REFLECTANCE-BASED CROP COEFFICIENTS REDUX: FOR OPERATIONAL EVAPOTRANSPIRATION ESTIMATES IN THE AGE OF HIGH PRODUCING HYBRID VARIETIES

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Abstract

Methodologies based on earth observation remote sensing allow for a precise estimation of actual water requirements for irrigated crops across large areas. In spite of the many number of experiments using or analyzing the relationship between the basal crop coefficient (K_{cb}) and the soil adjusted vegetation index (SAVI) for maize, the development of new maize hybrid varieties with modifications related to canopy architecture suggest a possible change of the leaf area index (LAI) for maximum K_{cb} and its relationship with the SAVI or other vegetation indices. In addition, we noted a lack of analysis of these relationships for cultivated soybean. The objective of this paper is to analyze the K_{cb} , SAVI and LAI relationships in maize and soybean based on the non-linear relationships proposed by Choudhury et al. (1994). In addition, we propose a modification of the Choudhury et al. (1994) approach based on field-based experimental evidence of a minimum K_{cb} greater than 0. For sites with limited field data, we also analyze the utility of a simple linear regression based on the K_{cb} and SAVI values for bare soil and maximum K_{cb} values. The resulting K_{cb} -SAVI relationships are assimilated into a remote sensing based soil water balance model. The results of the model are analyzed in terms of irrigation requirements and crop evapotranspiration (ETa) for 11 growing seasons in two fields cultivated with irrigated and rain-fed maize and soybean in eastern Nebraska. Comparisons of measured and modelled ETa values indicate a good agreement, with RMSE lower than 0.7 mm d^{-1} for weekly averaged values. The comparison of actual irrigation applied and irrigation requirements indicate the central pivot systems could not supply adequate water in some growing seasons with higher demands.

Keywords: Soil water balance; SAVI; LAI; crop coefficient; maize; soybean

1. INTRODUCTION

The precise estimation of actual water requirements for irrigated crops over large areas is still a paramount concern in agriculture. The use of direct and indirect measurements (e.g. weighing lysimeters, eddy covariance/Bowen ratio techniques) has been shown to be valid for the assessment of crop evapotranspiration at field scales. However, the implementation of these techniques for operational applications is restricted by installation and maintenance costs and limited spatial representation. Moreover, the up-scaling of these approaches to larger areas is limited by field-to-field heterogeneity in crop development and cropping systems management. Nevertheless, the routine measurement of evapotranspiration in selected locations allows for the development and validation of remote sensing based models applicable over larger areas.

Common remote sensing methodologies used to estimate evapotranspiration fall into three categories. The first involves models using thermal band based energy-balance approaches (SEB) in either one-layer models such as SEBAL (Bastiaanssen et al, 1998) or two-layer models (Norman et al, 1995). The second method utilizes reflectance based basal crop coefficients (K_{cb}) derived from vegetation indices (VI) like the well-known normalized difference vegetation index (NDVI), the soil adjusted vegetation index (SAVI) and the enhanced vegetation index (EVI). These crop coefficients derived from remote sensing are used in water balance models (RSWB) such as the method described in the FAO-56 manual (Allen et al, 1998). A third method is to derive biophysical parameters for the direct solution of the Penman-Monteith equation for evapotranspiration assessment (Baselga et al, 1990, Vuolo et al. 2015, Autovino et al, 2016). These approaches are generally known as remote sensing Penman-Monteith (RSPM) techniques.

SEB models determine actual evapotranspiration that includes added evaporation due to wet soil and plant canopies as well as the presence of water stress in the root zone. For this reason, these models generate a remotely sensed indicator of the water content in the root zone (Gonzalez-Dugo et al., 2009). On the other hand, the product of the reflectance-based crop coefficient and the reference evapotranspiration (E_{Tr}) represents the potential transpiration for a given canopy growing under certain meteorological conditions. For the assessment of water stress, remote sensing water balance (RSWB) and RSPM models require the simulation of the water content in the root zone through a water balance or the inclusion of temperature indices in the RSPM formulation (Autovino et al. 2016) to simulate potential water stress. In consequence, we explicitly indicate in this manuscript that the

evapotranspiration (ET) measured in the field or modelled by the RS methods refers to actual ET. This actual ET integrates plant transpiration and soil evaporation and eventually the effect of water stress and is named ETa throughout the manuscript.

