect the soil water balance mainly irrigation, mulching and runoff reduction practices. The irrigation management refers to various irrigation systems and scheduling options.

The canopy ground cover (CC) is equivalent to f_c in FAO56 (Allen et al., 1998) and in SIMDualKc (Rosa et al., 2012a). However, while SIMDualKc uses observed f_c data, or f_c data derived from observed LAI, the AquaCrop model uses a computational algorithm to estimate CC. Model computations are performed in two phases (Raes et al., 2012). The first phase uses an exponential function of time, which begins at crop emergence and ends when half of the maximum CC is reached. The CC growth rate is identified with a canopy growth coefficient CGC. The second phase starts then until the maximum CC (CCx) is reached. An exponential decay function using the same CGC is then adopted. The decline of green canopy cover after senescence starts is taken into consideration using a canopy decline coefficient (CDC) (Raes et al., 2012).

CC may also be computed from the LAI of the green leaves using an exponential time decay function (Farahani et al., 2009; Hsiao et al., 2009; Araya et al., 2010a; Zeleke et al., 2011). Authors use diverse parameterization of that function, mainly different values for the coefficient of extinction of canopy (Jeuffroy and Ney, 1997), which is an indicator of crop shadow on the ground; however, the approximation used in FAO56 (Allen et al., 1998) is not adopted. Different extinction coefficients have been reported for peas in relation to plant density, row spacing, crop management and approaches used for measuring radiation, e.g., global radiation, photosynthetically active radiation, PAR, or the intercepted radiation, which neglects the radiation reflected by the soil and the canopy and is the approach used with the AccuPAR LP-80 device adopted in this study. Variation of the extinction coefficients also result from environmental conditions, e.g., the leaf angle, that can be affected by water stress. According to Jeuffroy and Ney (1997), the estimation of the extinction coefficient for peas is difficult because of the transformation of leaves into tendrils for both semi-leafless and leafless genotypes. Heath and Hebblethwaite (1985) reported extinction coefficients from 0.55 to 0.75 and Berntsen et al. (2004) refer to 0.85. In the present study the value 0.90 was assumed due to high plant density.

The AquaCrop model has been tested for several field crops, e.g., maize (Hsiao et al., 2009), barley (Araya et al., 2010a), canola (Zeleke et al., 2011), potato (García-Vila and Fereres, 2012), teff (Araya et al., 2010b), sugar beet and sunflower (Stricevic et al., 2011). However, the procedures for parameterization and calibration used are often not described with enough detail. Our article includes a first approach for the parameterization of the model for peas following the recommendations proposed by Hsiao et al. (2012).

7.2.4. Parameterization, calibration and validation procedures

The calibration and validation of the SIMDualKc model was performed using independent data sets, those of 2012 were used for calibration and those of 2011 for validation. A similar approach was used for AquaCrop after parameterization. Sinclair and Seligman (2000) proposed a set of criteria aimed at publishing papers on crop models, which can be defined as dynamic representations of crop processes with the objective of simulating and explaining crop development and behaviour, yield and quality as a function of environmental and management conditions or of genetic variation. SIMDualKc aims only at representing the water use and evapotranspiration processes considering well defined environmental and management conditions. Differently, AquaCrop aims at simulating crop growth, biomass and yield responses to water, thus involving more complex processes than SIMDualKc.

The SIMDualKc model was previously presented (Rosa et al., 2012a and b) in terms that agree with recommendations by Sinclair and Seligman (2000), i.e., with clearly defined objectives, concept and structure, as well as its background on various aspects of water use and evapotranspiration and related testing. AquaCrop was also presented in similar terms (Steduto et al., 2009). The calibration of a water balance model such as SIMDualKc refers to a few parameters that have a well-established physical and biological meaning and relate to the crop and the soil under consideration. Validation is then used to demonstrate that the calibrated parameters are well adjusted for soil water and ET simulation of peas in the considered Mediterranean environment. Differently, because a large number of parameters is used with

AquaCrop, parameterization is more focused than calibration and validation (Faharani et al., 2009; Hsiao et al., 2009) and papers often do not describe calibration and validation (e.g., Araya et al., 2010b; García-Vila and Fereres, 2012). In the current application, both calibration and validation are considered. To demonstrate the performance of the models a set of goodness of fit indicators described below is used.

The calibration of the SIMDualkc model was aimed at finding the crop parameters K_{cb} and p relative to the considered crop growth stages, the soil evaporation parameters TEW, REW and Z_e and the deep percolation parameters a_D and b_D that minimize differences between observed and simulated available soil water (ASW). The procedure follows those reported by Rosa et al. (2012b) and Martins et al. (2013). The calibration was performed to the entire root depth using all field data observed at plot 1 (Alpiarça) in 2012. To perform the related iterations, the initial depletion for the entire root zone was set at 10% of TAW and that of the evaporable layer was set at 10% of TEW. A trial and error procedure was developed. The procedure initiated with adjusting K_{cb} and p parameters until small errors were achieved; after that, the trial and error procedure was applied to the soil evaporation parameters TEW, REW and Z_e, and the percolation parameters a_D and b_D. In the following, the procedure was applied again to the crop parameters until error values do not decrease from an iteration to the next. The validation of SIMDualKc consisted of using the parameters previously calibrated (K_{cb}, p, TEW, REW, Z_e, a_D and b_D) with data of the both experiments of 2011. Based upon soil water observations, the initial depletion for the effective root zone was then set at 0 and 20% of TAW respectively for plot 1 and 2, and the initial depletion of the evaporable layer was set at 0 and 10% of TEW respectively.

Since there were no predetermined parameters for peas, the AquaCrop model parameterization received particular attention. Following Farahani et al. (2009), that parameterization consisted of the adjustment of specific model parameters to crop and soil characteristics. These included plant density, maximum CC, HI, and dates relative to emergence, maximum coverage, maturity and senescence as well as soil hydraulic properties (Table 7.1). Model calibration consisted of adjusting some parameters to the location and crop variety, which could be assessed through validation using an independent data set. The first trial and error procedure was performed for the conservative parameters that influence the canopy cover curve, i.e., the above referred coefficients CGC and CDC, as well as parameters relative to water stress affecting leaf expansion and senescence. Once the CC curve was properly simulated, the trial and error procedure applied to the maximum K_{cb}, the water depletion threshold relative to stomatal closure, the soil REW and the curve number (CN), now comparing observed and simulated ASW. The conservative parameters retained after parameterization and calibration using the 2012 data were used for the validation with data from both plots observed in 2011.The initial soil water conditions and climatic data used in AquaCrop computations were the same used with SIMDualKc both for calibration and validation.

To assess the goodness of fit of both models, various statistical approaches were used as previously adopted in the procedures referred above (Rosa et al., 2012b; Martins et al., 2013):

a) A linear regression forced to the origin was performed between observed and simulated ASW values. A regression coefficient (b) close to 1 indicates that the predicted values are statistically close to the observed ones while a determination coefficient (R^2) close to 1.0 indicates that most of the variation of the observed values is explained by the model.

b) Indicators of residual estimation errors following Green and Stefenson (1986), Loague and Green (1991) and Moriasi et al. (2007) were adopted: the root mean square error (RMSE), the average absolute error (AAE) and average relative error (ARE). These indicators were automatically calculated at each iteration, which helped to find the calibrated parameters leading to smaller errors.

c) Indicators of the quality of modeling: the Nash and Sutcliff (1970) modelling efficiency (EF), defined by the ratio of the mean square error to the variance in the observed data subtracted from the unity, and that is a normalized statistic determining the relative magnitude of the residual variance compared to the measured data variance (Moriasi et al., 2007); and the Willmott (1981) index of agreement (d_{IA}), that represents the ratio between the mean square error and the "potential error" (Moriasi et al., 2007). The target value for EF is 1.0, while a null or negative value means that the average of observations is as good or better predictor than the model; $d_{IA} = 1$ indicates perfect agreement between the observed and predicted values, and $d_{IA} = 0$ indicates no agreement at all (Moriasi et al., 2007).

7.3. Results and discussion

7.3.1. Models calibration and validation

As referred above, the calibration of the SIMDualKc model was performed through minimizing the differences between observed and simulated ASW values relative to plot 1 in 2012 and the validation was performed using the data from both plots in 2011. All calibrated values (K_{cb}, p, TEW, REW, Z_e, a_D and b_D) are presented in Table 7.4 together with the respective initial values. The K_{cb} values obtained are similar to those proposed by Allen et al. (1998). The $K_{cb\ end}$ depends upon crop management and its high value results from early harvest for industry, which was performed few days after the start of senescence of the bottom leaves. The calibrated REW, TEW, a_D and b_D values resulted different for plots 1 and 2 due to differences in soil properties given in Table 7.1.

Table 7.4. Calibrated peas basal crop coefficients (K_{cb}), depletion fractions for no stress (p), soil evaporation parameters (TEW, REW and Z_e) and deep percolation parameters used with SIMDualKc model.

Parameter	Values		
	Initial	Calibrated	
$K_{cb\ ini}$	0.15	0.15	
$K_{cb\ mid}$	1.10	1.10	
$K_{cb\ end}$	0.90	1.05	
p_{ini}	0.35	0.40	
p_{dev}	0.35	0.40	
p_{mid}	0.35	0.40	
p_{end}	0.35	0.40	
		Plot 1	Plot 2
REW (mm)	8	10	7
TEW (mm)	14	24	28
Z_e (m)	0.10	0.10	0.10
a_D	300	370	240
b_D	-0.0173	-0.015	-0.020

* REW and TEW are the readily and total evaporable water; Z_e is the depth of the soil evaporation layer; CN is the curve number; a_D and b_D are the parameters of the deep percolation equation (Liu et al., 2006).

The conservative and non-conservative parameters used to parameterize the AquaCrop model are presented in Table 7.5. The initial values are also included for the parameters that were calibrated. The presentation of parameters follow that by Heng et al. (2009) and Hsiao et al. (2009).

Table 7.5. Conservative and generally applicable parameters of the crop data file of AquaCrop model used for the vining peas simulations

Description	Units or symbol meaning	Value	
Conservative (generally applicable)			
Base temperature	º C		5.0
Cut-off temperature	º C		30.0
Canopy cover per seedling at 90% emergence (cc_o)	cm^2		4.05
Maximum canopy cover (CC_x)	%, almost entirely covered		95
Decline of crop coefficient after reaching CC_x	f_{sen}, % d^{-1}		0.30
Soil water depletion threshold for leaf growth threshold	Fraction of TAW at which CGC becomes 0, p_{exp}, lower		0.15
Leaf growth stress coefficient curve shape	Moderately convex curve		3.0
Stomatal conductance coefficient curve shape for water stress	Highly convex curve		3.0
Biomass water productivity (WP_b*) normalized for the year 2000	g (biomass) m^{-2}, function of atmospheric CO_2		13.0
Soil water depletion threshold for leaf growth threshold	Fraction of TAW at which CGC starts to be reduced, $p_{exp,\ upper}$		0.60
Soil water depletion threshold for stomatal conductance	Fraction of TAW at which stomata start to close, p_{sto}		0.60
Soil water depletion threshold for failure of pollination	Fraction of TAW at which pollination starts to fail, p_{pol}		0.75
Considered to be conservative but that may be cultivar-specific			
Reference harvest index (HI_o)	%		30
Coefficient, inhibition of leaf growth on HI	HI increase by inhibition of leaf growth at anthesis		4.0
Coefficient, inhibition of stomata on HI	HI increase by inhibition of stomata at anthesis		3.0
Calibrated parameters		Initial	Calibrated
Basal crop coefficient for transpiration at max. CC_x	Crop transpiration coefficient (K_{cbx}) when complete canopy cover but prior to senescence	1.10	1.13
Canopy decline coefficient (CDC) at senescence	Decline per day due to leaf aging	0.015	0.030
Readily evaporative water, REW	mm	8	10 and 7*
Curve number, CN		70	75

* plot 1 and plot 2 respectively

Fig. 7.2 shows the comparison between the observed and simulated ASW values throughout the crop seasons. They refer to calibration and validation of both models. Table 7.6 presents the respective goodness of fit indicators. Results for SIMDualKc show a very good agreement between observed and simulated ASW for all three experiments, with regression coefficients b = 1.0 for plot 1 and b = 1.03 for plot 2, and determination coefficients ranging 0.81-0.95. For AquaCrop, results show a slight trend for over-estimation of ASW, with b ranging 1.03 - 1.05. R^2 are similar to those of SIMDualkc, with values between 0.82 and 0.92. These regression results, together with the graphical analysis of Fig. 7.2, indicate that the variation of observed ASW is well explained by the model.

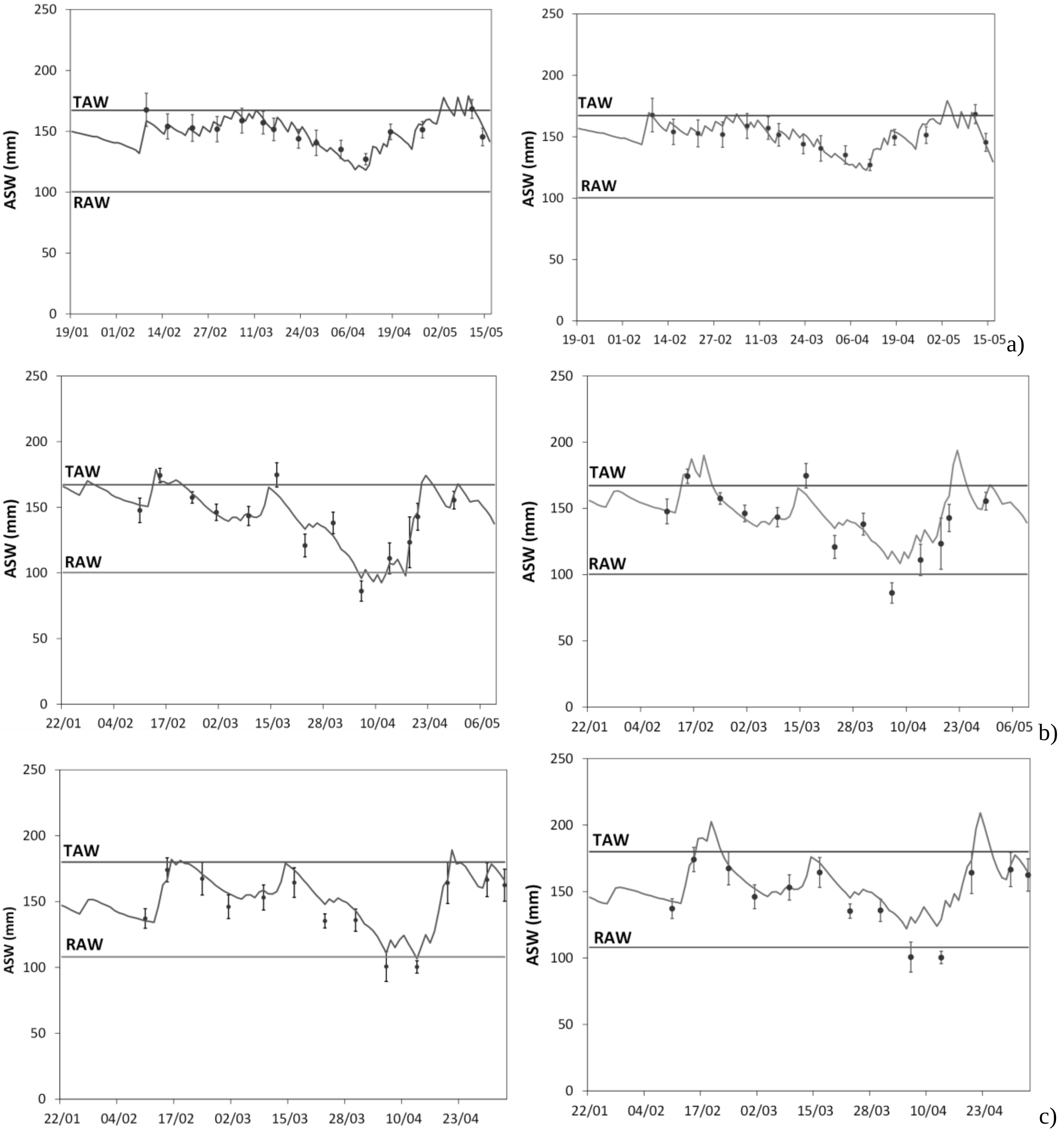

Fig. 7.2. Daily available soil water (ASW) observed (•) and simulated (——) by (left) SIMDualKc and (right) AquaCrop models for the peas experiments: a) plot 1 in 2012(calibration),b) plot 1 in 2011, and c) plot 2 in 2011.

Table 7.6. Indicators of goodness of fit relative to simulated soil water by the SIMDualKc (SIM) and AquaCrop (Aqua) models

Goodness of fit indicators	2011 Plot 1		2011 Plot 2		2012 Plot 1 (calibration)		All experiments	
	SIM	Aqua	SIM	Aqua	SIM	Aqua	SIM	Aqua
b	1.00	1.03	1.03	1.05	1.00	1.01	1.01	1.03
R^2	0.92	0.82	0.95	0.92	0.81	0.83	0.91	0.82
RMSE (mm)	7.1	13.2	7.3	12.8	5.1	4.8	6.5	10.8
RMSE/TAW (%)	4.3	7.9	4.2	7.1	3.2	2.9	-	-
AAE (mm)	5.7	9.6	6.5	9.0	4.3	4.1	5.4	7.4
ARE (%)	4.3	8.2	4.7	7.5	2.9	2.8	2.6	3.4
EF	0.91	0.70	0.91	0.71	0.77	0.80	0.90	0.72
d_{IA}	0.97	0.89	0.97	0.90	0.95	0.95	0.96	0.85

b and R^2 are the coefficients regression and determination; RMSE is the root mean square error; TAW is the total available water; AAE and ARE are the average absolute and relative errors; EF is the model efficiency, d_{IA} is the index of agreement

The estimation errors with SIMDualKc (Table 7.6) are small, with RMSE ranging from 5.1 to 7.3 mm, which correspond to only 3.2 to 4.3% of the TAW of both plots. ARE are in the range 2.9 to 4.7%, thus also showing that estimation errors of the soil water are very small. The index of efficiency EF ranges from 0.77 to 0.91, which indicates that the residuals variance is comparable to the measured data variance, i.e., the model is a good predictor of the soil water dynamics. d_{IA} ranges from 0.95 to 0.97, thus indicating that the mean square error is close to the potential error due to modelling. In conclusion, the indicators of goodness of fit show that simulation modelling was appropriately performed with SIMDualKc and that calibrated values are appropriate for further use of the model. Therefore the model outputs could be later used with small potential errors for estimating peas' yields using the Stewarts' model (Section 7.2). However, errors of estimate are larger for AquaCrop (Table 7.6), with RMSE of 12.8 and 13.2 mm for the validation which represent less than 8% of TAW. ARE are also larger for validation: 7.5 and 8.2%. Consequently, both indices EF and d_{IA} are smaller than for SIMDualKc. The AquaCrop model validation presents higher errors and lower goodness of fit indicators than calibration. Those errors mainly reflect differences in deep percolation D_p and soil evaporation E_s. This is likely due to the fact that calibrating only one K_{cb} value and REW, in addition to a few parameters of the CC curve, is definitely insufficient to properly simulate the season variation of ET and soil water. However, the model does not allow users to calibrate other related values. This fact also justifies differences relative to SIMDualKc.

7.3.2. Water use and partition of crop ET

The terms of the soil water balance computed for the season with both models show large differences between ET and water use components (Table 7.7). The differences in T_c between models (Table 7.7) indicate a non-negligible underestimation by AquaCrop. In SIMDualKc all K_{cb} and p values relative to all crop growth stages are calibrated while in AquaCrop only one K_{cb} value is calibrated, which is likely to be insufficient to further describe the dynamics of transpiration through the crop season. The model adjusts T_c with the computed, non-observed canopy cover (CC) and the user inputs various parameters of the calculation of the CC curve. Nevertheless, the CC curve was adjusted for the calibration year, when a good agreement between the CC derived from LAI measurements and estimated by the model was obtained (Fig. 7.3). The RMSE is good (6.1%) and the EF and d_{IA} are high, respectively 0.96 and 0.99. RMSE results are similar to those obtained by others: Zeleke et al. (2011) reported a RMSE ranging 8.4 to 12.4% for canola, and García-Vila and Fereres (2012) reported RMSE of 4.4% for cotton, of 11.9% for potato and 13.1% for sunflower.

Table 7.7. Simulated season water balance components for sprinkler irrigated peas, seasons 2011 and 2012.

Season	Model	Precipitation (mm)	Irrigation (mm)	Season variation of ASW (mm)	Deep percolation (mm)	Runoff (mm)	Crop transpiration (mm)	Soil evaporation (mm)
2011								
Plot 1	SIMDualKc	337	71	28	74	45	254	63
	AquaCrop			19	89	52	218	30
Plot 2	SIMDualKc	337	75	-19	55	45	219	66
	AquaCrop			-19	67	52	203	30
2012								
Plot 1	SIMDualKc	128	210	8	18	2	225	100
	AquaCrop			27	58	5	200	103

The method used in SIMDualKc for partition of ET_c is the one proposed in FAO56 (Allen et al., 1998), which bases upon the observed ground cover fraction (or its estimation from the observed LAI). That method is well proved (Allen et al., 2005; Allen and Pereira, 2009). Therefore, the SIMDualKc model allows the user to introduce observed f_c values to adjust K_{cb} of the mid and end seasons, which allows also adjusting E_s (Rosa et al., 2012a). Other models use similar approaches such as inputting observed f_c or LAI data to improve T_c adjustments, e.g., the STICS model (Brisson et al., 2003).

