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

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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.

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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 water–yield 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

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S1	global Stewarts' model
S2	multi-phasic Stewarts' model
AAE	average absolute error (units of the variable)
a_D	parameter of the deep percolation equation
ASW	available soil water (mm)
b_D	parameter of the deep percolation equation
BWUF	beneficial water use fraction ( )
d_{IA}	Willmott index of agreement ( )
EF	modeling efficiency ( )
$ET_{c\ adj}$	actual crop evapotranspiration (mm)
ET_c	maximum crop evapotranspiration (mm)
ET_o	reference evapotranspiration (mm)
E_s	soil evaporation (mm)
EWP	economic water productivity (€ m^{-3})
EWP_{irrig}	economic irrigation water productivity (€ m^{-3})
EWPR	economic water productivity ratio ( )
$EWPR_{full\ cost}$	economic water productivity ratio ( ) using full production costs
f_c	fraction of soil covered or shaded by vegetation ( )
h	crop height (m)
I	net irrigation depth (mm)
IWU	irrigation water use (m^3)
K_c	crop coefficient ( )
$K_{c\ mid}$	crop coefficient at the mid-season stage ( )
$K_{c\ act}$	actual crop coefficient ( )
K_{cb}	basal crop coefficient ( )
$K_{cb\ ini}$	basal crop coefficient during the initial growth stage ( )
$K_{cb\ mid}$	basal crop coefficient during the mid-season growth stage ( )
$K_{cb\ end}$	basal crop coefficient at end of the late season growth stage ( )
$K_{cb\ adj}$	adjusted basal crop coefficient ( )
K_e	evaporation coefficient ( )
K_s	water stress coefficient ( )
K_y	yield response factor for the entire crop growth season ( )
p	soil water depletion fractions for no stress ( )
RAW	readily available soil water (mm)
REW	readily evaporable water (mm)
RMSE	root mean square error (units of the variable)
RYL	relative yield losses (%)
T_a	actual transpiration (mm)
TAW	total available soil water (mm)
T_c	maximum crop transpiration (mm)
T_d	transpiration deficit (mm)
$T_{d,f}$	transpiration deficit for flowering period (mm)
$T_{d,m}$	transpiration deficit for maturation period (mm)
$T_{d,v}$	transpiration deficit for vegetative period (mm)
TEW	total evaporable water (mm)
TWU	total water use (m^3)
WP	water productivity (kg m^{-3})
WP_{irrig}	irrigation water productivity (kg m^{-3})
Y_a	actual yield (kg ha^{-1})
Y_m	maximum (expected) yield (kg ha^{-1})
Z_e	thickness of the evaporation soil layer (m)
Z_r	root depth (m)
β_f	yield response factor for flowering period
β_m	yield response factor for the maturation period
β_v	yield response factor for vegetative period
θ_{FC}	volumetric soil moisture at field capacity ($m^3\ m^{-3}$)
θ_{WP}	volumetric soil moisture at wilting point ($m^3\ m^{-3}$)

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.

2. Material and methods

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 (39.16°N, 8.33°W 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 1.

Fields were cropped with *Zea mays* L. var. PR33Y74 (FAO 600) with a density of approximately 82,000 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 2 presents the main soil characteristics of these fields. Groundwater is quite deep and capillary rise was not considered.

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 min. 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 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.

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