In the RSWB methodology, the product $K_{cb} \cdot ETr$ provides valuable information, as the accumulated value over time represents the potential water requirement of the crop during the analysis period. These requirements should be satisfied by the water stored in the root volume, the eventual precipitation and, in irrigated areas, the applied irrigation water. Thus, irrigation requirements are estimated in a simple and precise manner and adapted to the actual field crop development through the reflectance-based crop coefficients. Other components of the root zone water balance are the water runoff after watering events, deep percolation, the capillary rise to/from water tables, the evaporation of water from the bare soil, and the water intercepted by the plant canopy. These components must be adequately evaluated for a precise and realistic estimate of crop water requirements.

Reflectance-based crop coefficients have been widely evaluated and applied to herbaceous and woody crops (Campos et al., 2016; Choudhury et al., 1994; Duchemin et al., 2006; Er-Raki et al., 2007; González-Dugo et al., 2013; Hunsaker et al., 2003a; Jayanthi et al., 2007; Mateos et al., 2013; Neale et al., 1989). Usually the K_{cb} values for crop canopies describe a smooth curve over time, and their values can be interpolated with adequate precision when the actual values are known for critical periods and inflexion points. Currently, the possibility of combining data from operational platforms such as Landsat 8 and Landsat 7 for some areas as well as Sentinel 2 images, allow for a precise description of the K_{cb} curve for most of the agricultural areas in the world using freely available datasets. The K_{cb} -VI relationships are generally established in terms of a K_{cb} minimum for bare soil and a K_{cb} maximum for a SAVI or a leaf area index (LAI) threshold at effective cover. The LAI threshold at effective cover is when a further increase in vegetation density, LAI or VI, does not lead to an increase in the transpiration rate. Neale et al. (1989) indicated that the saturation of the LAI- K_{cb} relationship occurred for a $LAI > 3.2$, coinciding with $NDVI > 0.8$. Based on these results, Bausch (1993) suggested that K_{cb} should be capped at effective cover ($LAI = 3$) because the SAVI index still increases for $LAI > 3$. The evidence of the saturation effects described by Neale et al. (1989) and used by Bausch (1993) were found for maize varieties first grown commercially in the 1980s (Pioneer 3732 and Garst 8702). However, over the last 30 years, maize varieties have undergone significant morphological changes and present hybrid varieties have significant canopy structure differences and are planted to higher densities than the varieties in the 1980s.

Experiments analyzing morphological changes in maize lines do not indicate clear changes in those parameters related to leaf area per plant or canopy height. Conversely, experiments analyzing the leaf angle distribution describe a consistent tendency towards more upright leaves. Lauer et al. (2012) analyzed the morphological changes in seventy-eight parental lines of Pioneer brand maize hybrids primary used from 1934 to 2007. These authors did not find significant tendencies in those parameters related to leaf area such as leaf width and length, but they found a significant decrease in the plant height. Other authors reported no changes in the number of leaves per plant for the period 1930 to 1990 for representative hybrids grown in Iowa (Duvick et al., 2010) or slight increases (10%) from the 1930s to the 1970s (Meghji et al., 1984). In a complete review, Duvick (2005) concluded that no consistent trends exist in leaf area resulting from the variability for each reported experiment, but increases in LAI at field scale can be expected considering the increasing trend in plant densities. In contrast, with the lack of consistent trends in leaf area or related parameters, Lauer et al. (2012) reported significant decreases in the leaf angle with respect to the stalk of about -0.8° per decade, in agreement with the work done by Meghji et al. (1984) and Russell (1991) for different hybrids in the US corn belt. The reason for the reported shift toward lower leaf angle with respect to the stalk (or more upright leaves) is the introduction of Iowa State University's B73 inbred (Russell et al., 1971) into breeding programs during the 1970s. This change in architecture results in a better distribution of incoming light into the canopy, balancing the light interception across the plant and reducing the shading of leaves at the bottom of the canopy. A consequence of these morphological changes is that the new varieties are more efficient intercepting light as planting densities have increased (Tian et al., 2011). These canopy architectural changes and higher planting densities raise the possibility of a change in the effective cover LAI vis-à-vis the VIs and maximum plant transpiration. Consequently, the K_{cb} -VI relationship developed in the 1980s may no longer be valid and should be reassessed using more recent varieties. The present study is based on maize hybrid lines developed and patented in the late 1990s.