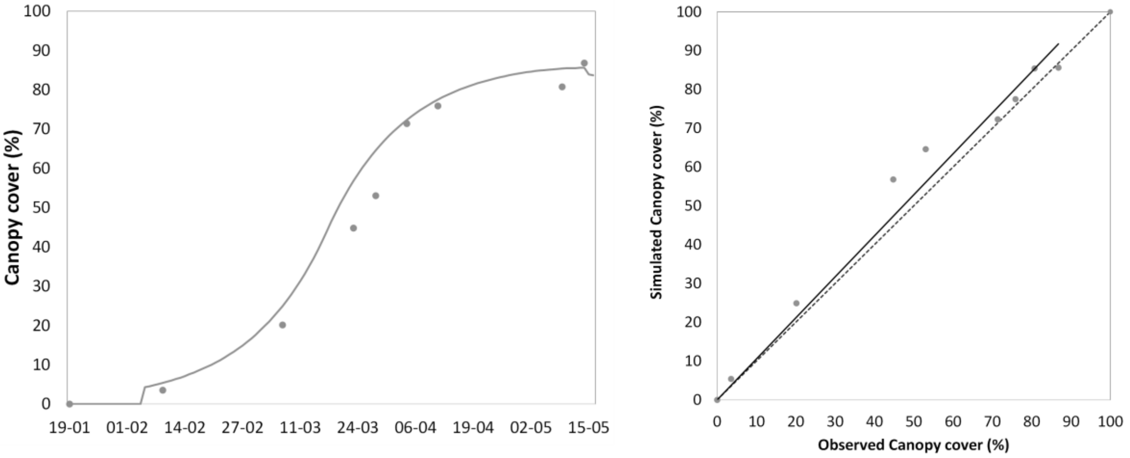

Fig. 7.3. Canopy cover (CC) for peas crop for the calibration (2012): (left) daily simulation (——) and observations (●); (right) regression between observed and simulated values.

Deep percolation is estimated with SIMDualKc with a parametric function (Liu et al., 2006) whose parameters a_D and b_D are calibrated for each soil-watertable application. Differently, with Aquacrop D_p is estimated internally by the model with a function of the saturated hydraulic conductivity. For this application, a sensitivity analysis of D_p relative to changes of up to 90% of the observed K_{sat} value was performed (results not shown). The adopted function has shown poorly reactive to changes in K_{sat}. For 2012, the estimated D_p is too large (58 mm), and much greater than the value estimated with SIMDualKc (18 mm). That value is questionable because application depths were very small, ranging 8 to 15 mm, and the precipitation observed was quite low, with the highest precipitation event of 22 mm only. It is not possible to find a justification for the difference of 40 mm between both models except the inadequacy or lack of calibration of the K_{sat} function used. For 2011 values from both models are less different but larger for AquaCrop. Farahani et al. (2009) found great differences between D_p computed by AquaCrop and field observations, thus concluding that discrepancies could be due to some inadequacy of the model approach to compute D_p. Hsiao et al. (2009) also reported an over-estimation of D_p. Results allow to conclude that the algorithm for estimation of deep percolation in AquaCrop requires further improvements.

SIMDualKc estimates E_s with the Ritchie's model (Allen et al., 1998, 2005) with calibration of the soil evaporation parameters TEW, REW and Z_e referred before. The approach with SIMDualKc has been verified by several field studies reported above (Paço et al., 2012; Pôças et al., 2013; Wei et al., 2013; Zhao et al., 2013). Differently, for AquaCrop only REW is calibrated and there are no studies available assessing the quality of E_s simulations. Most of the

AquaCrop model applications only compare model predictions with observations of CC, biomass and yield, hence lacking the comparison with evaporation measurements. In this study, we observed negligible differences of E_s between both models for the calibration year but very large ones for the validation. As referred before, the simple calibration of REW is likely insufficient to take into consideration the dynamics of soil evaporation with the Ritchie's model. A large underestimation of E_s was also noticed by Farahani et al (2009) for cotton and Katerji et al. (2013) for maize, thus concluding that AquaCrop estimates of soil evaporation may be questionable.

Soil evaporation in AquaCrop shows low sensitivity to wetting events, which were frequent in 2011. Comparing both models, a large discrepancy can be observed for 2011 during the crop development stage, when the soil is not yet fully covered by the crop: E_s is 38 and 39% of ET respectively for plot 1 and 2 when computed with SIMDualKc, and only 15 and 10% when using AquaCrop (Table 7.8). To be noted that E_s estimates with SIMDualKc have been tested in field as referred above. AquaCrop also underestimates E_s relative to SIMDualKc for other stages in 2011. However, for the calibration year differences are minor. It results that seasonal E_s/ET for the validation year (12 and 13%, Table 7.8) are much smaller than those reports by various authors, e.g., Siddique et al. (2001) for peas and Wei et al. (2013) for soybeans, with E_s/ET ratios larger than 34%.

Table 7.8. Simulated soil evaporation (Es) and ratioEs/ETc adj along the crop growth stages for the 2011 and 2012 seasons.

		2011				2012	
		Plot 1		Plot 2		Plot 1 (calibration)	
Crop growth stages		SIMDualKc	AquaCrop	SIMDualKc	AquaCrop	SIMDualKc	AquaCrop
Initial	E_s (mm)	25	20	28	21	46	43
	$E_s/ET_{c\ adj}$ (%)	87	95	85	92	86	89
Rapid growth	E_s (mm)	24	7	27	6	43	42
	$E_s/ET_{c\ adj}$ (%)	38	15	39	10	45	49
Mid-season	E_s (mm)	11	2	9	2	10	15
	$E_s/ET_{c\ adj}$ (%)	8	2	6	2	7	12
Late season	E_s (mm)	3	1	2	1	1	3
	$E_s/ET_{c\ adj}$ (%)	5	2	6	4	2	8
Season	E_s (mm)	63	30	66	30	100	103
	$E_s/ET_{c\ adj}$ (%)	20	12	23	13	31	34

The analysis above indicate the need for improving the estimation of both T_c and, mainly E_s, in AquaCrop, what could be achieved if the FAO56 dual K_c approach could be adopted in FAO66.

Possible errors in the estimation of deep percolation need that the respective algorithm be revised.

7.3.3. Yield predictions

The observed biomass and yield are presented in Table 7.9. These results were used to validate predictions with both approaches: the Stewarts' model in combination with SIMDualKc and AquaCrop. Results from both model approaches are presented in Table 7.10 showing quite small deviations between observed and predicted yields, ranging from 0.3 to 6.4 % for the Stewart's model and from 1.7 to 6.9% when using AquaCrop. Results are therefore similar.

Table 7.9. Peas final above ground biomass and yield for all plots and seasons.

	2011				2012	
	Plot 1		Plot 2		Plot 1	
	Mean	SD	Mean	SD	Mean	SD
Fresh total above ground biomass (kg ha^{-1})	45625	6966	48097	13783	53373	11039
Fresh total peas yield (kg ha^{-1})	10929	1999	13689	4814	11153	2609
Dry total above ground biomass (kg ha^{-1})*	6147	894	8295	2400	8969	1550
Dry total peas yield (kg ha^{-1})*	3281	289	3101	1172	2357	449

SD - standard deviation; * dried at 65±5ºC

The accuracy of the Stewart's model relate to the yield response factor K_y and the quality of estimating crop evapotranspiration. The AquaCrop yield prediction accuracy depends on the estimation of biomass and transpiration, with T_c derived from CC (Steduto et al., 2009). Since the CC curve was well simulated for the calibration year (Fig. 7.3), the prediction accuracy was then quite high (Table 7.10). Accuracy results were similar to those obtained with AquaCrop for other crops as reported by Zeleke et al. (2011) for canola and Stricevic et al. (2011) for maize. Present results are better than those presented by Hsiao et al. (2009) for maize and Araya et al. (2010a, b) for barley and teff. However, this study does not assess the model performance when deficit irrigation is practiced. Katerji et al. (2013), in addition to limitations referred above, reported that the AquaCrop model is less adequate than other models, e.g., STICS and Stewarts' models, for application to deficit irrigated maize.

Table 7.10. Indicators of goodness of fit relative to the prediction of peas final yield (kg ha^{-1}) with the SIMDualKc combined with Stewarts' and AquaCrop models.

Year	Plot	Observed (kg ha^{-1})	SIMDualKc-Stewarts' models			AquaCrop model		
			Predicted (kg ha^{-1})	Deviation (kg ha^{-1})	%	Predicted (kg ha^{-1})	Deviation (kg ha^{-1})	%
Dry total yield								
2012 (calibration)	1	2357	2205	152	6.4	2397	-40	1.7
2011	1	3281	3271	10	0.3	3053	228	6.9
	2	3101	3201	-100	3.2	3198	-97	3.1

7.4. Conclusions

Using soil water content and crop observations at two peas fields, the SIMDualKc model was calibrated and validated. The calibrated K_{cb} obtained are similar to those proposed in FAO56: 0.15 for the initial period, 1.10 for the mid-season and 1.05 at harvesting since the vining peas are harvested fresh. Results of AquaCrop relative to the soil water balance components have shown to be less accurate than those obtained with SIMDualKc. This is likely due to insufficiencies in parameterization and calibration as analysed before. These results call for improvements in AquaCrop ET partition and deep percolation estimation.

The SIMDualKc model was combined with the Stewarts' model to predict peas yields. Results of this simplified approach show high accuracy, with a deviation from observations smaller than 6.4%. Yield predictions by Aquacrop were similar, with deviations lower than 6.9%.

Overall results show that both modelling approaches are acceptable to predict peas yields but AquaCrop is more demanding in terms of parameterization and data input. Further studies are advisable to improve models estimation of vining peas yields.

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Capítulo 8 - Modeling water use, partition of evapotranspiration and predicting yields of barley under supplemental irrigation in a Mediterranean environment

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Modeling water use, partition of evapotranspiration and predicting yields of barley under supplemental irrigation in a Mediterranean environment

Abstract

Data from two malting barley (*Hordeum vulgare* L. cv. Publican) seasons, one dry (2012) and the second wet (2012-13), cropped in a farmer's field located in the Ribatejo region, Portugal, were used with the soil water balance SIMDualKc model. It applies the dual crop coefficient approach for computing and partitioning crop evapotranspiration. Model calibration and validation have shown a good agreement between observed and predicted available soil water (ASW), with low errors of estimate (RMSE < 9% of the total available water) and high modelling efficiency (> 0.85). The calibrated basal crop coefficients for the initial, mid-season and at harvesting were respectively 0.15, 1.10 and 0.10. The AquaCrop model was calibrated for the canopy cover curve using LAI data and then tested using the same ASW data, however with less accuracy than SIMDualKc. This is likely due to less good ET partition and less good estimation of deep percolation. Using SIMDualKc combined with the Stewart's model and the AquaCrop model provided appropriate prediction of barley yields, with deviation not exceeding 10.6%. Both models were used to assess yield impacts of sowing dates and irrigation management strategies for dry climate conditions. Results have shown advantages in early sowing and in adopting supplemental deficit irrigation.

Keywords: Dual crop coefficient, crop transpiration, soil evaporation, SIMDualKc water balance model, Stewarts' water-yield model, AquaCrop model, Portugal

8.1. Introduction

In Portugal, barley (*Hordeum vulgare* L.) is presently the third winter-spring cereal in terms of production but occupying the lowest percentage area (FAOSTAT 2013). Barley is mainly produced in the Ribatejo region, representing 22% of the cropped area with winter-spring cereals (IFAP 2013).

In the Mediterranean area most of the winter-spring grains are rainfed cropped; this is the case of barley. Due to the uncertainty of the amount of rainfall and events variability along crops season, which may be a main constraint for high yields, supplemental irrigation is sometimes required, especially during the most critical crop growth stages (Austin et al. 1998).

Hadjichristodoulou (1982) experiments with rainfed barley showed that grain yield were mainly affected by the distribution of rainfall and pointed out that the impacts are also related with soil water availability.

Several studies have been performed on barley to assess the impacts of various abiotic stresses on yields, such as water and temperature stresses (e.g. Jamieson et al. 1995; Ugarte et al. 2007; Yau and Ryan 2013) or focusing the interaction of both on barley yields (e.g. Hossain et al. 2012) as well as the interaction of water with nitrogen fertilization (Albrizio et al. 2010). The impact of water stress on barley yields depends upon its intensity and on the crop growth stage when it is imposed (Szira et al. 2008). However, there is a controversy around the most critical stage. For some authors it is the stage between double ridge to anthesis since it causes reductions in potential grain number per unit land area (e.g. Cossani et al. 2009); other studies found that the most sensitive stages are flowering and ear formation which lead to the decrease in the numbers of ears per plant and of grains per ear (Thameur et al. 2012). When water stress is imposed during grain formation it will affect grain quality (Qureshi and Neibling 2009) while water stress combined with high temperatures during grain filling leads to the reduction of grain weight (Carter and Stoker 1985; Ugarte et al. 2007; Hossain et al. 2012). Some studies demonstrated that barley grain yield may be also largely influenced by severe water stress imposed throughout the whole crop growth under semi-arid conditions (De Ruitter 1999; Francia et al. 2011; Rajala et al. 2011). Qureshi and Neibling (2009) studied the quality of barley grain for malt production and found that it is affected by soil water availability. The same conclusion was drawn by Carter and Stoker (1985). However, water applied by a sprinkler system close to the barley harvest can cause water-related diseases that reduce grain weight and quality required for malting (Forster 2003).

The sowing date of rainfed barley depends upon the climatic conditions, land surface conditions and harvesting time of the preceding crops (Alam et al. 2007; Yau et al. 2011); yield tends to decrease if barley is sown late since it is exposed to higher risks of heat and water shortage during the grain filling period; contrarily, an early sowing and emergence leads to earlier flowering and maturity, allowing an escape from terminal heat and water stress (Yau et al. 2011). However, dates of sowing need to consider vernalization requirements, which limits anticipation of sowing. Vernalization is mandatory for winter barley varieties but not for spring barley varieties (Karsai et al. 2001; Saisho et al. 2011). Usually vernalization and photoperiod responses are associated; these two mechanisms allow plants to synchronize their growth and reproductive stages with the seasonal weather changes (Van Oosterom and Acevedo 1992; Fowler et al. 2001).

From the above referred, it is important to manage barley water stress without adversely affecting yield and its quality. To help with this task several crop growth models, which relate yield with water and other abiotic stresses (*e.g*. temperature, nutrients), are available for predicting barley yield. Examples of model applications to barley are: AquaCrop (Araya et al. 2010; Abrha et al. 2012; Abi Saab et al. 2014), CERES-Barley (Nain and Kersebaum 2007), Cropsyst (Donatelli et al. 1997; Belhouchette et al. 2008), WOFOST and SWAP (Eitzinger et al. 2004). Recently, Rötter et al. (2012) tested several crop growth simulation models for spring barley yield prediction at several sites in Northern and Central Europe using minimal input data. Simplified approaches for predicting the water stress impacts on barley yield, such as the Stewarts' water-yield model (Stewart et al. 1977), are not available in literature but some studies were performed for wheat (Doorenbos and Kassam 1979; Dehghanisanij et al. 2009; Li et al. 2011; Rao et al. 2013). Moreover, studies assessing possible impacts of climate change on barley are available for Northern Europe (Holden and Brereton, 2006; Högy et al. 2013) but are lacking for Mediterranean conditions. However, such type of studies is available for wheat in the Mediterranean context (Lhomme et al. 2009; Ferrise et al. 2011; Saadi et al. 2014).

Based upon the above, the main objectives of the present study were: (1) To assess water use of barley, including the partition of evapotranspiraton into crop transpiration and soil evaporation using the SIMDualKc water balance model (Rosa et al. 2012a), particularly to derive the basal crop coefficients (K_{cb}) and depletion fractions for no stress (p), and the AquaCrop model. (2) To predict malting barley yields adopting a simplified modelling approach consisting of combining SIMDualKc with the Stewarts' water-yield model (Stewarts et al. 1977) and the crop growth model AquaCrop, as well as comparing both approaches. (3) To assess alternative irrigation schedules and management scenarios in a climate change context focusing dry and very dry climatic conditions considering different sowing dates and various levels of water stress using both modelling approaches.

8.2. Material and methods

8.2.1. Experimental site

The experiments were carried out at a farmers' field in Quinta da Lagoalva de Cima, located in Alpiarça, Ribatejo region, Portugal (39.28º N; 8.55º W and 24 m elevation). The climate is Mediterranean, characterized by mild but rainy winters and dry hot summers. The average annual rainfall (1975-1993) is 689 mm, of which 73% occurs from October to April. Air temperature varies from 9.0 to 24.4ºC in winter and from 14º to 39.6ºC during summer. The weather data were measured with an automatic station located nearby (39.27º N, 8.55º W and 24 m elevation) including daily values of maximum and minimum temperature (ºC), wind speed (m s^{-1}), global solar radiation (W m^{-2}), relative humidity (%) and precipitation (mm). Figure 8.1 shows temperatures, precipitation and ET_o (mm) computed with the FAO-PM method (Allen et al. 1998), relative to the period January 2012 to July 2013. It shows that the 2012 season was dry while the following one was very wet.

The soil is a eutric fluvisol (FAO, 2006) presenting a loamy sand texture where most of the sand is fine (Table 8.1). The total available water (TAW) in the root zone, which represents the difference between the water storages at field capacity (10 kPa) and wilting point (15 000 kPa), is 171 mm m^{-1}. The top 0.20 m of soil present a moderate organic matter (SOM) content of 24.8 mg g^{-1} for the first 0.10 m and 9.1 mg g^{-1} in the second layer. The main soil physical properties are presented in Table 8.1. The saturated hydraulic conductivity (K_{sat}, cm d^{-1}) values were obtained using pedotransfer functions of texture and bulk density (Ramos et al. 2014). The soil presents moderate K_{sat} for the profile except for the top 0.10 m, where the high values are associated with the high organic matter content due to crop residues from the previous crop season, since direct sowing is used by the farmer, and to manure additions. The K_{sat} values are generally in the range of those proposed by Rawls et al. (1998) and Raes et al. (2012) for loamy sand soils.

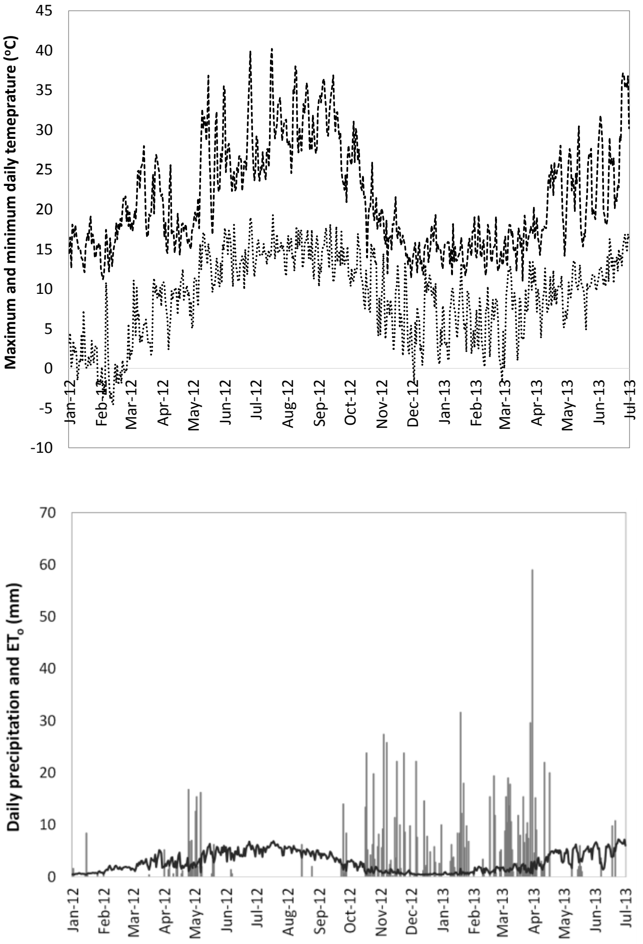


Fig. 8.1. Daily weather characteristics of the Alpiarça meteorological station during the period 2012-13: a) maximum (----) and minimum (······) temperatures; b) precipitation (▮) and FAO-PM reference evapotranspiration (ET_o) (—).

Table 8.1. Selected soil textural and hydraulic properties.

Depth	Particle size (%)			BD	θ_{sat}	θ_{FC}	θ_{WP}	K_{sat}
(m)	Sand	Loam	Clay	(g cm^{-3})		(cm^3 cm^{-3})		(cm d^{-1})
0.00-0.10	85	11	4	1.34	0.48	0.32	0.08	442
0.10-0.20	84	10	6	1.64	0.35	0.25	0.06	129
0.20-0.40	85	9	6	1.66	0.33	0.22	0.06	93
0.40-0.60	86	8	6	1.57	0.34	0.22	0.04	87
0.60-0.80	85	9	6	1.62	0.34	0.22	0.05	93
0.80-1.00	85	9	7	1.82	0.24	0.17	0.04	92

BD = bulk density; θ_{sat} = volumetric soil moisture at saturation, θ_{FC} = volumetric soil moisture at 10 kPa, θ_{WP} = volumetric soil moisture at 15 000 kPa, K_{sat} = saturated hydraulic conductivity.

The groundwater depth is approximately 10 meters and therefore capillary rise does not influence the root zone moisture conditions.

Farmer's fields were cropped with 200 kg ha^{-1} of malting barley (cv. Publican) seeds using an inter-row spacing of 0.15 m. A density of 342 and 319 plants per m^2 was measured after emergence, respectively in 2012 and 2012-13. This variety is for sowing from November to January. Management practices, which include irrigation and fertilization scheduling, were performed according to the standard practice followed by local growers.

8.2.2. Experimental set up and measurements

Field experiments began in January 2012 and continued until June 2013, including two barley seasons. The 2012-13 season was rainy (Fig. 8.1) and barley was rainfed. The observations were performed inside a field plot, with a surrounding area cropped with barley of approximately 30 ha.

Field observations and measurements included:

(i) The dates of each crop growth stage (Table 8.2) and crop height (h, m) at that time,

(ii) The rooting depth (Z_r, m), with root depths observed in randomly distributed plants, from emergence until maximum canopy cover.

(iii) The fraction of soil covered or shaded by the crop canopy near solar noon (f_c, 0 - 1.0) (Allen et al. 1998; Allen and Pereira 2009). Observations of f_c were visually performed at key dates by mid-day and with help of photographs of the ground shadow.

(iv) The leaf area index (LAI, cm^2 cm^{-2}), that was measured along the crop season at four locations using a non-destructive method with a Decagon AccuPAR LP-80 device following the methodology by Johnson et al. (2010).

(v) The final crop yield that was determined by harvesting plant samples in 0.2 x 0.2 m^2 areas, with a total of seven samples collected per season. The samples were placed in refrigerated containers until transport to the lab, where they were separated into stems, leaves, ear and grains; samples were weighted to obtain fresh weight and oven dried at 65±5ºC until constant weight to obtain dry weight.

(vi) The irrigation system performance. The plot was sprinkler irrigated with a center-pivot system equipped with overhead rotator sprinklers. Evaluations of the distribution uniformity were performed several times along the irrigation season using the methodology proposed by Merriam and Keller (1978) and Martin et al. (2007). The application depths (D, mm) were measured using rain gauges placed at the soil surface near the access probe tubes. The net irrigation depths cumulated to the crop growth stages and to the season were obtained by cumulating these D values.

(vii) The soil water content was monitored with a previously calibrated Sentek DIVINER 2000 probe. Measurements were performed at each 0.10 m until the maximum depth of 0.90 m, with three replications. A total of 16 soil water observation points were monitored. Measurements were performed on a weekly basis, except during the period when precipitation occurred nearly every day (April 2013). Recommendations for accuracy by Allen et al. (2011) were taken into consideration.

8.2.3. Modeling strategies

Two barley seasons were surveyed and used for modelling, the first started by January 2012 and finished at harvesting by June; the second developed from December 2012 to June 2013. The bottom boundary of the simulation domain was the maximum rooting depth and the upper boundary was the top of the canopy. Two modeling strategies were used and compared. One consists in a simplified approach to estimate yields, provided by the combination of the soil water balance model SIMDualKc (Rosa et al. 2012a) and the Stewart's water-yield model (Stewart et al. 1977). The SIMDualKc aims at representing the water use and the evapotranspiration processes as a response of defined environmental and management conditions, without conceptually growing the crop. The other strategy is based upon the AquaCrop model which simulates crop growth and predicts biomass and yield responses to water, thus involving more complex processes than SIMDualKc model.

8.2.3.1. The simplified approach: SIMDualKc and Stewart's models

The water balance model SIMDualKc (Rosa et al. 2012a) uses a daily time step to compute crop ET based on the dual crop coefficient approach (Allen et al. 1998, 2005; Allen and Pereira 2009). Crop evapotranspiration (ET_c, mm) is obtained from the sum of the crop transpiration (T_c) and soil evaporation (E_s). T_c and E_s are obtained from the reference evapotranspiration (ET_o, mm) and the basal and evaporation coefficients (K_{cb} and K_e, dimensionless), thus,

$$\mathrm{T_c} = \mathrm{K_{cb}}\ \mathrm{ET_o} \tag{8.1}$$

$$\mathrm{E_s} = \mathrm{K_e}\ \mathrm{ET_o} \tag{8.2}$$

The SIMDualKc model adjusts the $K_{cb\ mid}$ and $K_{cb\ end}$ values (when $K_{cb\ end} > 0.45$) for local climatic conditions where the minimum relative humidity (RH_{min}) differs from 45% and/or where the average wind speed is different from 2 m s^{-1} (Allen et al. 1998, 2007). The model also allows adjusting K_{cb} when crop partially covers the ground by using a density coefficient, K_d (Allen and Pereira 2009). K_d depends on the effective fraction of ground covered by the crop ($f_{c\ eff}$) and crop height (h). Evaporation from the soil is limited by the amount of energy available at the soil surface in conjunction with the energy consumed by transpiration (Allen et al. 1998, 2007). Thus, the evaporation coefficiente (K_e) is maximum when the topsoil is wet by rain or irrigation and the soil shaded by the crop is small, thus in early stages of crop development.

The actual ET ($ET_{c\ adj}$, mm) is computed as a function of the available soil water in the root zone using a water stress coefficient (K_s, 0 - 1). K_s is expressed as a linear function of the deplection in the effective root zone (D_r)

$$K_s = \frac{\mathrm{TAW} - D_r}{\mathrm{TAW} - \mathrm{RAW}} = \frac{\mathrm{TAW} - D_r}{(1-p)\ \mathrm{TAW}} \quad \text{for } D_r > RAW, \tag{8.3a}$$

$$K_s = 1 \qquad \text{for } D_r \leq RAW \tag{8.3b}$$

where *TAW* and *RAW* are, respectively, the total and readily available soil water (mm) relative to the rooting depth Z_r, and p is the depletion fraction for no water stress (dimensionless), then resulting RAW = p TAW. Thus, $ET_{c\ adj}$ equals ET_c when $K_s = 1$, otherwise $ET_{c\ adj} < ET_c$ since $K_s < 1$.

The model input data (Rosa et al. 2012a) include climate, crop characteristics, soil properties and management practices (irrigation method and scheduling, mulch, active ground cover). The model flowchart is also presented by Zhang et al. (2013). The input data necessary for the computation of soil evaporation includes the characteristics of the soil evaporation layer, namely its depth Z_e (m); the total evaporable water (TEW, mm), i.e., the maximum depth of water that can be evaporated from the layer when it has been completely wetted (mm) and the readily evaporable soil water (REW, mm), which is the maximum depth of water that can be evaporated without restrictions. The model computes deep percolation through the bottom of the root zone (DP, mm) using a parametric equation described by Liu et al. (2006), and runoff using the curve number approach (USDA-SCS 1972; Allen et al. 2007).

The model has been calibrated and validated for a wide variety of field crops and environments (Rosa et al. 2012b; Martins et al. 2013; Zhang et al. 2013), and for tree crops and vineyards (Paço et al. 2012; Fandiño et al. 2012). The validation of the Ritchie's soil evaporation approach (Ritchie 1972) adopted by the model to compute E_s (Allen et al. 1998, 2005) was performed for a peach orchard (Paço et al. 2012), for maize and wheat (Zhao et al. 2013) and for soybeans (Wei et al. 2013). Ding et al. (2013) also validated the Ritchie's approach for maize with plastic mulch and bare soil.

In the present study, the SIMDualKc model was combined with the Stewarts' model (Stewart et al. 1977) to assess the impacts of water deficits on yields. The Stewarts' approach assumes that yield losses vary linearly with the evapotranspiration deficits according to a yield response factor and may then be expressed as follows:

$$1 - \frac{\mathrm{Y_a}}{\mathrm{Y_m}} = \mathrm{K_y}\left(1 - \frac{\mathrm{ET_{c\ adj}}}{\mathrm{ET_c}}\right) \tag{8.4}$$

where $ET_{c\ adj}$ and ET_c are respectively the actual and maximum crop evapotranspiration (mm), Y_m and Y_a are the potential and actual yields (kg ha^{-1}) corresponding to optimal and actual water supply conditions, and K_y is the crop yield response factor (dimensionless).

The component of ET which is directly responsible for yield formation is crop transpiration; thus it was adopted in the present study instead of ET_c. This combination approach was previously successfully applied to maize (Paredes et al. 2014). Furthermore, this approach prevents bias due to differences in E_s/ET ratios relative to different deficit experiments or locations. The actual yield ($\widehat{Y_a}$) is then estimated as:

$$\widehat{\mathrm{Y_a}} = \mathrm{Y_m} - \frac{\mathrm{Y_m K_y T_d}}{\mathrm{T_c}} \tag{8.5}$$

were T_d is the difference between T_c and T_a, which were obtained using SIMDualKc model after proper calibration; Y_a was the dry yield observed at each year; Y_m were obtained from the highest yields achieved in the study area and then adjusted with the estimation obtained with the 'Wageningen method' (Doorenbos and Kassam 1979). Thus, the dry maximum yield for the 2012 experiment was set at 7912 kg ha^{-1} and for 2012-2013 at 6465 kg ha^{-1}.

No studies are available in literature relative to the application of the Stewarts' approach for barley; however, a linear relationship between yield and evapotranspiration was found in a 13-year study with barley (Metochis and Orphanos 1997), which allows assuming the applicability of the Stewart's model. Moreover, the relatively common application of this model (Eq. 8.4) for wheat also allows that assumption. Examples include the K_y for winter and spring wheat, respectively 1.0 and 1.15, reported by Doorenbos and Kassam (1979). Dehghanisanij et al. (2009) reported seasonal K_y of 1.03 and 1.23 for winter wheat in two different locations in Iran. Rao et al. (2013) found K_y ranging 0.87 to 1.09 for various locations of India. Li et al. (2011) reported K_y ranging 0.89 to 1.31 for several locations in North China Plain. The variability of K_y values is generally due to the crop varieties, timing of application of water stress, the irrigation method, the planting date and the variability of local climate conditions (Kaboosi and Kaveh 2012). Taking into consideration the studies available in literature, adjustments to local conditions and the fact that transpiration was used instead of ET (Paredes et al. 2014), a K_y = 1.25 was used in the present study.

8.2.3.2. The AquaCrop model

The AquaCrop model (Steduto et al. 2009; Raes et al. 2012) uses a daily time step for computing and separating ET components, T_c and E_s. To estimate T_c the model includes a simple canopy growth and senescence model depending upon the canopy ground cover (CC, %). The model applies a semi-empiric approach to compute yields. The above ground dry biomass (B, kg ha^{-1}) is estimated using the water transpired by the crop along the season and the biomass water productivity (WP_b*, g m^{-2}) that represents the above ground biomass produced per unit of land area considering both the cumulative transpiration, after normalization for atmospheric CO_2 concentration, and ET_o (Raes et al. 2012). The crop yield (Y, kg ha^{-1}) is obtained from B as

$$Y = f_{HI}\ HI_o\ B \tag{8.6}$$

where HI_o is the reference harvest index, which indicates the harvestable proportion of biomass, and f_{HI} is an adjustment factor relative to five water stress factors relative to inhibition of leaf growth, inhibition of stomata, reduction in green canopy duration due to senescence, reduction in biomass due to pre-anthesis stress, and pollination failure (Raes et al. 2012).

In this study, HI_o relative to barley dry yields was observed in both seasons and the average $HI_o = 0.46$, assumed for no stress conditions, was used in the AquaCrop simulations. This averaging approach follows those adopted in other studies with the same model (Araya et al. 2010; Zeleke et al. 2011; Yuan et al. 2013). That HI_o value is in the range of values reported for barley by López and Arrùe (1997) [0.28-0.55], whose values varied with the year, location and tillage impacts, Cantero-Martínez et al. (2003) [0.39 - 0.46], Belhouchette et al. (2008) [0.48] and Abi Saab et al. (2014) [0.40 to 0.48].

The AquaCrop model is the combination of four sub-models for handling: 1) the soil water balance; 2) the crop development, growth and yield; 3) rainfall, ET_o and CO_2 concentration in the atmosphere; and 4) crop management, which includes irrigation and fertilization (Raes et al. 2012). The model simulates the impact of water stress in crop growth using various stress coefficients. Water stress is assumed to impact crop growth processes through i) reducing the canopy expansion rate; ii) acceleration of senescence; iii) closure of stomata; and iv) changes in the harvest index after the start of the reproductive growth (Raes et al. 2012).

The model input data (Raes et al. 2012) include daily climatic data concerning minimum and maximum air temperatures, reference evapotranspiration (ET_o), precipitation, and mean annual carbon dioxide concentration in the atmosphere. The soil input data refer to a maximum of five layers and, for each layer, include K_{sat}, θ_s, θ_{FC} and θ_{WP} as described in Table 8.1; data for the two lower layers were averaged. The crop input parameters consisted of: a) the dates relative to emergence, maximum coverage, maturity and senescence; b) the maximum canopy cover (CC_x), the canopy growth coefficient (CGC), the canopy decline coefficient (CDC), which describe the canopy cover (CC) curve; c) the crop transpiration coefficient at CC_x ($K_{c\,Tr\,x}$), that corresponds to the maximum basal crop coefficient; d) the biomass water productivity (WP_b*) and the harvest index (HI_o) used to compute the yield. Input data also include the readily evaporable water (REW) and the curve number (CN), that are the same variables used with SIMDualKc. The model computes deep percolation with an algorithm that uses K_{sat}, θ_s, and θ_{FC} (Raes et al. 2006). The field management input data include irrigation dates and respective depths.

The canopy cover is equivalent to the fraction f_c in FAO56 (Allen et al. 1998) and in SIMDualKc (Rosa et al. 2012a); however, in AquaCrop, CC is used differently. While SIMDualKc uses observed f_c data, or f_c data derived from observed LAI to compute the $K_{cb\,adj}$

using the input K_{cb} curve throughout the crop cycle (section 8.2.3.1), AquaCrop uses a computational algorithm to estimate CC and to proportionally estimate the K_{cb} along the season from the single input value of $K_{c\ Tr\ x}$ (Raes et al. 2012).

To test the goodness of the AquaCrop estimation of the CC curve, CC values obtained from the observed LAI of the green leaves may be used for comparison. To obtain CC from LAI an exponential function of time is commonly used with diverse parameterization (Farahani et al. 2009; Hsiao et al. 2009; Araya et al. 2010; Zeleke et al. 2011). Generally, parameterization focus the coefficient of extinction of canopy, α, which is an indicator of crop shadow on the ground (Jeuffroy and Ney 1997). These authors, using data from various crops, discussed the variability of α values relative to differences in plant density, row spacing, crop management, environmental conditions (*e.g.* water stress) and approaches used for measuring radiation. Some model applications report extinction coefficients for barley: Araya et al. (2010) report $\alpha = 0.65$ while lower values are reported by Bernstsen et al. (2004) [0.50], Belhouchette et al. (2008) [0.48], and Donatelli et al. (1997) [0.45]. Similar low values are reported for wheat: $\alpha = 0.48$ (Benli et al. 2007) and $\alpha = 0.50$ (Singh et al. 2008). In the present study the value $\alpha = 0.50$ was assumed since it is a common value for both barley and wheat.

8.2.4. Models parameterization, calibration and validation

SIMDualKc was calibrated with 2012 data. An iterative trial-and-error procedure was applied in order to minimize error propagation along the simulated processes. The control variable for the calibration was the available soil water (ASW). Validation was performed with an independent set of data collected in 2012-2013.

The calibration of SIMDualkc aimed at optimizing the crop parameters (K_{cb} and p) relative to the various crop growth stages, the soil evaporation parameters (TEW, REW and Z_e), the deep percolation parameters (a_D and b_D), and the runoff curve number (CN). The procedure follows those reported by Rosa et al. (2012b) and Martins et al. (2013). The initial conditions consisted of the initial depletion of the evaporable layer, that was 10% of TEW, and the initial depletion for the entire root zone, that was 20% of TAW. The trial and error procedure progressively adjusted K_{cb} and p until small errors were achieved; after that, the procedure was applied to the percolation parameters a_D and b_D and the soil evaporation parameters TEW, REW and Z_e. In the following iterations, the procedure was applied again to the crop parameters until error values did not decrease from an iteration to the next. The validation of SIMDualKc consisted of using the previously calibrated parameters (K_{cb}, p, TEW, REW, Z_e, a_D and b_D) with the 2012-2013 data. The initial depletions for both the effective root zone and of the evaporable layer were set at 30% of TAW and 10% of TEW respectively. That value for the effective root zone depletion is lower than the one used in the calibration season because less precipitation occurred before sowing.

The AquaCrop model uses a large number of parameters including various conservative parameters that are expected to change little with time, management or location, which are described and tabled by Raes et al. (2012). These tabled values were used together with other conservative parameters that were adjusted for barley on basis of field experiments reported by Araya et al. (2010) and Abi Saab et al. (2014). The model was first parameterized for appropriately describing the CC curve given its importance to model simulation of both transpiration (T_c) and soil evaporation (E_s). The first trial and error procedure focused the parameters that influence the CC curve, i.e., CC_x, CGC and CDC. Different parameters values were searched for both years.

In the following, trial and error focused on adjusting $K_{c\,Tr\,x}$ comparing simulated and field ASW data. This was performed using the REW and CN parameters first obtained when calibrating SIMDualKc. In addition, the model was also parameterized for WP_b* using observed total above ground dry final biomass (B) and yield (Y). The model was parameterized with 2012 data and tested using the same parameters with data of the 2012-13 season. Data on soil, irrigation schedules and climate used with AquaCrop were the same as used with SIMDualKc including those for the initial soil water conditions.

The “goodness-of-fit” of the models was assessed similarly to previously performed by Rosa et al. (2012b) and Zhang et al. (2013), thus using:

(i) a linear regression forced to the origin between observations and simulations; the regression coefficient (b) and the determination coefficient (R^2) were used as indicators;

(ii) a set of indicators of residual estimation errors (Moriasi et al. 2007) computed from the pairs of observed and predicted values O_i and P_i (i = 1, 2, ..., n), whose means are $\overline{O}$ and $\overline{P}$, respectively:

a) the root mean square error (RMSE), which expresses the variance of the errors

$$\mathrm{RMSE} = \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n} \right]^{0.5} \tag{8.7}$$

b) the average absolute error (AAE) and the average relative error (ARE) which express the average size of estimated errors

$$\mathrm{AAE} = \frac{1}{n} \sum_{i=1}^{n} |O_i - P_i| \tag{8.8}$$

$$\mathrm{ARE} = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{O_i - P_i}{O_i} \right| \tag{8.9}$$

(iii) a set of quality of modelling indicators (Moriasi et al. 2007) consisting of

a) the Nash and Sutcliff (1970) modelling efficiency (EF, dimensionless), that is used to determine the relative magnitude of the residual variance compared to the measured data variance:

$$\mathrm{EF} = 1.0 \quad \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2} \tag{8.10}$$

b) the Willmott (1981) index of agreement (d_{IA}, dimensionless) that represents the ratio between the mean square error and the "potential error" due to modelling

$$d_{IA} = 1 - \frac{\sum_{i=1}^{N} (O_i - P_i)^2}{\sum_{i=1}^{N} \left(|P_i - \overline{O}| + |O_i - \overline{O}| \right)^2} \tag{8.11}$$

8.3. Results and discussion

8.3.1 Crop development and yield

Table 8.2 shows the observed barley growth stages along both seasons; the delay in barley sowing date in 2012 was due to heavy rainfall during the pre-planting period, October-December of 2011, with a total precipitation of 303 mm, and to relatively high temperatures during December. Differently, in the following season sowing was performed by December since few rainfall and low temperatures occurred by November-December 2012 (Fig. 8.1). It was also observed (Table 8.2) that harvesting was performed late in 2012 relative to 2013, which relates to the cumulative growth degree days (GDD) required for completing the crop cycles.

Table 8.2. Barley growth stages dates for each experimental season.

	Crop growth stages				
Year	Initial	Crop development	Mid-season	Late-season	Harvest
2012	16/01 to 06/02	7/02 to 02/04	03/04 to 19/05	20/5 to 25/06	26/06
2012-2013	06/12 to 12/01	13/01 to 09/03	10/03 to 04/05	05/05 to 05/06	06/06

Table 8.3 shows the measured values of LAI (cm^2 cm^{-2}) for both barley seasons. Results show that during the 2012 season the highest observed LAI value was 4.84 cm^2 cm^{-2} while in 2012-2013 the highest observed LAI value was 3.55 cm^2 cm^{-2}. This low LAI may be explained by a smaller plant density after emergence and tillering, and by a less good crop development due to heavy rain and lower radiation energy during 2013.

Table 8.3. Measured leaf area index (LAI, cm^2 cm^{-2})

Dates	LAI (cm^2 cm^{-2})	Dates	LAI (cm^2 cm^{-2})
07/02/2012	0.24	05/02/2013	1.54
04/04/2012	2.68	19/02/2013	2.53
01/05/2012	3.37	25/02/2013	2.77
07/05/2012	3.82	13/03/2013	3.47
13/05/2012	4.84	23/04/2013	3.55
29/05/2012	3.88	22/05/2013	3.16
31/05/2012	3.75	04/06/2013	2.19
14/06/2012	2.45		

During both crop seasons, roots surveillance showed that higher root densities were found in the top 0.30 m soil layer. Though, more roots, including those of smallest diameter, were found down to 0.85 m depth. These observations results are in agreement with those by Dwyer et al. (1988) and Hansson and Andrén (1987).