In addition, there is a lack of information in the literature on the K_{cb} -VI relationships for cultivated soybean. Previous attempts (Singh and Irmak, 2009) were based on combining SEB models and NDVI images to derive an experimental relationship between NDVI and the crop coefficient (K_c) for many crops including soybean; these analyses included plant transpiration and a proportion of soil evaporation. Similarly, Kamble et al. (2013) obtained a general K_c -NDVI relationship for maize and soybean based on meteorological measurements including data from the same area of this study. Considering that the previous experiences are based on K_c ,

and after an in-depth analysis of the existing literature, we conclude that the relationship between K_{cb} and VI for soybean has not yet been developed. Such a relationship could present some operational advances with respect to the K_c -VI approaches previously presented. Considering the variability of the climatic conditions where soybean are cultivated, the amount of precipitation and irrigation applied will vary dramatically. These events impact soil evaporation and crop interception, inducing a large fluctuation of K_c with respect to K_{cb} , which represents dry soil surface conditions. In our study area in eastern Nebraska, and other growing sites in the soybean belt, these effects could be important considering the frequent presence of rainfed fields for which lower soil evaporation could be expected. For these reasons, there is a need to develop a K_{cb} -SAVI relationship for soybean. Such a relationship a) would not depend on meteorological nor management conditions and b) allow for a more precise estimation of ETa and the root zone water balance as well as estimates of irrigation requirements.

Therefore, the objective of this paper is a reassessment of the K_{cb} -SAVI relationship for maize for recent hybrids and the development of a new K_{cb} -SAVI relationship for soybean. The analysis gives particular attention to the saturation effects for high LAI values and we propose a modification of the analytical approach to the K_{cb} -SAVI formulation to improve the precision of K_{cb} estimation during the early stages of growth. These analyses are based on the analytical methodology of Choudhury et al. (1994) who proposed a non-linear relationship between K_{cb} , LAI and VI. In addition, we analyzed the performance of the linear approach based on the values of K_{cb} and VI for bare soil and effective cover as proposed by Neale et al. (1989).

2. METHODOLOGY

2.1. Analytical approach to the K_{cb} -VI relationship

The use of remote sensing methodologies to assess crop water consumption has had a long development since Heilman et al. (1982) described the capability of vegetation indices to describe crop temporal evolution in terms of crop coefficients. The work done by Choudhury et al. (1994) is considered to be the theoretical framework for these relationships and presents some advances over common empirical correlation such as a better representation for the entire range of crop stages from bare soil to full development. The Choudhury approach is based on analytical relationships between LAI and the transpiration coefficient (K_t) (Equation 1) and the relationship between LAI and multispectral VI (Equation 2). Both relationships are combined to obtain the relationships between K_t and the VI at effective cover (VI_{eff}) and bare

soil (VI_{min}) (Equation 3). The relationship between K_t and VI is not necessarily linear depending mainly on the effect of the background reflectance and the plant properties. Numerically, the linearity of the K_t - VI relationship depends on the ratio between the coefficients α and β for the K_t -LAI and LAI- VI relationships, respectively. The coefficient K_t does not exactly coincide with K_{cb} because the upper limit for K_t is always less than 1 and $K_t = 0$ for bare soil. The relationship between K_t and K_{cb} is described by González-Dugo and Mateos (2008) as $K_{cb} = K_{cb,max} \cdot K_t$. Taking into account this modification, the final relationship between K_{cb} and VI is presented in Equation 4 as proposed by González-Dugo and Mateos (2008). Equation 4 considers a K_{cb} value equal to 0 for the minimum VI values obtained for bare soil, and its maximum value for the VI representing canopies at effective cover.

$$K_t = 1 - e^{(-\alpha \cdot LAI)} \quad \text{Equation 1}$$

$$VI = VI_{eff} - (VI_{eff} - VI_{min}) \cdot e^{(-\beta \cdot LAI)} \quad \text{Equation 2}$$

$$K_t = \left[1 - \left(\frac{VI_{eff} - VI}{VI_{eff} - VI_{min}} \right)^{\alpha/\beta} \right] \quad \text{Equation 3}$$

$$K_{cb} = K_{cb,max} \cdot \left[1 - \left(\frac{VI_{eff} - VI}{VI_{eff} - VI_{min}} \right)^{\alpha/\beta} \right] \quad \text{Equation 4}$$