Field evaluations of the center-pivot irrigation system were performed along the 2012 season that allowed to compute an average distribution uniformity of 79%. Since the system was equipped with overhead sprinklers, this value indicates the influence of wind. The measured application depths were about constant throughout the season and averaged D = 7 mm. Table 8.4 presents the cumulated values of the precipitation (mm) observed for each crop growth stage and, for 2012, when supplemental irrigation was adopted, the cumulated net irrigation depths (mm).

Table 8.4. Net irrigation depths (mm) and precipitation (mm) for each growth stage

Crop growth stages	2012		2012-2013
	Precipitation (mm)	Irrigation (mm)	Precipitation (mm)
Initial	2	0	78
Crop development	5	94	159
Mid-season	100	40	270
Late-season	8	10	61
Total	115	144	568

As referred in Section 8.2.2, several samples were collected at harvest. The observed final biomass, yield characteristics (number of spikes per square meter and weight of 1000 grains) and total yield are presented in Table 8.5. These results were used to validate predictions with both above described approaches: the Stewarts' model in combination with SIMDualKc, and AquaCrop. Results show that higher yields were attained in the 2012 season relative to 2012-2013, which related to a higher number of spikes per m^2 despite a lower weight of 1000 grains was observed. Differences relate with the above referred smaller LAI and less favorable climate conditions in 2013.

Table 8.5. Dry final above ground biomass and yield for both barley seasons

	Number of spikes per m^2	1000 grains dry weight (g)	Dry total above ground biomass (kg ha^{-1})	Dry total yield (kg ha^{-1})
2012	1225	30.4 (± 1.7)	14463 (± 417)	6331 (±417)
2012-2013	950	41.0 (± 0.9)	12503 (±1160)	5843 (±612)

Standard deviation between brackets; * dried at 65±5ºC

8.3.2. Models parameterization, calibration and validation

The initial and final values of the calibration parameters relative to the SIMDualKc model - K_{cb}, p, TEW, REW, Z_e, CN, a_D and b_D - are presented in Table 8.6. The initial values for K_{cb}, p, TEW, REW and Z_e were based on Allen et al. (1998), those of CN on tabled values in USDA-SCS (1972), and those for a_D and b_D on the study by Liu et al. (2006). The calibrated K_{cb} values obtained are similar to those proposed by Allen et al. (1998) but the $K_{cb\ end}$ value, which depends upon crop management, is much lower because delayed harvesting was adopted. The values for p at all crop stages are the same as proposed by Allen et al. (1998). The initial values of REW and TEW were obtained using the textural and water holding characteristics of the evaporable layer, and the calibrated ones are close to those proposed by Allen et al. (1998) for medium textured soils. The CN calibrated value is close to those proposed by the USDA-SCS (1972) for soils with medium texture and cereal land use. The value of a_D was adjusted taking into consideration the soil water storage at saturation and at field capacity, while b_D depends upon the soil draining characteristics; thus the values proposed by Liu et al. (2006) were used to initiate simulations; the calibrated values are not far from the initial ones (Table 8.6).

Table 8.6. Initial and calibrated values of the parameters used with SIMDualKc

	Initial	Calibrated
Crop parameters		
K_{cbini}	0.15	0.15
$K_{cb\ mid}$	1.10	1.10
$K_{cb\ end}$	0.30	0.10
$p_{ini,}$ p_{mid} and p_{end}	0.55	0.55
Soil evaporation parameters		
REW (mm)	10	7
TEW (mm)	30	28
Z_e (m)	0.10	0.10
Runoff and deep percolation parameters		
CN	72	75
a_D	270	300
b_D	-0.0173	-0.020

The conservative and non-conservative parameters used with AquaCrop are presented in Table 8.7. The presentation of parameters follow that by Hsiao et al. (2009). The $K_{c\ Tr\ x}$ = 1.12 (Table 8.7) is similar to the $K_{cb\ mid}$ =1.10 calibrated with SIMDualKc (Table 8.6). For barley, Abrha et al. (2012) adopted a $K_{c\ Tr\ x}$ = 1.10 while Abi Saab et al. (2014) used a value of 1.15, and Araya et al. (2010) reported $K_{c\ Tr\ x}$ = 1.05.

Table 8.7. Conservative and calibrated crop parameters in AquaCrop model

Description	Units or symbol meaning	Value	
Conservative parameters		Adopted	
Base temperature	ºC	0	
Cut-off temperature	ºC	30	
Canopy cover at 90% emergence (CC_o)	cm^2 per plant	5	
Soil water depletion threshold for canopy expansion	Upper threshold	0.20	
Soil water depletion threshold for canopy expansion	Lower threshold	0.50	
Shape factor for water stress coefficient for canopy expansion	Curve shape moderately convex curve	1.3	
Soil water depletion threshold for stomatal control	Fraction of TAW at which stomata start to close	0.55	
Shape factor for water stress coefficient for stomatal control	Highly convex curve	2.5	
Soil water depletion threshold for failure of pollination	Fraction of TAW at which pollination starts to fail	0.85	
Calibrated parameters		Initial	Calibrated
Crop coefficient for transpiration at CC_x	Basal crop coefficient ($K_{c\,Tr\,x}$)	1.10	1.12
Biomass water productivity (WP_b*)	g m^{-2}	15.0	13.0
Parameters of the canopy cover curve		1st year	2nd year
Maximum canopy cover, CC_x,	%	90	85
Canopy growth coefficient, CGC*	Fraction per growing degree day	0.40	0.64
Canopy decline coefficient, CDC*	Fraction per growing degree day	0.44	0.33

* these values depend upon the adopted base and cut-off temperatures

The WP_b* used in the present study (13 g m^{-2}) is within the range of the model default values set for C3 plants (Raes et al. 2012). The same value was found by Abi Saab et al. (2014) in a Mediterranean environment and by Araya et al. (2010) in Ethiopia. Abrha et al. (2012) reported an average WP_b* of 15 g m^{-2} for several locations in Ethiopia, Italy, Syria and Montana, USA.

The ability of AquaCrop to produce good prediction results for soil evaporation, crop transpiration and yield definitely depends upon the appropriate parameterization of the CC curve. This importance was not stressed by other researchers or by the authors (*e.g.*, Raes et al. 2012). It was possible to obtain reasonably good results for yield with runs of the model without a very careful parameterization but results for simulating ASW as well as for E_s and T_c could only be highly improved when a more accurate parameterization of CC curve was achieved. As previously referred, the CC observed values used for that parameterization were obtained from LAI measurements using an extinction coefficient α = 0.50. Different CC_x, CGC and CDC were obtained for 2012 and 2012-13 (Table 8.7); thus, contrarily to most models, it was not possible to perform a calibration and validation but different parameterizations for the CC curves for both crop seasons (Fig. 8.2).

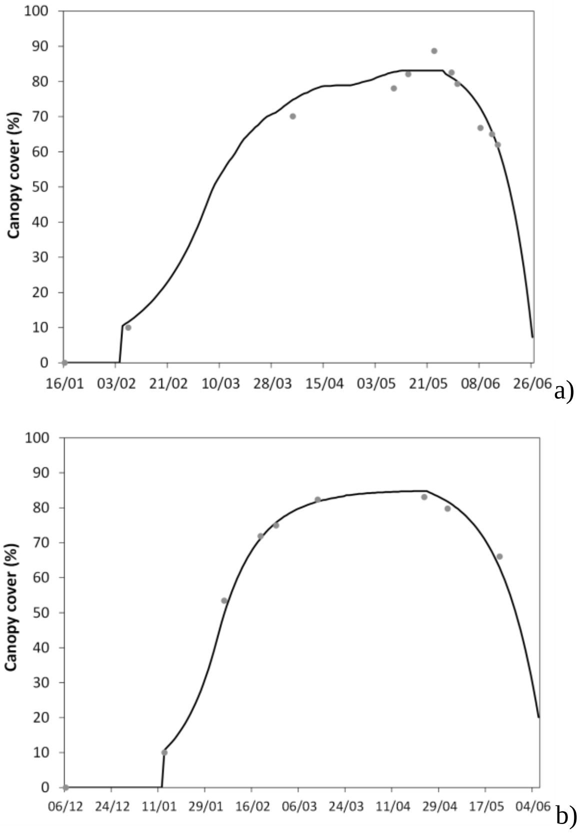
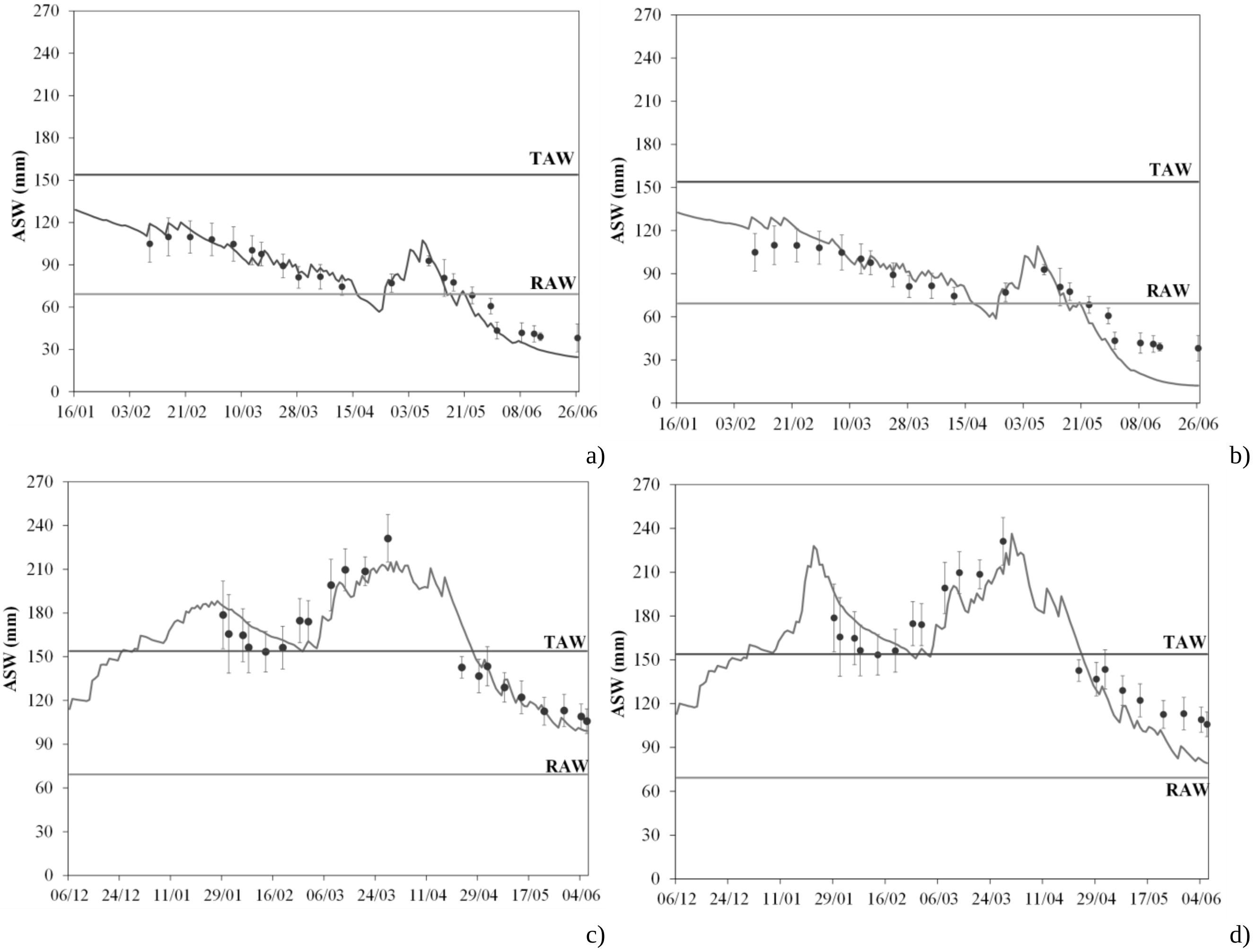


Fig. 8.2. Barley canopy cover (CC) simulation (—) and observations (●) for the seasons of: (a) 2012 and (b) 2012-13.

The “goodness-of-fit” of both CC curves show no tendency for over- or under-estimation, with b = 1.00 and R^2 = 0.99 for the regression forced to the origin relating observed and simulated CC values. Low estimation errors (Eq. 8.7) were observed, with RMSE = 3.2 and 1.9% respectively for the 2012 and 2012-13 seasons. Other AquaCrop applications reported comparisons between observed and simulated CC showing a wide range of adequacy of CC fitting. Hsiao et al. (2009), for maize, reported RMSE ranging 4.8 to 13.6%. Wellens et al. (2013) for cabbage and Zeleke et al. (2011) for canola reported RMSE values ranging from 8.4 to 13.3%. García-Vila and Fereres (2012) reported also RMSE ranging: 4.4% to 13.1% for various crops. It can be concluded that the errors of simulation of CC in this study are definitely low.

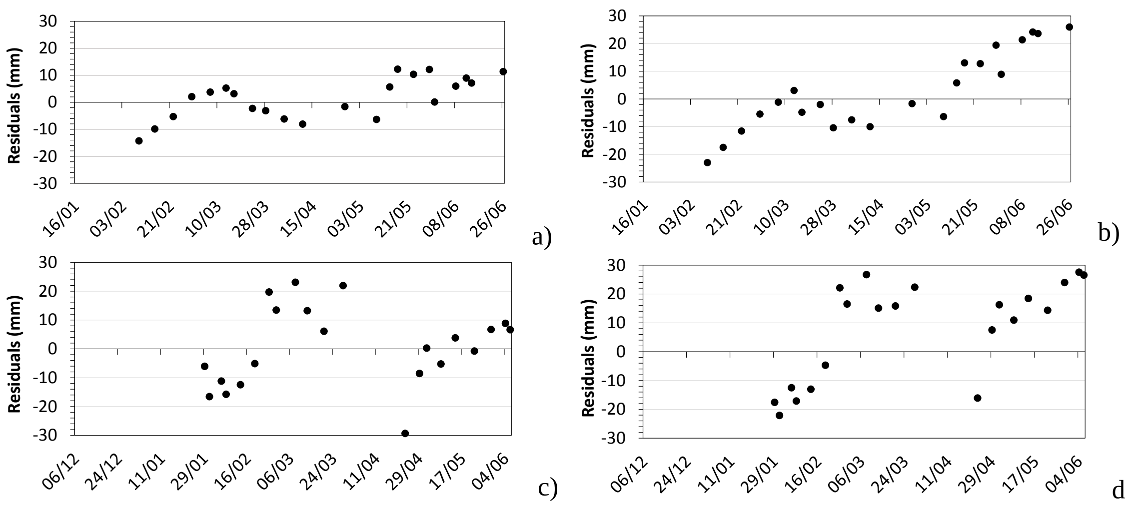
Fig. 8.3 shows the comparison between the observed and simulated ASW values throughout both crop seasons. Results show that a late season stress occurred during the 2012 season (observed ASW below the RAW threshold) because irrigation was ceased 30 days before harvesting; contrarily, in 2012-2013, no water stress occurred due to abundant rains during this crop season. Fig. 8.3a and c shows that SIMDualKc simulates well ASW, however with a low bias of estimation in the wet period of 2013 (ASW above TAW). Fig. 8.3b, which corresponds to the parameterization of AquaCrop for the dry season, shows that the model over-estimated ASW during most of the season but highly under-estimated ASW during the late season, thus indicating a non-negligible bias of estimation during that late season. For 2012-13 (Fig. 8.3d), simulations show again high under-estimation of ASW during the late season period and part of the mid-season.

Figure 8.4 presents the simulation residuals (O_i - P_i) of ASW along both crops seasons when using both modelling approaches. Residuals for the wet season of 2013 are larger because most of values are quite large, above TAW. Higher residuals with some heterogeneity can be seen in AquaCrop simulations showing a possible non-stationarity of the residuals distribution. Actually, AquaCrop residuals tend to be large in the late season of both experiments revealing that the model tends to under-estimate ASW in that period. The SIMDualKc model presents (Fig. 8.4a and c) lower residuals, with more residuals close to zero, especially in the calibration year. Overall results lead to consider that the SIMDualKc model is a more adequate model for ASW predictions.



a) b) c) d)

Fig. 8.3. Observed (•) and simulated (——) daily available soil water (ASW) by the SIMDualKc – (a) 2012 and (c) 2012-13 - and AquaCrop - (b) 2012 and (d) 2012-13 (error bars correspond to the standard deviation of ASW observations).



a) b) c) d)

Fig. 8.4. ASW residuals (●) when using SIMDualKc – (a) 2012 and (c) 2012-13 - and AquaCrop - (b) 2012 and (d) 2012-13.

The "goodness-of-fit" indicators relative to daily ASW predictions by SIMDualKc and AquaCrop models are presented in Table 8.8. Results for SIMDualKc show a very good agreement between observed and simulated ASW, with regression coefficients b of 1.00 and 0.99 and determination coefficients R^2 of 0.96 and 0.85, respectively for 2012 (calibration) and 2012-13 (validation) seasons. Regression coefficients equal to 1.0 indicate that the predicted and observed values were statistically similar. High R^2 indicates that the total variance of the observed ASW values was explained by the model.

Table 8.8. "Goodness-of-fit" indicators relative to daily ASW predictions by SIMDualKc and AquaCrop models

Season		b	R^2	RMSE (mm)	RMSE/TAW (%)	AAE (mm)	ARE (%)	EF	d_{IA}
2012	SIMDualKc	1.00	0.96	7.6	5.0	6.6	10.1	0.91	0.98
2012-2013	SIMDualKc	0.99	0.85	13.5	8.7	11.2	7.5	0.85	0.96
2012	AquaCrop	1.01	0.85	14.2	9.2	11.8	20.1	0.66	0.95
2012-2013	AquaCrop	0.96	0.82	18.5	12.0	17.5	11.9	0.72	0.94
All experiments	SIMDualKc	0.99	0.95	10.9	7.1	8.8	8.6	0.95	0.99
	AquaCrop	0.97	0.91	16.4	10.6	14.5	16.0	0.89	0.97

Estimation errors with SIMDualKc were low, with RMSE (Eq. 8.7), which characterizes the variance of the errors, of 7.6 and 13.5 mm respectively for the calibration and validation seasons, which correspond to less than 9% of TAW. The ARE (Eq. 8.9), which express the relative size of estimation errors, were 6.6 and 11.2% respectively for the calibration and validation seasons, thus showing good modelling estimates. The Nash and Sutcliff model efficiency (EF) were 0.91 and 0.85 respectively for calibration and validation. These high EF (Eq. 8.10) values indicate that the residuals variance is much smaller than the measured data variance (Moriasi et al. 2007), i.e., the model is a good predictor of the soil water dynamics. The Willmott indices of agreement (d_{IA}, Eq. 8.11) were respectively 0.98 and 0.96 for the calibration and validation seasons, thus indicating that the mean square error is close to the potential error due to modelling. When combining all observed ASW values and comparing them with the simulated ones it results b = 0.99 and R^2 = 0.95. These values also support that no bias of estimation occurred as referred above, and that the variation of observed ASW is well explained by the model. The RMSE represents approximately 7% of TAW when combining all data. In conclusion, the indicators of "goodness-of-fit" show that SIMDualKc appropriately simulates ASW.

For AquaCrop, results for b, 1.01 in the first season and 0.96 in the second one, indicate no overall trend for over- or under-estimation in the first year and a slight tendency to under-estimate in the second; however, as analysed before, a bias exist. R^2 values are smaller than those for SIMDualKc, with values of 0.85 and 0.82 respectively for 2012 and 2012-13 seasons. Results also show higher RMSE values for AquaCrop, 14.2 and 18.5 mm, respectively for 2012 and 2012-13 seasons, i.e. larger than 9% of TAW. ARE are also much higher, 20.1 and 11.9% respectively for 2012 and 2012-13. Consequently, the EF indicators highly decrease relative to SIMDualKc, with EF = 0.66 for 2012 and EF = 0.72 for 2012-13, thus indicating that the variance of residuals is relatively large (Eq. 8.10). The less good indicators of "goodness-of-fit" of AquaCrop simulations of ASW reflect the above referred bias of estimation and that, as for the previous analysis, AquaCrop is less accurate than SIMDualKc for predicting ASW. Results clearly point out that SIMDualKc model outputs are appropriate to be used for estimating barley yields in combination with the Stewarts' model, and to assess impacts of alternative irrigation schedules aimed at adaptation to future dryness of the climate.

8.3.3. ET partitioning and water use

The components of the soil water balance computed for both crop seasons are presented in Table 8.9. Both models produce some different estimates of ET for both seasons. The partition of ET is also somewhat different in absolute terms. Contrarily to SIMDualKc, the model AquaCrop estimates a smaller E_s in the wet year relative to the dry year (2012). Farahani et al. (2009) for cotton and Katerji et al. (2013) for maize reported a large underestimation of E_s, thus concluding that the approach used in AquaCrop to estimate soil evaporation is questionable. However, most of the studies with AquaCrop only report comparisons between observations and model predictions of CC, biomass and yield, hence lacking the comparison with evaporation and/or transpiration measurements, thus not providing an appropriate assessment of E_s and T_c simulations.

Seasonal E_s represents 21 and 23% of ET respectively for 2012 and 2012-13 seasons when using both models (Table 8.9). These results for the seasonal E_s/ET are in the range of those reported in literature for winter wheat (which has a similar canopy), e.g., Angus and Herwaarden (2001) that reported values ranging 20 to 26%, Yu et al. (2009) who reported 21 to 28%, Chen et al. (2010) referring E_s/ET ranging 19 to 28%, and Zhao et al. (2013) reporting an average E_s/ET of 29%.

Relative to the non-consumed fraction of the soil water balance, runoff is estimated with the same curve number approach in both models. Thus, while CN was similarly calibrated for both models and runoff estimates are quite similar (Table 8.9), differences occur for deep percolation since approaches are different. SIMDualKc estimates DP with a parametric function (Liu et al. 2006) whose parameters a_D and b_D are calibrated for each soil based upon the soil water storage and decay characteristics. Good results for DP have been previously observed when using SIMDualKc (*e.g.* Rosa et al. 2012b). In AquaCrop, DP is estimated using a deterministic approach based upon the soil water contents at field capacity and saturation in the various soil layers and a drainage characteristic depending of the saturated hydraulic conductivity (Raes et al. 2006; Raes et al. 2012). These different approaches may explain the differences in DP estimation for the wet season of 2012-2013 (Table 8.9), i.e., 200 mm with AquaCrop and 178 mm with SIMDualKc. Hsiao et al. (2009) also reported an over-estimation of DP. Farahani et al. (2009) reported significant differences between DP computed by AquaCrop and field observations, concluding that discrepancies could be due to some inadequacy of the approach used in AquaCrop to compute DP. Thus, the corresponding algorithm may require further improvements.

Table 8.9. Simulated water balance for sprinkler irrigated barley, 2012 and 2012-13 seasons (all terms are in mm).

Season	Model	P	I	ΔASW	DP	R	E_s	T_a	$ET_{c\ adj}$	E_s/ $ET_{c\ adj}$
2012	SIMDualKc	115	145	108	0	2	77	289	366	21
	AquaCrop			118	0	1	81	296	377	21
2012-13	SIMDualKc	568	0	23	178	56	82	275	357	23
	AquaCrop			39	200	62	78	267	345	23

P = precipitation, I = irrigation, ΔASW = variation in available soil water, DP= deep percolation, R = runoff; E_s = soil evaporation, T_a= crop transpiration, $ET_{c\ adj}$ = crop evapotranspiration

Results of soil evaporation and crop transpiration simulations along the crop growth stages are presented in Table 8.10. They show some discrepancies between models results for both crop seasons. During the initial stage, E_s and T_a values are similar but AquaCrop estimated higher E_s. During the crop development stage E_s simulated results were the same for 2012 but smaller with AquaCrop (18 *vs*. 23 mm). During this period, transpiration was much higher in 2012 relative to 2013 due to climatic conditions determining ET_o; this one was 131 mm in 2012 and 64 mm in 2013. E_s for the mid-season period were similar for both years but, contrarily to expectancies, the estimates by AquaCrop were smaller during the wet year. This fact may reflect that soil evaporation calculation in AquaCrop is less sensitive to wetting events, which were very frequent during the 2012-13 season. This is in agreement with the referred conclusions reported by Farahani et al. (2009) and by Katerji et al. (2013) that estimation of E_s is questionable.

Table 8.10. Simulated soil evaporation (E_s), actual transpiration (T_a) and transpiration deficits (T_d) and ratio $E_s/ET_{c\ adj}$ along the crop growth stages for the barley 2012 and 2012-13 seasons

Crop growth stages		2012		2012-13	
		SIMDualKc	AquaCrop	SIMDualKc	AquaCrop
Initial	E_s (mm)	15	12	21	22
	T_a (mm)	3	1	3	1
	T_d (mm)	0	0	0	0
	$E_s/ET_{c\ adj}$ (%)	83	92	88	96
Development	E_s (mm)	42	42	23	18
	T_a (mm)	84	90	39	49
	T_d (mm)	0	0	0	3
	$E_s/ET_{c\ adj}$ (%)	33	32	37	27
Mid-season	E_s (mm)	16	17	19	15
	T_a (mm)	142	142	156	140
	T_d (mm)	3	0	0	19
	$E_s/ET_{c\ adj}$ (%)	10	11	11	10
Late season	E_s (mm)	4	10	19	23
	T_a (mm)	60	63	77	77
	T_d (mm)	39	59	0	0
	$E_s/ET_{c\ adj}$ (%)	6	14	20	23
Season	E_s (mm)	77	81	82	78
	T_a (mm)	289	296	275	267
	T_d (mm)	42	59	0	22
	$E_s/ET_{c\ adj}$ (%)	21	21	23	23

Transpiration results during the mid-season period are similar for both models in 2012. However, in the wet year of 2013 T_a simulated with AquaCrop was 16 mm smaller than with SIMDualKc; moreover, a transpiration deficit T_d = 19 mm was estimated by AquaCrop, which is not possible to physically explain since 2013 was a wet year with abundant precipitation during the mid-season. In addition, Fig. 8.3d does not show any stress during that period, with ASW maintained above TAW. These results call for the need to revise the T_a computation in combination with the referred need to improve E_s estimation as well as DP computation. During the late-season period results by both models are again different. In 2012 (Table 8.10) T_a and E_s were respectively 63 and 10 mm when obtained with AquaCrop, which are higher than those simulated with SIMDualKc (60 and 4 mm). However, as shown in Fig. 8.3b, the AquaCrop model highly under-estimated the ASW during that late season which means that the simulated soil evaporation and crop transpiration were over-estimated. During the late-season of 2013 differences are smaller but ASW is again underestimated with AquaCrop (Fig. 8.3.d).

The less accurate estimation of T_c and E_s in AquaCrop is likely due to the insufficient parameterization of the model relative to K_{cb}, p, TEW and percolation, thus making it not possible to describe the dynamics of water use through the crop season. In fact in SIMDualKc the K_{cb} and p crop parameters, that determine T_c, are calibrated relatively to all crop growth stages (Table 8.6) and the K_{cb} are adjusted to stress as depicted in Fig. 8.5. Differently, in AquaCrop only an approximation to the maximum K_{cb} value ($K_{c\ Tr\ x}$) is calibrated (Table 8.7). Relative to E_s, while three parameters of the Ritchie's model (TEW, REW and Z_e) are calibrated in SIMDualKc, only REW is considered for AquaCrop calibration (Raes et al. 2012). The fact that deep percolation parameters are also calibrated in SIMDualKc but not in AquaCrop is likely to impact the estimation of water use components, thus ET and its partition.

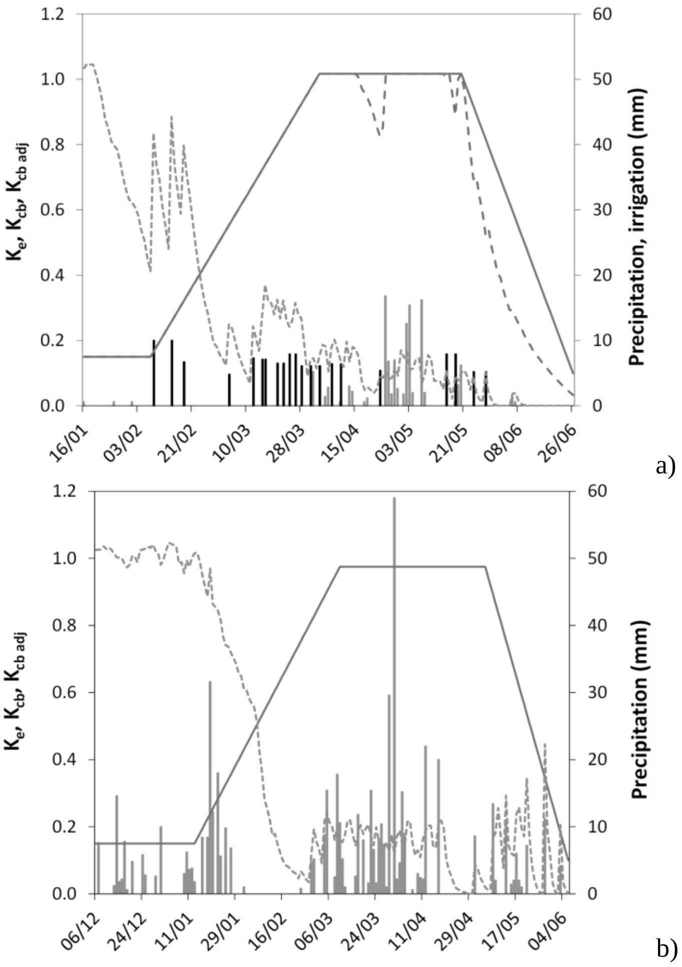


Fig. 8.5. Daily variation of the basal crop coefficient (K_{cb}, ——), adjusted to water stress basal crop coefficient ($K_{cb\ adj}$, – –), and the evaporation coefficient (K_e, - - -), along with precipitation (▮) and irrigation (▮) for: a) 2012 and b) 2012-13 seasons.

Analysing the seasonal variation of the evaporation and basal crop coefficients (K_e and K_{cb}) when using SIMDualKc, results in Fig. 8.5 show that the adjusted basal crop coefficient $K_{cb\ adj}$ lays below the K_{cb} curve for some periods in 2012 (Fig. 8.5a) when water stress occurred. Differently, because no stress occurred during 2012-13 (Fig. 8.5b) $K_{cb\ adj} = K_{cb}$ for the entire season. The soil evaporation coefficient K_e has numerous peaks in both crop seasons due to the soil wettings by irrigation and precipitation in 2012 and by frequent precipitation events in 2012-13. The soil evaporation coefficient is higher during the earlier crop growth stages, when the soil is incompletely covered by the crop, and decreases during the mid-season when the f_c fraction of soil covered by vegetation increases, hence the amount of energy available for evaporation at the soil surface is small. In 2012-13 several peaks of K_e are also shown in the late season due to a decreasing f_c related to crop senescence and high soil moisture content due to precipitation.

8.3.4. Yield predictions

Results presented in Table 8.11 show the deviations between observed and predicted yields by both models. Deviations vary 6.4 to 10.6% for the combination of the SIMDualKc and Stewart’s models (SIM-STE in the following) and 0.7 and 10.4%, when using AquaCrop. As referred in Section 8.3.1, the lower yield in 2012-13 is likely due to a smaller plant density after emergence and tillering, and by a less good crop development due to heavy rain and lower radiation energy during 2013. Both models show to be able for barley yield predictions but less well under unfavorable crop growth and yield conditions.

Table 8.11. Indicators of “goodness-of-fit” relative to the prediction of barley final yield (kg ha-1) with the SIMDualKc combined with Stewarts’ and AquaCrop models

		SIM-STE models			AquaCrop model		
		Predicted	Deviation		Predicted	Deviation	
Year	Observed* (kg ha^{-1})	(kg ha^{-1})	(kg ha^{-1})	%	(kg ha^{-1})	(kg ha^{-1})	%
2012	6331(±417)	6740	409	6.4	6287	-44	0.7
2012-13	5843(±612)	6465	622	10.6	6455	612	10.4

* dried at 65±5ºC; Standard deviation between brackets

The prediction accuracy of the Stewart’s model relates with the yield response factor K_y and the accuracy in estimating crop transpiration; the latter revealed appropriate as analysed in previous Sections. In AquaCrop, the yield prediction accuracy depends upon the estimation of biomass and transpiration, with T_a derived from CC (Raes et al. 2012). Since yield is tied with transpiration, the less good results of AquaCrop for 2012-13 relate to the large transpiration deficit computed for the mid-season, as discussed above (Table 8.10). Thus, if the estimation of E_s and mainly T_a could be improved, the yield prediction could be better.

The accuracy of the predictions obtained with both modelling approaches are comparable with those referred by Araya et al. (2010) when using AquaCrop for barley yield prediction. They reported deviations ranging 9 to 11% for full irrigation and 2 to 18% for deficit irrigation. Using the Cropsyst model for barley yield predictions, Donatelli et al. (1997) reported a deviation of 2% and Belhouchette et al. (2008) reported 2 to 4% of deviation. Deviations ranging 2 to 8% were obtained by Nain and Kersebaum (2007) with the CERES-Barley model. In contrast, Eitzinger et al. (2004) using CERES-Barley, WOFOST and SWAP models for barley yield predictions reported deviations ranging from 5 to 69%, 13 to 52%, and 38 to 73% respectively. Therefore, both modeling approaches used in this study are appropriate for further assessing impacts of mild to moderate deficit irrigation on barley yields.

8.4. Assessing alternative climatic demand and irrigation scenarios

In a climate change context, considering an expected increase of temperature and dryness due to a decrease in rainfall (Pereira 2011; Saadi et al. 2014), it is important to use calibrated and validated models to assess the impacts of different sowing dates and water stress levels upon crop yields under an adaptation perspective.

Maintaining a fixed net irrigation depth of 10 mm per irrigation event, which is common under center-pivot irrigation, alternative irrigation scenarios were designed considering different levels of water stress:

(1) not irrigated – Rainfed;

(2) full satisfaction of crop water requirements and irrigation ceasing 25 days before harvesting – Full;

(3) mild stress during the entire season with MAD = 1.10 p (i.e., management allowed depletion 10% larger than the p depletion fraction for no stress) and irrigation ceasing 25 days before harvesting – Mild;

(4) moderate stress during the entire season with MAD = 1.20 p and irrigation ceasing 25 days before harvesting - Mod.

Each of the above scenarios was run for two different climatic demand years, dry and very dry, and for two sowing dates in both crop seasons. The dry and very dry years correspond to the barley seasons having a probability of 80 and 95% for the net irrigation requirements (NIR) not being exceeded. Using a data series (1975-1993) of precipitation and ET_o from the nearby meteorological station of Santarém (39.25° N, 8.70°W and 54 m elevation) NIR were computed for the full data set and, following Pereira et al. (2002), a probability analysis was performed assuming that NIR follows a normal distribution. Two sowing dates - 6th December and by 16th January - were used similarly to the sowing dates observed in the experimental 2012 and 2012-13 seasons. However, the crop growth stages were defined using cumulative growth degree days (GDD) with a base temperature of 0 ºC and a cut off temperature of 30 ºC (Raes et al. 2012; Abi Saad et al. 2014).

In the application of the SIMDualKc-Stewarts' approach (SIM-STE), Y_m was obtained using the 'Wageningen method' (Doorenbos and Kassam 1979) for the dry and very dry climatic conditions and for both sowing dates. The resulting Y_m values and those obtained with AquaCrop for the same dates are presented in Table 8.12 together with the results for the different scenarios using both modeling approaches.

Results show that late sowing (by 16 January) leads to high irrigation requirements and to lower yields (Table 8.12), which relate to extend the crop season into the drier late Spring. While water stress was not identified for the initial and vegetative stages because precipitation was then enough to satisfy crop water requirements, the transpiration deficits simulated for the mid- and late-season under rainfed conditions are higher for the late sowing date. This explains that NIR are also higher for all irrigation strategies when adopting the late sowing date. Overall, results point out for the advantage of early sowing, which is in agreement with the commonly proposed adaptation measure for anticipating sowing of winter cereals (Saadi et al. 2004).

Table 8.12. Soil evaporation (E_s), actual transpiration (T_a) and transpiration deficits (T_d), simulated actual yield (Y_a) for the different irrigation and management scenarios for the dry and very dry climatic conditions

Dry climatic conditions														
			Sowing by December 6th						Sowing by January 16th					
			Prec. (mm)	Irr. (mm)	E_s (mm)	T_a (mm)	T_d (mm)	Yield (kg ha^{-1})	Prec. (mm)	Irr. (mm)	E_s (mm)	T_a (mm)	T_d (mm)	Yield (kg ha^{-1})
Potential yield (Y_m)		SIM-STE						7637						6827
		AquaCrop						7012						6222
Irrigation scenarios	Rainfed	SIM-STE	226	-	70	249	67	5612	212	-	68	248	113	4151
		AquaCrop		-	38	280	57	6134		-	46	270	127	4467
	Full	SIM-STE		90	77	312	4	7605		160	83	358	4	6762
		AquaCrop		90	40	337	0	6985		160	49	390	7	6128
	Mild	SIM-STE		80	77	303	13	7253		130	81	338	23	6273
		AquaCrop		80	40	335	2	6959		130	48	370	27	5863
	Mod	SIM-STE		60	74	291	26	6862		100	78	317	45	5775
		AquaCrop		60	40	323	14	6798		100	48	346	51	5559
Very dry climatic conditions														
			Sowing by December 6th						Sowing by January 16th					
			Prec. (mm)	Irr. (mm)	E_s (mm)	T_a (mm)	T_d (mm)	Yield (kg ha^{-1})	Prec. (mm)	Irr. (mm)	E_s (mm)	T_a (mm)	T_d (mm)	Yield (kg ha^{-1})
Potential yield (Y_m)		SIM-STE						7839						6631
		AquaCrop						7313						6141
Irrigation scenarios	Rainfed	SIM-STE	257	-	88	264	90	5342	220	-	55	230	153	3322
		AquaCrop		-	35	276	103	5778		-	50	234	171	3471
	Full	SIM-STE		120	75	346	8	7776		210	84	378	5	6515
		AquaCrop		120	43	355	24	6900		210	55	400	5	5866
	Mild	SIM-STE		100	73	334	20	7289		180	77	359	24	6105
		AquaCrop		100	42	342	37	6721		180	58	377	28	5561
	Mod	SIM-STE		80	72	317	36	6833		140	71	335	48	5584
		AquaCrop		80	42	327	52	6470		140	57	349	56	5176

Analysing the ET components, it is observed that E_s and T_a are often different when computed by one or the other model. The E_s predictions represent 11 to 18% of ET_a when computed with AquaCrop and vary from 17 to 25% of $ET_{c\ adj}$ for SIM-STE, i.e., when the water balance is performed with SIMDualKc. These results are coherent relative to the previous analysis, thus support the conclusion that AquaCrop tends to underestimate E_s. (Section 8.3.3) Contrarily, T_a estimations by AquaCrop tend to be higher than with SIMDualKc. However, T_d estimates with AquaCrop tend also to be higher, which could not be justified by data as referred in Section 8.3.3.

The estimated actual yields ($\widehat{Y_a}$) by both models are not very different but higher deviations occurred for the “Full” irrigation scenario (620 to 876 kg ha^{-1}), with the SIM-STE approach estimating higher Y_a for all scenarios except the rainfed. This fact relates with the higher estimates of transpiration deficits by AquaCrop. Results from both models show that rainfed barley may be non-economic under very dry climatic conditions particularly if late sowing is adopted. Overall, results also show that adopting supplemental deficit irrigation under dry and very dry climatic conditions are likely to be appropriate, particularly when early sowing is adopted. However, economic data are required to base an appropriate conclusion.

8.5. Conclusions

The SIMDualKc model was calibrated and validated for two malting barley crop seasons in a Mediterranean environment, using soil and crop field data. K_{cb} values were then obtained: 0.15 for the initial period, 1.10 for the mid-season, and 0.10 at harvesting because the malting barley is harvested very dry. Results show the good ability of the model to simulate the available soil water, with RMSE < 9% of the total available water. The AquaCrop model was parameterized and tested for the same field data and results have shown that its performance was less accurate than SIMDualKc. It was also observed that the performance of AquaCrop highly depended from the calibration of the canopy cover curve, which is required for every experiment.

Analysing the terms of the soil water balance as simulated by both models it was observed that: a) Soil evaporation tends to be underestimated by Aquacrop, which was already observed by other authors. To improve E_s estimates it is advisable to calibrate both parameters of the Ritchie’s model, TEW and REW instead of parameterizing REW only. b) Crop transpiration shows variable results with overestimation of the transpiration deficit; it is advisable that all K_{cb} values are calibrated and not only the $K_{c\ Tr\ x}$; c) deep percolation was likely overestimated, as also reported by other authors; the respective computational algorithm needs to be revised.

Two distinct approaches for crop yield prediction were compared. The one consisting in combining the SIMDualKc and the Stewarts’ models has shown good accuracy, with deviations of 6.4 and 10.6% respectively for the calibration (2012) and validation (2012-13) seasons. The crop growth model AquaCrop led to a much small deviation in 2012 (0.7%) but similar for 2012-13 (10.4%). Both modelling approaches are acceptable to predict malting barley yields when assessing alternative irrigation strategies; however, AquaCrop was more demanding in terms of parameterization and data input.

The application of both models to assess yield impacts of sowing dates under dry and very dry climatic conditions did show that early sowing dates lead to less irrigation requirements and higher yields because late Spring dry weather conditions are then better avoided. Thus, effects of water stress are then smaller. When assessing yield impacts of various full and deficit irrigation strategies, results show the advantage of adopting supplemental deficit irrigation.