The occurrence of a K_{cb} value greater than 0 for bare soil conditions has been repeatedly shown in the literature. Wright (1982) proposed the use of a residual K_{cb} equal to 0.15 even in the absence of a crop; this is also found in the FAO-56 manual (Allen et al., 1998) and in most of the published empirical relationships between K_{cb} and VI (e.g., Bausch and Neale, 1987; Campos et al., 2010; Hunsaker et al., 2003b; Neale et al., 1989). As demonstrated empirically by Torres and Calera (2010), this residual evaporation can be expected for bare soil over more than 30 days after watering events, even in total absence of live plants transpiring in the field. According to these experiments, a residual K_{cb} can be expected for bare soil conditions but the accumulated water use does not depend on plant activity. Thus, a relationship with minimum K_{cb} values greater than 0 for bare soil conditions is expected to be more realistic in simulating the ETa process and estimating irrigation requirements. As indicated, the value of K_{cb} for bare soil conditions is generally assumed to be equal to 0.15 for those experiments using the FAO Penman-Monteith reference evapotranspiration for short reference crops. The analyses performed in this research are based on the ASCE tall crop reference evapotranspiration; therefore, the minimum K_{cb} for bare soil was set to 0.12 by considering the relationship between both reference ET values (Wright et al., 2000). In order to integrate the noted empirical evidences of bare soil evaporation in the K_{cb} - VI formulation,

we modified Equation 1 by adding a new term equal to $0.12/K_{cb,max}$ (Equation 5) which led to a modified K_{cb} -SAVI relationship (Equation 6).

$$K_t = 1 - e^{(-\alpha \cdot LAI)} + 0.12/K_{cb,max} \cdot e^{(-\alpha \cdot LAI)} \quad \text{Equation 5}$$

$$K_{cb} = K_{cb,max} \cdot \left[1 + \left[\frac{(VI_{eff} - VI_{min})}{VI_{eff} - VI_{min}} \right]^{\alpha/\beta} \cdot \left[\frac{0.12}{K_{cb,max}} - 1 \right] \right] \quad \text{Equation 6}$$

2.2. Linear approach to the K_{cb} -VI relationship

Considering that the analysis previously described is not possible for many applications with scarce data availability, we also analyzed the use of a simple linear regression to describe the K_{cb} -VI relationship. Even under experimental conditions, the availability of K_{cb} -SAVI and K_{cb} -LAI pairs during the development period could be seriously impacted by soil evaporation. The reduction of irrigation frequency to obtain denser datasets is not always possible because it limits the water availability for the crop, reducing crop transpiration from the required optimal conditions. Under these conditions, the best solution may be the use of a linear relationship as proposed by Neale et al. (1989) and based on the K_{cb} and VI values for bare soil ($K_{cb,min}$ and VI_{min}) and the value of both parameters at effective cover ($K_{cb,max}$ and VI_{eff} ; see Equation 7). As indicated by Neale et al. (1989), VI at effective cover could differ from the maximum VI measured in the field. For many canopies, including maize and soybean, we can expect a saturation of K_{cb} at threshold values of ground cover or LAI depending on canopy architecture (Allen and Pereira, 2009). In parallel, the different VIs described in the literature may (Gamon et al., 1995) or may not (Anderson et al., 2004) exhibit similar saturation effects depending on the characteristics of the analyzed VI. The saturation points for both target parameters, K_{cb} and VI, generally do not coincide which could lead to mismatches when developing experimental relationships based only on the maximum and minimum values.

An alternative approach is to regress every K_{cb} -SAVI pair available (Campos et al., 2010; Hunsaker et al., 2005). However, the validity of both of these approaches is generally restricted to the range for which they were developed. For this reason, we recommend the development of a linear relationship based on the extreme points because it has the advantage of making good estimates of water requirements for periods of higher demand (effective cover).

$$K_{cb} = K_{cb,max} - \left[\frac{(K_{cb,max} - K_{cb,min}) \cdot (VI_{eff} - VI)}{VI_{eff} - VI_{min}} \right] \quad \text{Equation 7}$$