However, an economic assessment would be required to properly advising farmers on these strategies

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Capítulo 9 - Modelling transpiration, soil evaporation and yield prediction of soybean in North China Plain

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Modelling transpiration, soil evaporation and yield prediction of soybean in North China Plain

Abstract

The main objectives of this study were to assess and partition soybean evapotranspiration and modelling to predict yields. The SIMDualKc water balance model, that adopts the dual crop coefficient approach, was used to evaluate the transpiration and soil evaporation components. Transpiration estimates were then used with the Stewart's water-yield model to predict soybean yields. SIMDualKc was calibrated and validated using soil water observations relative to four crop seasons and six treatments. In addition, the adopted soil evaporation approach using the Ritchie's model was validated against microlysimeter observations, also for the four years of study. The calibrated K_{cb} was 1.05 for the mid-season and 0.35 at harvesting. Model results show a good agreement between available soil water data observed and predicted by the model, with root mean square errors of estimates (RMSE) smaller than 5% of the total available soil water. Testing the soil evaporation approach also produced good fitting results, with RMSE averaging 0.50 mm d^{-1}, hence confirming the appropriateness of the Ritchie's model to estimate soil evaporation of a cropped soil. The yield prediction through combining SIMDualKc and the Stewart's model was successful for all treatments, leading to a small RMSE of 381 kg ha^{-1} representing less than 11.5% of the maximum observed yield. These results indicate that yield may be predicted with that simple empirical approach provided that transpiration is accurately estimated and the water yield factor K_y is adequately calibrated. Consumptive water productivity WP_{ET} were high, ranging 0.95 to 1.46 kg m^{-3}, showing that both the crop variety and the agronomic practices may be extended in North China Plain.

Keywords: Dual crop coefficient approach, Evapotranspiration partition, SIMDualKc model, Soil water balance, Microlysimeters, Stewarts' yield model

9.1. Introduction

Soybean is a major legume crop in North China and a significant source of high-quality protein and edible fat for human beings. Appropriate irrigation schedules in supplement to rainfall are crucial to ensure the normal growth and yield of soybean because they are vulnerable to water stress, mainly during flowering and seed filling (*e.g.*, Stegman et al., 1990; Foroud et al., 1993; De

Costa and Shanmugathasan, 2002; Karam et al., 2005). However, there are not studies available for North China Plain where supplemental irrigation of soybeans may be used.

The irrigation requirements of soybean are generally determined adopting the single crop coefficient (K_c) and the reference grass evapotranspiration (ET_o) (Mao, 2009; Suyker and Verma, 2009), whose product is the crop evapotranspiration (ET_c). However, as referred by Odhiambo and Irmak (2012), the dual crop coefficient approach may be more suitable for operational applications where daily estimates of ET_c are available. Crop evapotranspiration consists of crop transpiration (T_c) and soil water evaporation (E_s). The dual crop coefficient method separately estimates both T_c and E_s through partitioning K_c into two coefficients, the basal crop coefficient (K_{cb}), which is crop-specific and represents the ratio of T_c to ET_o, and the soil evaporation coefficient, K_e, that represents the daily ratio of E_s to ET_o, thus providing for estimating E_s. When using the dual crop coefficient method, the K_{cb} values are adjusted for local climate (Allen et al., 1998); under water stress conditions K_{cb} are adjusted using a water stress coefficient, K_s, *i.e.*, $K_{cb\ adj} = K_s\ K_{cb}$. The K_e values are computed daily considering soil surface cover and wetness (Allen et al., 1998; 2005).

The computation of the soil water dynamics is often based on the direct calculation of the soil water balance with a daily time step, or on the accurate simulation of soil water fluxes. The later approach is highly demanding in terms of data acquisition and model parameterization, particularly relative to the soil hydraulic properties. In addition, these deterministic models are too complex to apply in the irrigation management practice but are appropriate when it is required to assess water table and salinity behaviour, or when it is aimed to recognize the dynamics of fertilizers and related biomass production. Typical examples include models such as CropSyst (Stöckle et al., 2003), CROPGRO-soybean (Wang et al., 2003), HYDRUS (Ramos et al., 2011), or SWAP (Xu et al., 2013). In contrast, soil water balance models are of more easy application to irrigation scheduling and allow appropriate understanding of the crops behaviour when submitted to diverse management strategies. Examples are the models ISAREG (Liu et al., 1998), OSIRI (Chopart et al., 2007), PILOTE (Khaledian et al., 2009) and SIMDualKc (Rosa et al., 2012a). However, these models often need coupling with water yield functions describing the relationships between ET and yield, *e.g.*, the Stewart’s models (Stewart et al., 1977) as reported by Paredes et al. (2014).

Various studies report the applicability of the dual K_c methodology to several field crops, namely for the North China Plain (Liu and Pereira, 2000; Pereira et al., 2003; Liu and Luo, 2010; Zhang et al., 2013; Zhao et al., 2013). However, applications to the soybean crop are not reported for China. The use of the dual K_c methodology is more demanding than the single K_c approach, which justifies the need for implementing an appropriate model application but few model applications are available. Therefore updated research is required to appropriately implementing the dual crop coefficient approach and calibrating/validating an irrigation scheduling model using that approach. The SIMDualKc model (Rosa et al., 2012a) was therefore selected. Moreover, since studies relative to assess soil evaporation for soybeans are not available, it was advisable to test the soil evaporation component of the model. This model implementation should contribute to better using the available water resources and coping with water scarcity, that is a major challenge in the North China regions.

The main purposes of this study consist of implementing the dual crop coefficient approach and the use of the SIMDualKc model for soybean, hence performing the partitioning of ET into crop transpiration and soil evaporation, as well as calibrating the Stewart's model for yields prediction using transpiration data. In addition, it was also aimed to validate the soil evaporation approach used in SIMDualKc using microlysimeter observations performed along four crop seasons.

9.2. Material and methods

9.2.1 Site characteristics

The field experiments with soybean (*Glycine max* (L) var. Zhonghuang No.13) were conducted at the Irrigation Experiment Station of the China Institute of Water Resources and Hydropower Research (IWHR) located at Daxing (39°37′ N, 116°26′E, and 40.1 m altitude), south of Beijing. The soybean variety Zhonghuang No.13 is a high-protein and high-yielding semi-determinate cultivar of maturity group II (Hao et al., 2012; Wang et al., 2013). The climate in the experimental site is sub-humid of monsoon type, with cold and dry winter and hot and humid summer. An automatic meteorological station is installed inside the experimental station over clipped grass, which provides for measurements of precipitation, air temperature, relative humidity, global and net radiation, wind speed at 2 m height, and soil temperature at various depths. Meteorological data sets from the automatic weather station were used to compute the reference ET using the FAO Penman-Monteith method (Allen et al., 1998). Data sets were checked for quality as recommended by Allen et al. (1998). The climatic characterization relative to the experimental seasons of 2008 to 2011 is presented in Fig. 9.1. The total precipitation during the four experimental soybean seasons was 238, 328, 212 and 288 mm, respectively.

The soil is an alluvial silt loam whose basic hydraulic properties are summarized in Table 9.1. The total available soil water (TAW) is 198 mm m^{-1}.The average groundwater table is at approximately 18 m depth; thus, capillary rise from the groundwater was not considered. Deep percolation was computed using the parametric equation developed by Liu et al. (2006), which is a component of the SIMDualKc model. More information on the soil and the study area were given by Cai et al. (2009) and Zhao et al. (2013).

Table 9.1. Basic soil hydraulic properties of Daxing experimental station

Layer	Depth（m）	θ_S (cm^3 cm^{-3})	θ_{FC} (cm^3 cm^{-3})	θ_{WP} (cm^3 cm^{-3})
1	0.00-0.10	0.46	0.32	0.09
2	0.10-0.20	0.46	0.34	0.13
3	0.20-0.40	0.47	0.35	0.10
4	0.40-0.60	0.45	0.33	0.11
5	0.60-1.00	0.44	0.31	0.16

θ_{FC}, θ_{WP} and θ_S represent the soil water content at field capacity, wilting point and saturation respectively.

The irrigation experiments were developed from June 2008, when the first soybean season started, to October 2011, at the harvest of the fourth soybean season. The irrigation thresholds for treatments T1 and T2 were 75% and 60% of θ_{FC}, respectively; lower thresholds were not selected because the crop develops during the monsoon season and those were not likely to be attained. Therefore, water stress was avoided. In seasons with abundant rainfall no distinction could be made among treatments when analyzing related data. The treatments were performed with three replications in plots of 30 m^2 each. The irrigation water was delivered to the field by a PVC pipe and irrigation water depths were measured with a flow meter installed at the well pump outlet. Basin irrigation was used. The applied irrigation schedules are described in Table 9.2. Pre-planting irrigation were applied in 2008 and 2010 to assure adequate soil water conditions for emergence; differently, in 2009 and 2011, there was abundant rainfall that made not necessary pre-planting irrigation. Furthermore, due to abundant rainfall along 2011 season no irrigation was applied.

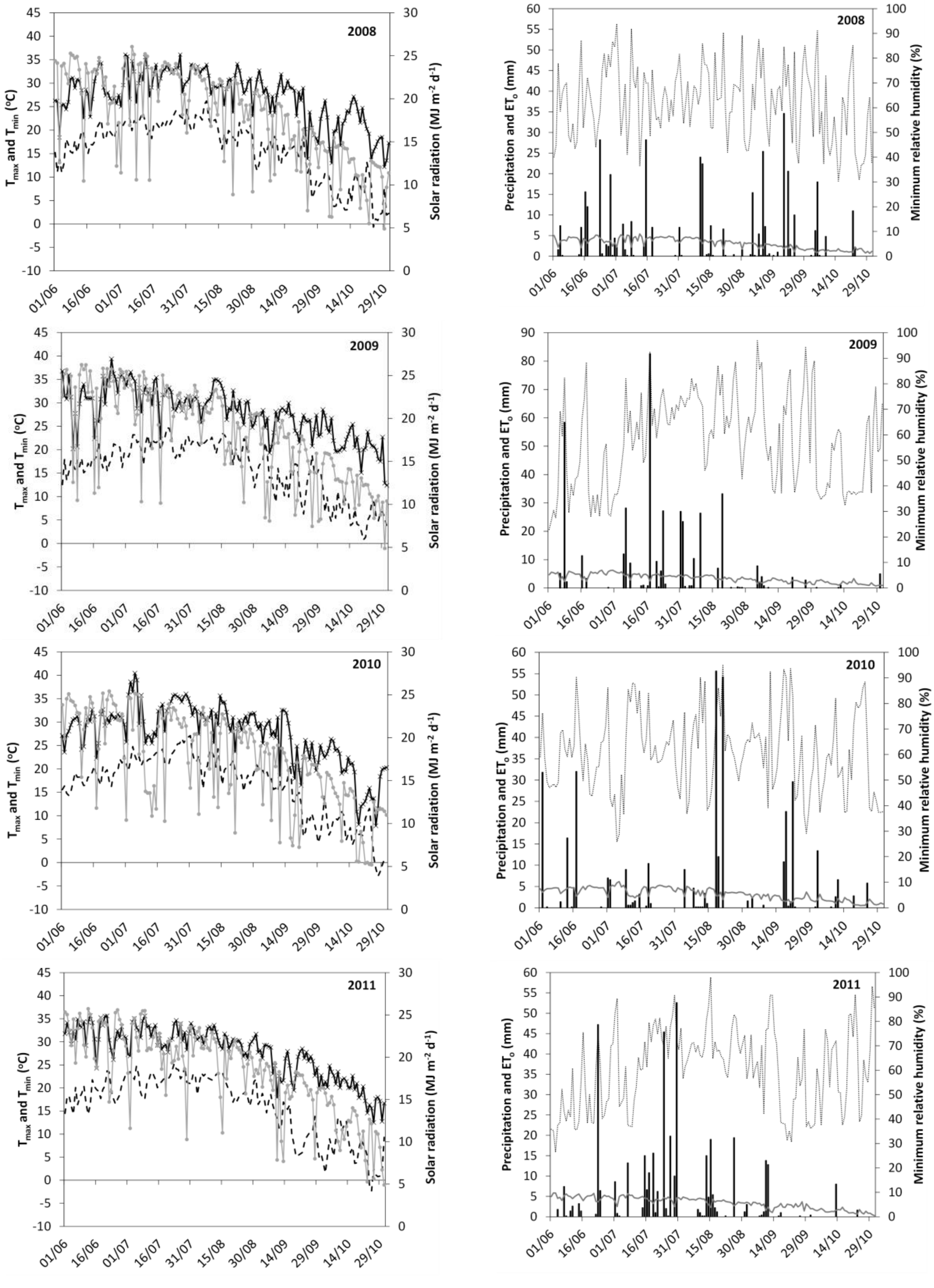


Fig. 9.1. On left: daily maximum and minimum temperature (—×— and – –), and solar radiation (—●—), On right: daily minimum relative humidity (·······), precipitation (▮) and reference evapotranspiration (——) during the four experimental seasons

Table 9.2. Irrigation treatments: applied water depths and dates.

Irrigation season	Plot	Date	Irrigation depth (mm)
2008-T1	1	23-6-2008 [a]	45
		4-9-2008	50
2008-T2	2	23-6-2008 [a]	45
2009	2	30-6-2009	30
2010-T1	2	23-6-2010[a]	30
		24-7-2010	35
		11-8-2010	45
2010-T2	1	23-6-2010[a]	30
		2-8-2010	40

[a] pre-planting irrigation

9.2.2 Field observations

Soybean was sown by early June and harvested by mid-October. Conventional tillage was adopted. Fertilization varied according the chemical analysis of soil samples and no nitrogen fertilizer was applied. Weeds control was performed manually. The crop density was 15 plants m^{-2} with an inter-row spacing of 0.4 m. Dates for each crop growth stage and all experimental years are presented in Table 9.3; no differences in dates of crop growth stages were observed between treatments of the same year. The crop height (h) was observed every 5 days (Table 9.4). The root depth (Z_r) at start of the mid-season approached 1.0 m, hence with observations in agreement with those of Yan (2007).

Table 9.3. Dates of crop growth stages relative to the four experimental years.

Crop growth stages	Soybean			
	2008	2009	2010	2011
Initial	24-06 to 13-07	14-06 to 09-07	25-06 to 18-07	22-06 to 07-07
Crop development	14-07 to 07-08	10-07 to 31-07	19-07 to 20-08	08-07 to 07-08
Mid-season	08-08 to 16-09	01-08 to 09-09	21-08 to 19-09	08-08 to 13-09
Late Season	17-09 to 08-10	10-09 to 01-10	20-09 to 07-10	14-09 to 01-10
Harvest	09-10	02-10	08-10	02-10

The soil water content was measured with a TDR system (TRIME®-T3/IPH) with measuring accuracy of 2%, that was previously calibrated (Cai et al., 2009). Observations were performed for the entire root zone at intervals of 0.10 m to a depth of 1.0 m every 5 days with two replicates per plot. When precipitation or irrigation event occurred, the soil water content was observed in the following day.

Table 9.4. Crop height (m) along the crop growth stages.

Season and treatment	Planting	Start crop development	Start mid-season	Start late-season	Harvest
2008-T1	0.05	0.20	0.40	0.57	0.57
2008-T2	0.05	0.20	0.40	0.57	0.57
2009	0.05	0.15	0.35	0.65	0.63
2010-T1	0.05	0.26	0.61	0.69	0.68
2010-T2	0.05	0.20	0.57	0.68	0.61
2011	0.05	0.25	0.60	0.75	0.69

The fraction of ground cover (f_c), required as input to SIMDualKc, was estimated from the observed leaf area index (LAI) and crop height using the approach proposed by Allen and Pereira (2009). The seasonal variation of f_c for all crop seasons and treatments is presented in Fig 9.2.

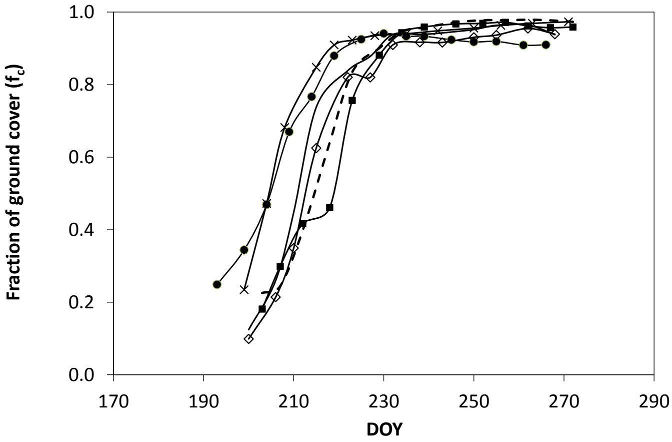


Fig. 9.2. Fraction of ground cover along all soybeans crop seasons and treatments: 2008-T1 (- -), 2008-T2 (–■–), 2009 (–●–), 2010-T1 (—), 2010-T2 (–◇–) and 2011 (–×–)

Soil evaporation was measured using microlysimeters. These were made of two PVC cylinders with diameters of 0.10 and 0.12 m respectively for the inner and outer cylinders and were 0.17 m high. Two microlysimeters were placed in each plot and weighting was performed every day around sunset, thus when energy available for evaporation and transpiration was reduced. An electronic balance with a precision of 0.1 g was used. In order to keep soil moisture coinciding with field conditions, the soil in the microlysimeters was replaced after significant precipitation or irrigation events. Due to heavy rain events during the initial and early crop development stages observations were not performed during this period in 2011; technical problems affected similar observations in 2010.

9.2.3 The SIMDualKc model and calibration and validation procedures

The SIMDualKc model (Rosa et al., 2012a) simulates the soil water balance using the dual crop coefficient approach (Allen et al., 1998; 2005) to compute crop evapotranspiration (ET_c), thus partitioning it into soil evaporation and crop transpiration. The actual crop evapotranspiration, which differs from ET_c when water stress occurs, is defined as:

$$ET_{c\ adj} = \left(K_s K_{cb} + K_e\right) ET_o \tag{9.1}$$

where $ET_{c\ adj}$ is the actual crop evapotranspiration (mm d^{-1}), K_s is the water stress coefficient, K_{cb} is the basal crop coefficient, K_e is the soil evaporation coefficient, and ET_o is reference evapotranspiration (mm d^{-1}). The $K_{cb\ mid}$ and $K_{cb\ end}$ (when $K_{cb\ end} > 0.45$) values were adjusted by the model for the local climatic conditions when the average minimum relative humidity (RH_{min}) differs from 45% and/or when the average wind speed u_2 differs from 2 m s^{-1} (Allen et al. 1998; Rosa et al., 2012a).

The simulations were performed with a daily time step using the observed soil, irrigation, meteorological and crop input data, hence including the fraction of ground cover (f_c), crop height (h) and root depth (Z_r). Other required data refer to the basal crop coefficients (K_{cb}), depletion fractions for no stress (p), total evaporable water (TEW), readily evaporable water (REW), thickness of the evaporation soil layer (Z_e) and the parameters for estimating deep percolation (a_p and b_p) as described by Liu et al. (2006). The detailed description of the SIMDualKc model is provided by Rosa et al. (2012a).

The calibration procedure consisted of adjusting the non-observed crop parameters K_{cb} and p, as well as the parameters characterizing soil evaporation (Z_e, TEW and REW) and deep percolation (a_p and b_p) to minimize the difference between observed and simulated available soil water relative to the whole root zone. Data from 2008 were used. The validation of the model consisted in using the calibrated parameters to simulate the experiments of 2009 through 2011. The soil evaporation computed using the Ritchie's model (Ritchie, 1972; Allen et al., 1998, 2005), which is incorporated in SIMDualKc, was tested by comparing model estimates of E_s with microlysimeters data.

The goodness of fit relative to both calibration and validation processes was assessed using a set of indicators described in previous SIMDualKc studies (Rosa et al., 2012b; Martins et al., 2013, Paredes et al., 2014). A linear regression forced through the origin was performed between observed and simulated values; thus, if the regression coefficient (b) is close to 1 it means that the predicted values are statistically close to the observed ones, while a determination coefficient (R^2) close to 1.0 indicates that most of the variation of the observed values is explained by the model.

Residual estimation errors were computed following Moriasi et al. (2007): the root mean square error (RMSE) and the average absolute error (AAE), which respectively express the variance of errors and the average size of estimated errors. These indicators are computed from the pairs of observed and predicted values O_i and P_i (i = 1, 2, ..., n), with means respectively of $\bar{O}$ and $\bar{P}$, as

$$\mathrm{RMSE} = \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n} \right]^{0.5} \tag{9.2}$$

and

$$\mathrm{AAE} = \frac{1}{n} \sum_{i=1}^{n} \left| O_i - P_i \right| \tag{9.3}$$

These indicators were calculated at each iteration to support finding the calibrated parameters which lead to minimize estimation errors.

In addition, indicators of the quality of modelling were also used.

a) the Nash and Sutcliffe (1970) modelling efficiency (EF), that is a normalized statistic determining the relative magnitude of the residual variance compared to the measured data variance, defined as

$$\mathrm{EF} = 1.0 \quad \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} \left(O_i - \bar{O}\right)^2} \tag{9.4}$$

The target value for EF is 1.0, while a null or negative value means that the average of observations is as good or better predictor than the model.

b) the Willmott (1981) index of agreement (d_{IA}), that represents the ratio between the mean square error and the potential error, defined as

$$d_{IA} = 1 - \frac{\sum_{i=1}^{N} (O_i - P_i)^2}{\sum_{i=1}^{N} \left(\left| P_i - \bar{O} \right| + \left| O_i - \bar{O} \right| \right)^2} \tag{9.5}$$

$d_{IA} = 1$ indicates perfect agreement between the observed and predicted values, and $d_{IA} = 0$ indicates no agreement at all (Moriasi et al., 2007).

9.2.4 Water-yield relations and yield prediction

A simple approach was used to predict the soybean yields as influenced by irrigation water managements, which consisted in coupling the SIMDualKc model with the water-yield model proposed by Stewart et al. (1977). The latter assumes a linear variation of the relative yield losses with the relative evapotranspiration deficits at the season scale:

$$1 - \frac{Y_a}{Y_m} = K_y \left(1 - \frac{ET_{c\ adj}}{ET_c} \right) \tag{9.6}$$

where ET_c and $ET_{c\ adj}$ are respectively the maximum crop evapotranspiration and the actual crop ET (mm) as defined in Eq. 9.1, Y_m and Y_a are the maximum and the actual yield (kg ha^{-1}) obtained under full and deficit irrigation, *i.e.*, when ET is respectively ET_c and $ET_{c\ adj}$, and K_y is the crop yield response factor (dimensionless).

Since crop transpiration T_c is the component of ET directly responsible for yield formation, T_c was adopted in the present study instead of ET. This approach prevents bias due to differences in E_s/ET ratios relative to different experiments, seasons or locations. The estimated yield ($\widehat{Y_a}$) is then obtained from adapting the Eq. 9.6 as:

$$\widehat{Y_a} = Y_m - \frac{Y_m\, K_y\, T_d}{T_c} \tag{9.7}$$

where T_d is the transpiration deficit, which is defined as the difference between the maximum (non-stressed) T_c and the actual T_a, *i.e.*, $T_d = T_c - T_a$. Both T_a and T_c were obtained through simulations with the SIMDualKc model after proper calibration. Y_a refers to the actual yields observed in each plot and year, and Y_m were obtained for all years using information on the highest yields achieved in the study area. These Y_m values were later compared with Y_m values estimated using the Wageningen method described by Doorenbos and Kassam (1979). It resulted the following maximum yields of 4052, 3708, 4470 and 3374 kg ha^{-1} for the experiments of 2008, 2009, 2010 and 2011, respectively (yields are expressed in dry weight).

There are several studies reporting K_y values for soybeans. Doorenbos and Kassam (1979) proposed a seasonal K_y of 0.85. Stegman et al. (1990) considered various levels of deficit irrigation at distinct growth stages and found K_y = 1.26, while Rosadi et al. (2007) reported K_y = 1.05 referring to regulated water deficit.

9.3 Results and discussion

9.3.1 Soil water model calibration and validation

Model calibration was performed with the 2008-T1 data set. Table 9.5 summarizes the initial and calibrated values of the parameters. The results from comparing the observed and simulated available soil water (ASW) calibration and validation are presented in Fig. 9.3. ASW was observed and computed for the maximum root depth. They show that the ASW dynamics is well simulated with no apparent bias in estimation. The calibrated values of K_{cb} and p values (Table 9.5) are in agreement with those proposed by Allen et al. (1998) as discussed in Section 9.3.3.

Table 9.5. Initial and calibrated values for the crop and soil parameters

	Initial values	Calibrated	
Crop coefficients			
$K_{cb\ ini}$	0.15	0.15	
$K_{cb\ mid}$	1.10	1.05	
$K_{cb\ end}$	0.30	0.35	
Depletion fractions			
p_{ini}	0.5	0.5	
p_{mid}	0.5	0.5	
p_{end}	0.5	0.5	
Soil evaporation			
		Plot 1	Plot 2
REW (mm)	8	12	8
TEW (mm)	28	45	25
Z_e (m)	0.1	0.15	0.15
Deep percolation			
a_p	370	355	355
b_p	-0.0173	-0.065	-0.065

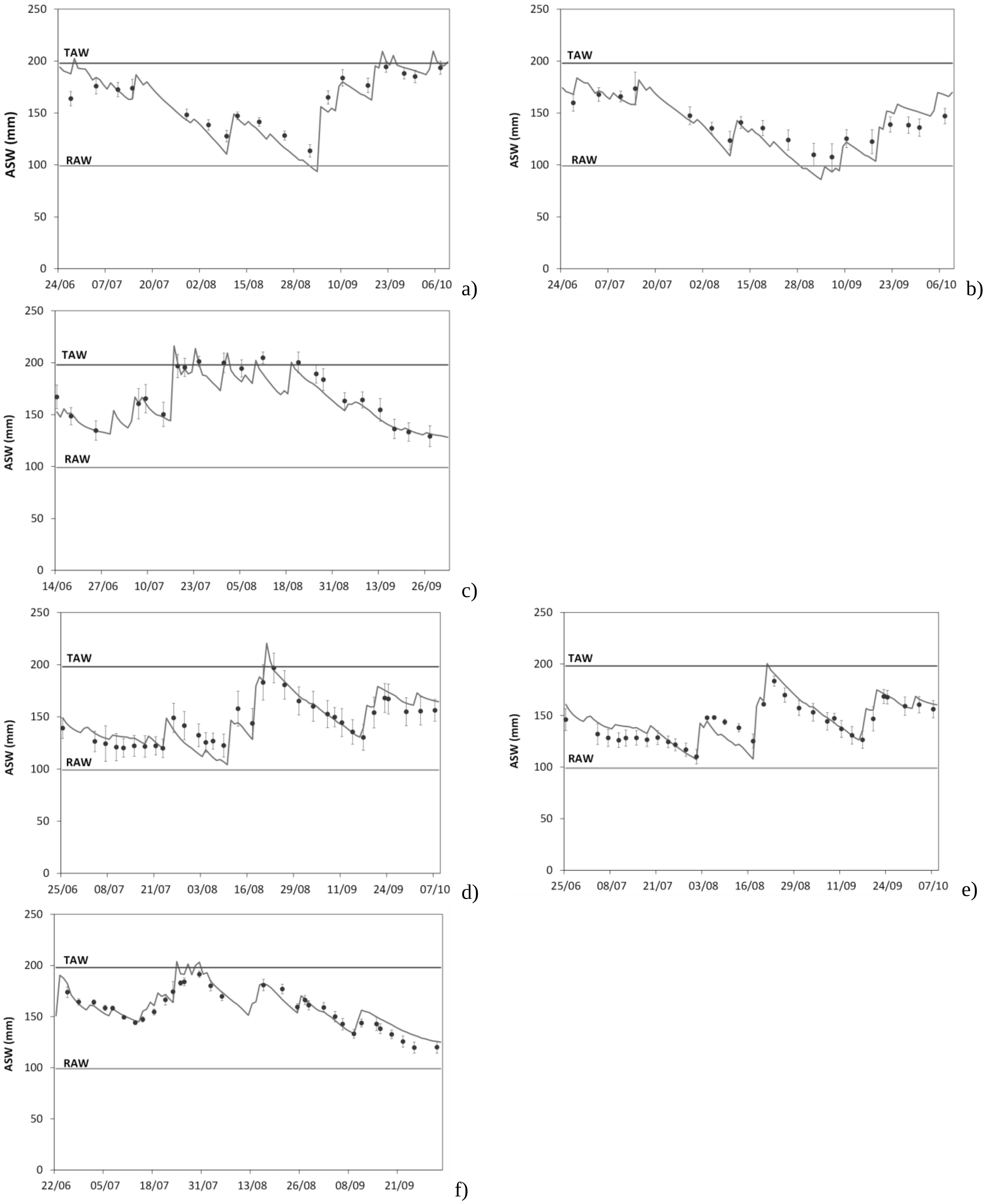


Fig 9.3. Simulated (—) vs. observed (●) available soil water (ASW): (a) 2008-T1, calibration; (b) 2008-T2; (c) 2009; (d) 2010-T1, (e) 2010-T2 and (f) 2011 (error bars represent the standard deviation of the mean observed values).

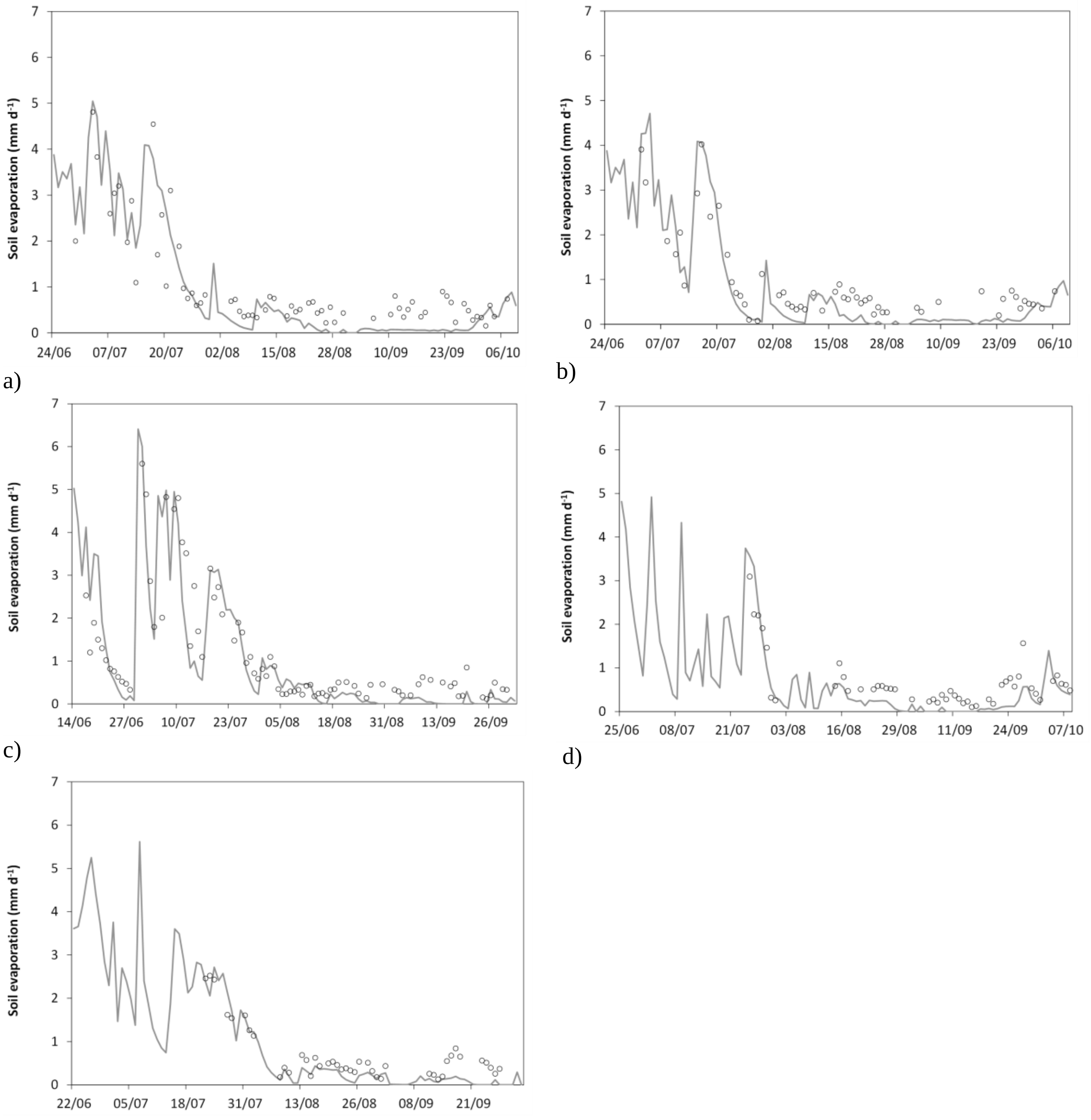
The goodness of fit indicators are presented in Table 9.6. They show that, for all cases, the regression coefficients are close to 1.0, thus indicating that the simulated ASW adhere well to the observations. The determination coefficients ranged from 0.83 to 0.93, thus meaning that most of the variance could be explained by the model. The RMSE using all data is 10 mm, representing about 5.1% of TAW. EF values range from 0.54 to 0.90, and $d_{IA} > 0.92$ for all crop seasons. Results show that SIMDualKc model is able to predict the variation of the available soil water throughout the soybean crop season and therefore may be further used for soybean irrigation management.

Table 9.6. Indicators of "goodness-of-fit" relative to the available soil water simulations.

Crop season and treatments	b	R^2	RMSE (mm)	RMSE/TAW (%)	AAE (mm)	EF	d_{IA}
2008-T1, plot 1(Calibration)	0.99	0.93	10.7	5.4	9.0	0.80	0.96
2008-T2, plot 2	0.98	0.84	12.5	6.3	11.7	0.54	0.92
2009, plot 2	0.97	0.95	7.8	3.9	6.2	0.90	0.97
2010-T1, plot 1	1.00	0.84	9.2	4.6	7.6	0.79	0.95
2010-T2, plot 2	1.02	0.83	8.6	4.3	7.0	0.76	0.95
2011, plot 2	1.03	0.86	9.3	4.7	7.5	0.76	0.94
All experiments	1.00	0.85	10.0	5.1	8.1	0.81	0.96

9.3.2 Testing soil evaporation estimates

Results for testing the soil evaporation component of SIMDualKc, which is based upon the Ritchie's model (Ritchie, 1972), are shown in Fig. 9.4. They show a good agreement between observed microlysimeter data and model simulated daily E_s values; however, simulated values tend to underestimate observations, especially during the mid-season. It results that the goodness of fit indicators of E_s estimations (Table 9.7) are not as good as those of the soil water simulation. The regression coefficients are all close to 1.0 for 2008 and 2009, but lower for 2010 and 2011, respectively 0.90 and 0.95. This means that model predicted values are not always very close to the observed ones despite predictions are generally good. The determination coefficients range from 0.79 to 0.89, hence indicating that most of variation of observed values is explained by the model. The errors of estimation are small: RMSE do not exceed 0.65 mm d^{-1}, averaging 0.50 mm d^{-1}, and AAE is less than 0.45 mm d^{-1}. EF are high, ranging 0.62 to 0.80, and d_{IA} are also high, larger than 0.93. Overall, results show that the SIMDualKc model predicts well the seasonal variation of the observed soil evaporation of a soybean cropped field.



a) b) c) d) e)

Fig. 9.4. Observed (○) and simulated (━━) soil water evaporation during the soybean seasons of (a) 2008-T1; (b) 2008-T2; (c) 2009; (d) 2010-T1; and (e) 2011

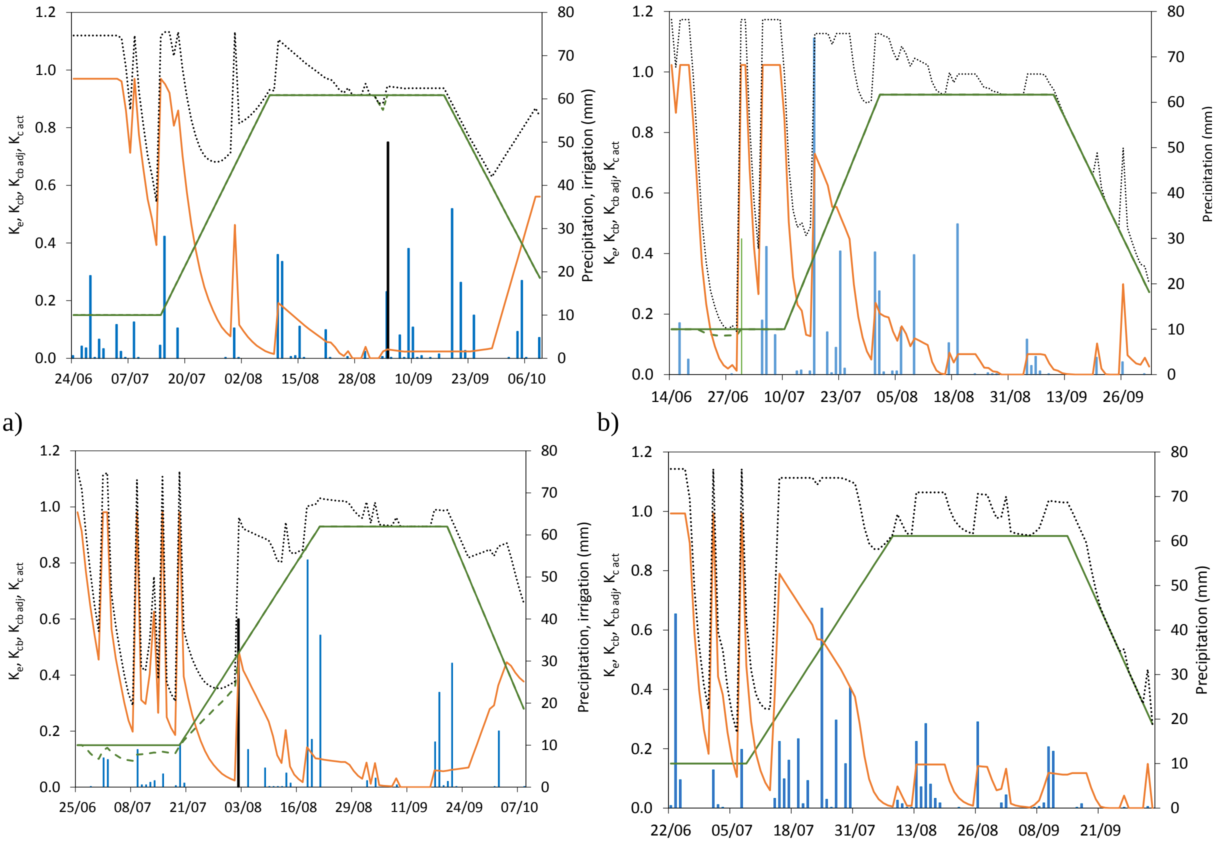
Table 9.7. Indicators of "goodness-of-fit" relative to the soil evaporation simulations

Crop season/treatment	b	R^2	RMSE (mm d^{-1})	AAE (mm d^{-1})	EF	d_{IA}
2008-T1, plot 1	0.97	0.85	0.52	0.41	0.76	0.95
2008-T2, plot 2	0.99	0.89	0.48	0.40	0.73	0.95
2009, plot 2	0.96	0.79	0.65	0.45	0.74	0.94
2010-T1, plot 1	0.90	0.86	0.38	0.31	0.62	0.93
2011, plot 2	0.95	0.84	0.24	0.19	0.85	0.97
All experiments	0.97	0.84	0.50	0.36	0.76	0.95

E_s results in Fig. 9.4, despite the goodness of fit indicators are good, show small but non-negligible differences between model estimates and microlysimeter observations, mainly during the mid-season. These differences are in agreement with conclusions by Klocke et al. (1990), who noted that water extraction by roots was excluded from the microlysimeters, hence resulting in higher soil water content in the microlysimeter than in the surrounding area, thus making that microlysimeter measurements are likely to overestimate soil evaporation. Daamen et al. (1993) also observed differences in E_s values when using microlysimeters compared with the gravimetric method and attributed these differences to the effect of water extraction by the roots. This fact was also noticed by Zhao et al. (2013) for maize and winter wheat. When analyzing the dynamic process of soil evaporation presented in Fig 9.4, it is noticed that model underestimations occur when the crop is well developed, the fraction of ground cover is high and soil evaporation is low, and when root extraction from the upper soil layer is higher. Therefore, the soil water extraction from the evaporation soil layer is larger when roots are active then when compared with extraction due to soil evaporation only, as it occurs in microlysimeters. It may be concluded that using the Ritchie's approach to simulate E_s in SIMDualKc produces good estimations of E_s, hence an appropriate partition of ET into transpiration and soil evaporation.

9.3.3 Crop coefficients curves

Examples of K_e, K_{cb} and K_c curves are shown in Fig. 9.5, where irrigation and precipitation depths are also represented. K_e values for soybean are high during the initial period, where soil moisture was high at planting and various wetting events occurred. Later, when ground cover was high and less energy was available at soil surface for evaporation, K_e remained low until the late season. By then it increased because the fraction of ground cover decreased due to the senescence of leaves. To be noted that soil water evaporation and K_e are submitted to a large variability dictated by the occurrence of wetting events, mainly by rainfall in this application. $K_{cb\ mid}$ in Fig. 9.5 is adjusted for climate as refereed in Section 9.2.3; because $RH_{min} > 45\%$ and $u_2 < 2$ m s^{-1} it resulted a $K_{cb\ mid}$ lower than the value presented in Table 9.5.



a) b)

c) d)

Fig. 9.5. Seasonal variation of the K_e (—), K_{cb} (—), $K_{cb\ adj}$ (- - -) and $K_{c\ act}$ (······), along the soybean seasons: (a) 2008-T1; (b) 2009; (c) 2010-T2; (d) 2011 including the respective data on irrigation (▮) and precipitation (■)

Results in Fig. 9.5 show that the K_{cb} and $K_{cb\ adj}$ curves are generally about coincident, thus indicating that no water stress or only mild and short stresses occurred as for a few days in the mid-season of 2008-T1 (Fig. 9.5a) and the initial stage of 2009 (Fig. 95b). A mild stress during the initial and crop development stages may be observed in Fig. 9.5c, which was due to the fact that soil water in the upper soil layer was not enough to prevent stress despite water was available in deeper layers. The daily K_c curves (Fig. 9.5 a to d) show a large variability due to the referred variability of K_e.

Odhiambo and Irmak (2012) reported dual crop coefficients for soybean: $K_{cb\ ini}$ = 0.15, $K_{cb\ mid}$ = 1.08 and $K_{cb\ end}$ =0.33, which are very close to our results, $K_{cb\ ini}$ = 0.15, $K_{cb\ mid}$ = 1.05 and $K_{cb\ end}$ =0.35 (Table 9.5 and Fig. 9.5). Studies adopting the single, time averaged crop coefficient for soybean may also be used to compare mid season values. Karam et al. (2005) and Tabrizi et al. (2012) found $K_{c\ mid}$ of 1.0. Suyker and Verma (2009) reported $K_{c\ mid}$ ranging

0.77-1.03 and Payero and Irmak (2013) reported $K_{c\ mid}$ ranging 1.07 to 1.33. Assuming a difference of 0.05 between mid season K_c and K_{cb} (Allen et al., 1998), it is then evident that the derived $K_{cb\ mid}$ = 1.05 shows to be higher than the reported values but fits well those by Payero and Irmak (2013). $K_{c\ end}$ depends upon crop management practices and therefore it is difficult to compare among reported results. Thus, it may be concluded that our K_{cb} estimates (Table 9.5) are appropriate for further use in North China Plain.