2.3. Field data

The two approaches presented in this work were analyzed in irrigated and rain-fed maize and soybean fields in eastern Nebraska for which the measurement of crop ETa and the needed biophysical parameters were available. The experimental fields are located at the University of Nebraska-Lincoln's Agricultural Research and Development Center (ARDC) near Mead, NE. According to the Köppen classification, the climate in this area is Dfa (humid continental climate), with cold winters but relatively dry, hot summers and occasionally humid. The records of the long-term weather station from the US National Weather Service located near Mead, indicate for the last 30 years (1981-2010) an average annual temperature of 9.9°C, average maximum temperature of 16.4°C and average minimum of 3.4°C. The average precipitation in this period was 746 mm year⁻¹. The precipitation is irregularly distributed throughout the year with higher amounts occurring during the spring and summer and relatively drier conditions during fall and winter. The soils at all three sites are deep silty clay loams (Suyker and Verma, 2009), typical of eastern Nebraska, consisting of four soil series: Yutan (fine-silty, mixed, superactive, mesic, Mollic Hapludalfs), Tomek (fine, smectitic, mesic Pachic Argialbolls), Filbert (fine, smectitic, mesic Vertic Argialbolls), and Filmore (fine, smectitic, mesic Vertic Argialbolls). The water availability for these soils, (the difference between the soil water contents at field capacity and wilting point) is about 0.165 cm³ cm⁻³ for all three sites (Soil Survey Staff).

The dataset used in this work consisted of LAI, ETa and Landsat 5 and Landsat 7 images available for the maize and soybean research fields for the 2002-2012 growing seasons. The fields analyzed comprise a continuously irrigated maize field (Mead 1, <http://fluxnet.ornl.gov/site/951>), an irrigated maize-soybean rotation field (Mead 2, <http://fluxnet.ornl.gov/site/952>) and a rain-fed maize-soybean rotation field (Mead 3, <http://fluxnet.ornl.gov/site/953>). The three sites are listed in the Ameriflux archive as US-Ne1 (Mead 1), US-Ne2 (Mead 2), and US-Ne3 (Mead 3). A complete description of the measurements of ETa and biophysical parameters, including LAI data, can be found in Suyker et al. (2005) and Suyker and Verma (2009). The maize and soybean hybrids used at each site for each year are presented in Table 1.

The energy balance fluxes were measured with an eddy-covariance flux tower located in the fields. For additional information about the instrumentation and tower characteristics, the reader is referred to Suyker et al. (2005). The fluxes, with 30 min averaging periods, including latent heat flux (LE), sensible heat flux (H), net radiation (Rn) and soil heat flux (G), were downloaded from the AmeriFlux archive ([www. http://ameriflux.lbl.gov/](http://ameriflux.lbl.gov/); Level 2 standardized data). The energy balance closure for all three sites (excluding the winter months and rain or irrigation periods) were estimated to be about 89% (Suyker and Verma, 2009), which was generally higher than closure reported from previous studies in similar ecosystems (Stoy et al., 2013). There is scientific debate as to the source of the lack of energy balance closure with fluxes measured using the eddy covariance technique. Causes such as ecosystem (biomass) energy and heat storage, the underestimation of the storage of heat in the soil layer over the heat flux plates, and metabolism could contribute to this imbalance (Stoy et al., 2013). For example, the analysis of the energy consumed by the canopy during photosynthesis in maize and soybean (Meyers and Hollinger, 2004), which is included in Suyker and Verma (2009), resulted in an increase of the energy balance closure of about 10% over the original fluxes. More recently, angle of attack errors noted in non-orthogonal sonic anemometers (models employed at these sites) cause turbulent fluxes to be underestimated. Nakai et al (2006) developed a correction algorithm which increased H and LE fluxes by 6% at these sites (this correction is incorporated in Level 2 data since 2001). However, data collected at the Mead sites a few months ago suggest the Nakai correction should be in the order of 12%. The magnitude of this correction is generally supported by a more recent study of angle of attack errors (Nakai and Shimoyama, 2012). Therefore, H and LE fluxes in this analysis were increased by an additional 6% resulting in an energy balance closure over 92%.

The spectral VI values were derived from Landsat 5 TM and Landsat 7 ETM+ images. The images were obtained from the atmospherically corrected reflectance provided by the Surface Reflectance Climate Data Record (CDR) of the USGS (http://landsat.usgs.gov/CDR_LSR.php). The VI values were calculated on a pixel-by-pixel basis and averaged at the plot scale avoiding the border pixels. Both the well-known soil adjusted vegetation index (SAVI) and the normalized difference vegetation index (NDVI) were used in this study. In order to maintain the independence between calibration and validation datasets, the statistical relationships between K_{cb} -LAI and SAVI were developed from Mead 2 (corn/soybean rotation irrigated field) for each crop and validated in Mead 1 and Mead 3.