9.3.4 Partitioning crop evapotranspiration

As analyzed above, the good results achieved in terms of model fitting and estimation of soil evaporation are likely to guarantee that partitioning crop evapotranspiration using the dual crop coefficient approach in SIMDualKc is appropriate. Moreover, it is enough accurate to support an analysis of the consumptive water use and yield prediction of the studied soybean crop. The soil evaporation ratio ($E_s/ET_{c\ adj}$) for all soybean experiments and every crop growth stage are presented in Table 9.8. Differences between seasons are apparent as they are related to climatic conditions and irrigation schedules, mainly to the frequency and amount of wettings (Fig. 9.5) and, less, with the inter-annual variability of the fraction of ground cover (Fig. 9.2).

Table 9.8. Evaporation ratio ($E_s/ET_{c\ adj}$) for each development stage and seasonal actual transpiration (T_a) and actual evapotranspiration ($ET_{c\ adj}$).

	Crop stage	Crop seasons and treatments					
		2008-T1	2008-T2	2009	2010-T1	2010-T2	2011
$E_s/ET_{c\ adj}$ (%)	Initial	85	83	80	72	73	80
	Crop development	40	34	43	28	22	43
	Mid-season	6	5	7	3	4	7
	Late-season	19	20	4	24	24	7
	Total	36	32	35	30	28	32
T_a (mm)	Seasonal	209	215	226	204	203	224
$ET_{c\ adj}$ (mm)	Seasonal	324	315	347	290	283	330

Results in Table 9.8 show that E_s is the main component of $ET_{c\ adj}$ during the initial crop growth stage, representing 72 to 85% of the consumptive water use, approximately 79% in average. During this period the soil was mostly uncovered and the frequency of wettings by rain was large (Fig. 9.5), which explains that very large share of E_s. Throughout the crop development stage, due to crop growth and the increase of the fraction of ground cover, E_s progressively decreases as shown in Fig. 9.5 for the K_e decay in that period. In average, during this period, E_s falls to 35% of $ET_{c\ adj}$. However, mainly due to the inter-annual variability of rainfall, $E_s/ET_{c\ adj}$ vary in a large range, from 22 to 43% (Table 9.8). In the mid-season E_s reduces to an average of 5% of $ET_{c\ adj}$ because ground cover by the crop is then maximal and the available energy for evaporation drops to a minimum. After that, in the late season, $E_s/ET_{c\ adj}$ increases to an average of 16% due to leaf senescence and precipitation events. Moreover, the inter-annual variability of crop cover and wettings lead to a large variation of $E_s/ET_{c\ adj}$ (Table 9.8) along the crop seasons.

The results on $E_s/ET_{c\ adj}$ in Table 9.8 are comparable with those reported by Brun et al. (1972) who found that $E_s/ET_{c\ adj}$ averaged 5% when LAI reached its highest value, thus at mid-season. Singer et al. (2010) referred $E_s/ET_{c\ adj}$ ranging from 4 to 11% during mid-season, which are values similar to those obtained in this study. Sauer et al. (2007) reported $E_s/ET_{c\ adj}$ ranging from 8% to 12% when ground cover reached the maximum, which are larger than values of our study. Differently, Kanemasu et al. (1976) found a seasonal $E_s/ET_{c\ adj}$ ranging 15 to 18%, which is lower than in our study, where the seasonal $E_s/ET_{c\ adj}$ ranged 28 to 36%. However, in the Kanemasu's study the frequency of wettings is smaller and plant density was higher, thus a higher fraction of ground coverage led to less energy available at soil surface for evaporation. However, because the impacts of plant density were not studied in both researches, it is not possible to raise further conclusions.

The seasonal transpiration ranged 203-229 mm for all six treatments analyzed. This low variability was expected when analyzing the K_{cb} and $K_{cb\ adj}$ curves, which are very similar (Fig. 9.5), without showing but very small water stress. Hence, those very similar transpiration values are in agreement with the low variation of yields observed (see Section 9.3.5). Differently, the variability of the actual evapotranspiration was higher, ranging 283 to 347 mm due to the variability of soil evaporation, which related with frequency of wettings and the variability of the fraction of ground cover as discussed above.

9.3.5. Soybean yield predictions and water productivity

The observed yields and respective standard deviation (SD), crop evapotranspiration and consumptive water productivity (WP_{ET}) and respective SD are presented in Table 9.9. WP_{ET} is the ratio between actual yield (kg ha^{-1}) and actual crop evapotranspiration (mm), *i.e.*, $WP_{ET} = Y_a/ET_{c\ adj}$ (this ratio is often called water use efficiency; a discussion on terminology is given by Pereira et al., 2012). Results show higher WP_{ET} in 2010 due to a combination of favourable crop growth factors that led to a very high yield. Nevertheless, in that year, the $E_s/ET_{c\ adj}$ ratios were smaller than for other seasons, which indicates that such a lower ratio favours WP_{ET}. For the seasons when treatments T1 and T2 produced different yields, the highest were obtained for T1, *i.e.*, when the highest irrigation threshold (75% of θ_{FC}) was adopted.

Table 9.9. Observed and predicted dry total soybean yields (and standard deviation, SD) using the SIMDualKc-Stewarts' approach (kg ha^{-1}), crop evapotranspiration ($ET_{c\ adj}$) and water productivity (WP_{ET}) for all treatments and seasons

Treatments	Observed			Predicted	
	Yield (and SD) (kg ha^{-1})	$ET_{c\ adj}$ (mm)	WP_{ET} (and SD) (kg m^{-3})	Yield (kg ha^{-1})	Deviation (kg ha^{-1})
2008-T1	3778 (± 272)	324	1.17 (±0.08)	4046	267
2008-T2	3549 (± 358)	315	1.13 (±0.11)	4009	461
2009	3454 (± 246)	347	1.00 (±0.07)	3689	234
2010-T1	4230 (± 222)	290	1.46 (±0.08)	4443	214
2010-T2	3578 (± 196)	283	1.26 (±0.07)	4260	682
2011	3222 (± 151)	340	0.95 (±0.04)	3374	152

A few studies have been performed with estimation of WP_{ET} for soybean. Gerçek et al. (2009) reported for full irrigated soybean in a semi-arid area WP_{ET} of 0.16 and 0.17 kg m^{-3}, which are much lower than in our study due to low yields (2260 and 2280 kg ha^{-1}) and very high ET (1261 and 1229 mm). Suyker and Verma (2009) report WP_{ET} averaging 0.74 kg m^{-3} for irrigated soybean and 0.69 kg m^{-3} for rainfed soybean; these results, referring to similar yields are lower than those of the current study because ET was higher. For a sub-humid climate, Candogan et al. (2013) found a smaller WP_{ET} averaging 0.46 kg m^{-3} for full irrigation and 0.48 kg m^{-3} for mild deficit irrigation. Differences to our study are mainly due to higher ET since yields are similar to those reported in Table 9.9. Therefore, we may assume that the soybean variety and the agronomic practices adopted are appropriate for North China Plain.

The observed yields were used to validate predictions with the Stewarts' model when used in combination with the SIMDualKc model. Prediction results using $K_y = 1.30$ show an over-estimation of yields (Table 9.9) with RMSE = 381 kg ha^{-1}. The deviation between observed and simulated soybean yields ranged 152 to 682 kg ha^{-1}, with higher deviations for treatments T2, which adopted the lowest irrigation threshold of 60% of $\theta_{FC.}$ Deviations between predicted and observed yields are generally smaller than SD; exceptions are treatments T2. It is likely that treatments T2 produced small but strong water stress at some sensitive crop stages that were not detected through field observations or modelling which caused impacts on yields out of modelling capabilities. It may be advisable to perform further experimental studies with well controlled water stress at various crop stages.

Despite insufficiencies discussed above, the accuracy of results obtained with the combined SIMDualKc-Stewart's model approach was similar or better than the accuracy of other prediction approaches reported in literature, including when obtained with crop growth models, which are more demanding in terms of parameterization. Stöckle et al. (2003) used the CropSyst model and found a RMSE of 381 kg ha^{-1}, thus equal to ours. Several applications of the CROPGRO-soybean model are available in literature. Sau et al. (1999) obtained a RMSE of 940 kg ha^{-1} when using the original version, and a RMSE = 333 kg ha^{-1} when an improved version of the model was used and where photosynthesis, nitrogen metabolism and genetic coefficients were adapted. Mercau et al. (2007) reported a RMSE of 743 kg ha^{-1} when using the original version of CROPGRO-soybean, and 584 kg ha^{-1} when adopting a revised version of the model; these RMSE represent 18 and 14.5% of the maximum observed yield. Differently, Wang et al. (2003) found a lower RMSE ranging 75 to 104 kg ha^{-1} for the calibration, but varying from 3 to 1856 kg ha^{-1} for the validation. Calviño et al. (2003) used the CROPGRO model and reported RMSE = 512 kg ha^{-1}; these authors also tested three empirical models and reported RMSE ranging from 298 to 702 kg ha^{-1}. Cabelguenne et al. (1999) used the EPIC and the EPIC-phase crop growth models finding RMSE ranging respectively 650 - 1000 kg ha^{-1} and 250 - 290 kg ha^{-1}. The best results are from Mohanty et al. (2012) that used the APSIM model and reported an under-estimation of only 100 kg ha^{-1}, corresponding to less than 6% of the observed yield. It can be concluded that our results, with an RMSE = 381 kg ha^{-1} and corresponding to an overestimation of 11.3% of the maximum yield observed in this study, may be considered good. They allow to assume that coupling the SIMDualKc and the Stewart's models may be recommended for further use in conditions where heavy water stress is not observed. Nevertheless, further studies that include deficit irrigation management should be performed to better confirm the modelling approach and the K_y value used.

9.4 Conclusions

The SIMDualKc water balance model was successfully calibrated and validated using four years of observations of the available soil water of a soybean crop in the North China Plain as demonstrated by excellent goodness of fit results. The basal crop coefficients obtained from the calibration are within the expected range for soybean and compared well with values reported in literature. Therefore, K_{cb} obtained in this study are appropriate for further use in North China Plain.

Model estimates of soil evaporation fitted well microlysimeter data, hence producing small under-estimation and quite low RMSE values. Estimation errors have shown to be influenced by the fact that microlysimeters evaporation, contrarily to natural conditions, do not include extraction by roots active in the soil evaporation layer. Thus, differences between observed and simulated soil evaporation were higher during mid-season. Results obtained allow to conclude that using the Ritchie's approach to simulate E_s in SIMDualKc produces good estimations of E_s, hence an appropriate partition of ET into transpiration and soil evaporation.

Transpiration has shown a small inter-annual variability while soil evaporation varied much with the frequency and volume of soil wettings, which also varied from one year to another. For this reason, the Stewart's water-yield model was modified to predict soybean yields from the transpiration deficit instead of the ET deficit. The estimation errors (RMSE = 381 kg ha^{-1}, or an overestimation of 11.3% of the maximum yield observed) are similar or smaller than errors reported in literature relative to yield predictions using crop growth and yield models. Therefore the use of the approach developed in this study, combining the water balance SIMDualKc model with the Stewart's water-yield model was adequate. It has been observed that yields relative to the treatment having a threshold of 0.60 of θ_{FC} had lower yields despite the water deficits were quite small. It is therefore desirable that further water-yield studies will be developed considering various levels of water deficits applied at various crop stages. A better calibration of the water yield response factor K_y is also desirable.

The water productivity WP_{ET} computed for all treatments is larger than other WP_{ET} values reported in literature. Differences refer mainly to ET that was smaller in this application, and in some cases also to yields. These results allow to assume that crop varieties and agronomic practices adopted are appropriate and may be extended in North China.

Acknowledgements

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Capítulo 10 - Conclusões e perspetivas futuras

10. Conclusões e perspetivas futuras

O Capítulo 2 descreve adequada calibração e validação do modelo SIMDualKc para o balanço hídrico do solo e calendarização da rega para as culturas de milho de silagem, algodão e trigo regados respetivamente por gravidade e aspersão em várias regiões do Mediterrâneo e na Ásia Central. Comparou-se o desempenho do modelo utilizando parâmetros tabelados e após calibração, tendo-se verificado que os ajustamentos nos parâmetros necessários á calibração foram pequenos. Os resultados permitiram verificar que o modelo não apresenta tendência para sub- ou sobrestimar a água disponível no solo ao longo dos ciclos culturais. Os erros associados á estimativa são relativamente pequenos, 3 a 6% da água disponível total. Assim, o modelo mostrou ser uma ferramenta adequada ao cálculo da evapotranspiração cultural e sua partição, mesmo no caso de ausência de dados de campo para a sua calibração. No entanto, verificou-se a necessidade de conhecimento das datas correspondentes aos estágios de desenvolvimento das culturas para uma correta simulação.

Após a calibração do modelo SIMDualKc para milho, efetuada no Capítulo 2, no Capítulo 3 são analisadas distintas estratégias de rega em condições de escassez de água para vários locais de Portugal Continental. A seleção das estratégias baseou-se na otimização das disponibilidades de água quando associada a uma quebra de produção relativamente pequena, que permitisse maximizar o uso da água de rega. Concluiu-se que, em condições de disponibilidade limitada de água, a seleção de uma estratégia de rega que otimize as disponibilidades de água em relação à menor quebra de produção possível depende não só da cultura e do local onde esta é praticada, mas ainda das condições de procura climática (forte e muito forte) a que aquela está sujeita. Os resultados mostram que as estratégias de rega que conduzem a elevadas poupanças de água acarretam elevadas perdas de produção, o que na conjuntura de preços do milho e custos da água torna impossível a sua adoção pelos agricultores. Assim, considera-se que em situação de seca severa e extrema a melhor opção será a adoção de défices muito reduzidos ou de rega completa mas reduzindo a área cultivada. Em resumo, verificou-se que o modelo SIMDualKc tem capacidade para apoiar eficientemente o gestor/agricultor na prática da rega, tanto em conforto hídrico como em rega deficitária.

No Capítulo 4 calibrou-se e validou-se o modelo SIMDualKc para a cultura do milho em parcelas de um agricultor utilizando observações da água disponível no solo. Os resultados mostraram a adequação do modelo para a simulação da água disponível no solo bem como para a partição da evapotranspiração da cultura nas suas componentes transpiração (T_a) e evaporação do solo (E_s). Os resultados de T_a foram utilizados em combinação com os modelos global e fásico de Stewart para a estimação da produção, tendo-se obtido bons resultados para a predição da produção de grão, com um erro médio quadrático representando 10 e 6.8% da produção média observada com os modelos global e fásico respetivamente. Os melhores resultados obtidos com o modelo fásico relacionam-se com o facto de o modelo considerar impactos distintos do stress hídrico ao longo do ciclo da cultura, dando maior enfase á suscetibilidade da cultura na fase da floração/formação do grão. No entanto, o modelo fásico requer que se conheçam com exatidão as distintas fases (vegetativa, floração/formação grão e maturação), os défices de transpiração que ocorrem nessas fases, assim como os respetivos fatores de resposta da cultura à água. Assim, no caso de não existir esta informação, deve ser utilizado o modelo global.

Em complemento a este estudo, efetuou-se a análise dos calendários de rega praticados pelo agricultor utilizando indicadores, nomeadamente a produtividade da água em termos físicos (WP e WP_{irrig}) e económicos (EWP e EWP_{irrig}), tendo-se verificado que estes indicadores são mais sensíveis á água utilizada e pouco sensíveis á produção, ou seja, são indicadores pouco adequados às necessidades do agricultor, dado que este valoriza a obtenção de elevada produção e retorno económico. No entanto, quando se utilizam todos os custos de produção no cálculo da razão da produtividade económica da água ($EWPR_{full\ cost}$) este indicador responde tanto às diferenças de quantidade produzida como ao preço do produto. Assim, tendo como restrição a dificuldade de obtenção dos dados económicos, concluiu-se que este indicador é apropriado para avaliar a viabilidade económica de distintos cenários alternativos.

No Capítulo 5 procedeu-se á a calibração e validação do modelo AquaCrop utilizando os mesmos dados de campo referidos no Capítulo 4. Foram utilizados para este processo de calibração e avaliação da capacidade do modelo mais dados observados do que no caso anterior, nomeadamente a fração de cobertura do solo pela cultura, água disponível no solo e ET, biomassa e produção. Verificou-se que o AquaCrop é muito sensível á parametrização da curva da fração de cobertura do solo pela cultura, a qual influencia muito a partição da ET. Adicionalmente, foram apontadas limitações do modelo quanto à estimação das componentes do balanço hídrico e na estimativa de T_a, em particular quando a cultura é sujeita a stress hídrico forte. Mostrou-se que as predições de biomassa e produção efetuadas pelo modelo são boas quando este é apropriadamente calibrado, com erros médios quadráticos inferiores a 9% da produção média observada, mas com uma ligeira tendência para sobrestimar a produção devido a sobrestimação de T_a. Os resultados da predição da produção são semelhantes aos obtidos com a utilização do modelo global de Stewart combinado com o SIMDualKc e apresentados no Capítulo 4.

O modelo AquaCrop foi adicionalmente avaliado quando se utilizam parâmetros tabelados tendo-se verificado que o modelo tende a subestimar a produção. Os erros associados aumentam para 14% da produção média observada. Pode concluir-se que se se pretender utilizar o modelo para investigação e por isso requerendo elevada exatidão existe a necessidade de o modelo ser calibrado utilizando todas as observações anteriormente apontadas. No caso de não existirem dados de campo para a calibração da simulação da água do solo, o modelo poderá ser utilizado com os parâmetros tabelados tendo em atenção que produzirá resultados menos adequados.

No Capítulo 6 procedeu-se á utilização dos dados e resultados do Capítulo 4 fazendo-se a aplicação a parcelas do Perímetro de Rega da Vigia. Utilizando os indicadores de produtividade da água anteriormente referidos, compararam-se cenários de rega alternativos visando a convivência com a escassez e analisando a adoção de distintos sistemas de rega. Foi efetuada a hierarquização das distintas soluções apresentadas com base em critérios de poupança de água e económicos, ou ponderando ambos os critérios. Concluiu-se que a adoção da rega deficitária neste perímetro está fortemente condicionada pelo preço do milho. O estudo permitiu demonstrar que se a prioridade é dada aos critérios económicos os sistemas de rega por aspersão apresentam melhores resultados. A análise conjugada dos impactos da rega deficitária na produção e em termos económicos mostraram ser uma excelente ferramenta para o apoio á decisão do agricultor.

Nos Capítulos 7, 8 e 9 descreve-se a calibração e validação do modelo SIMDualKc para as culturas da ervilha para indústria, cevada para indústria, e soja. Os resultados mostram uma boa capacidade do modelo para a predição da água disponível no solo e para a partição da ET. Tendo por base os resultados do défice de transpiração provenientes do SIMDualKc, aplicou-se o modelo global de Stewart tendo-se obtido bons resultados na predição da produção em todos os casos de estudo. Os desvios entre observação e simulação variaram entre 0.3 e 6.4%, 6.4 e 10.6%, e 5 e 19%, respetivamente. Concluiu-se que a aproximação simplificada permite uma boa precisão na estimativa da produção destas culturas podendo ser utilizada no apoio á tomada de decisões. Nos Capítulos 7 e 8 referiu-se também a calibração e teste do modelo AquaCrop utilizado para as mesmas condições e com resultados de predição da produção semelhantes á aproximação simplificada, a qual requer menor número de parâmetros. Nestes dois capítulos são, como no caso do Capítulo 5, apontadas algumas debilidades do modelo AquaCrop, nomeadamente na predição da água disponível no solo e quanto à percolação profunda.

No Capítulo 8 são adicionalmente analisados, com os dois modelos, datas de sementeira e calendários de rega alternativos em condições de seca severa e extrema. Os resultados mostram semelhança entre a produção predita pelos dois modelos para todos os cenários analisados e que existe vantagem em antecipar a sementeira. Adicionalmente os resultados mostram que cultivar a cevada em sequeiro em condições de seca severa e extrema pode não ser economicamente viável dados os elevados impactos na produção; assim, nestas condições deverá adoptar-se rega de complemento que minimize as perdas de produção.

Em resumo, ficou demonstrada a boa capacidade da aproximação simplificada (modelo SIMDualKc-Stewart) para a predição da produção das culturas estudadas e que a utilização do modelo AquaCrop não traz vantagens adicionais visíveis. Atualmente o modelo AquaCrop tem vantagem relativamente á aproximação simplificada dado poderem-se utilizar graus dias (GDD) em vez de datas do calendário, o que permite que não seja necessária a observação da data de cada fase da cultura e por isso se torne mais fácil o aconselhamento em tempo real. Assim, a introdução da aproximação dos GDD no SIMDualKc é desejável por conduzir a melhoria na aproximação simplificada. A utilização de dados meteorológicos de previsão, a integração de um modelo económico e a aplicação em SIG poderá ajudar na tomada de decisão dos agricultores em tempo real.