Mead 3 was excluded from the calibration dataset because it is a rainfed field and the crops can be under water stress conditions in several periods during the growing cycle. As indicated, the K_{cb} -SAVI relationships must be developed under non-water limitations because the model strongly relies on the potential transpiration and this potential is modulated by the stress coefficient based on the soil water balance. Mead 1 is continuous maize, so the analysis of the SAVI-LAI- K_{cb} relationships for soybeans was not possible in this field. The selection of the Field 2 as a calibration dataset provides enough data for the development of the relationships and the methodology can be validated in truly independent datasets (Mead 1 and Mead 3). Therefore the methodology was validated in irrigated maize, and rainfed maize and soybean. These relationships were developed for multiple hybrids cultivated during the study period in Mead 2. These relationships will be validated for alternate hybrids at Mead 1 and for some years the same hybrids at Mead 3. Furthermore, the characteristics of the Mead 3 rainfed field provided additional differences because the potential presence of water stress conditions during some campaigns must be considered and quantified. In addition, the noted relationships were developed for a limited set of daily values (around 20 values for the entire measurement period) where satellite overpasses coincided with field measurements of LAI and other biophysical properties. Thus, the model results can be compared with the whole dataset in the field (Mead 2) which include daily values during 11 growing seasons. This comparison includes irrigated maize and soybean and it is fair to say that for Mead 2, the calibration and the validation datasets are not truly independent. Nevertheless, the relatively low number of daily values used in the calibration, the differences in canopy development, and the occurrence of additional events such as precipitation and irrigation confer considerable variability to the validation datasets.

The development of the experimental relationships was restricted to the period from emergence to effective full cover (Wright, 1982). The analysis performed for the selection of the effective cover date is presented in the results section. Experimental K_c values were estimated for the calibration dataset as the ratio between experimental ET_a data, derived from the measured latent heat flux, and the reference evapotranspiration (ET_r). ET_r was estimated for the station of the Automated Weather Data Network (AWDN) at the ARDC near Mead (Coordinates: 41.15°N-96.48°W, Elevation=366 m) following the ASCE equation for tall crops (Alfalfa reference) and hourly meteorological data (Walter et al. 2001). Since the relationship between VI and crop coefficient is based on K_{cb} , the K_c values were filtered to only include the dates when the soil surface was dry but transpiration was occurring at the potential rate; considering that these values represent the experimental values of K_{cb} .

Consequently, only the K_c data after a minimum of 4 days following an irrigation or rain event were used, with the goal of minimizing the evaporation component from bare soil. Water stress conditions were not evident before effective full cover in Mead 2 during any analyzed growing season; thus, every experimental K_{cb} value obtained during the crop development was considered free of water stress. K_t was estimated as the ratio between experimental K_{cb} for the measurement data and the maximum K_{cb} ($K_{cb,max}$) measured in the field for each crop following the relationship between K_t and $K_{cb,max}$ (González-Dugo and Mateos, 2008). The restrictive conditions imposed to derive K_{cb} values free of water stress and in the absence of soil evaporation reduced the availability of experimental data for the analysis. Thus the VI data were correlated with synchronous measurements of LAI and K_{cb} wherever possible, or near-synchronous measurements when the ground canopy biophysical parameters were measured one day after or before the acquisition of the satellite image.

2.4. The remote sensing based soil water balance

To validate the proposed relationships, we evaluated the soil water balance based on these relationships in terms of simulated ET_a and irrigation requirements. The soil water balance model applied in this work does not differ from previous approaches published for herbaceous crops (Gonzalez-Dugo et al., 2009) and irrigated vineyard (Campos et al., 2016). The methodology is essentially the one-layer soil water balance proposed in the FAO-56 manual, with additions to simulate the soil top layer evaporation and assimilate the temporal evolution of K_{cb} derived from VIs. In addition, other parameters related to plant growth, such as ground cover and rooting depth, are rescaled between their maximum and the minimum values proposed in the FAO-56 manual (Allen et al. 1998) and considering the K_{cb} values derived from remote sensing. The main differences with other water balances applied for different crops are the values of the parameters related to the depth of the root systems and soil hydraulic properties, as presented in

Table 2. The plant's ability to extract water prior to the onset of water stress is characterized by the "soil depletion factor without stress" (p) (Table 2) and is also based on the values proposed in the FAO-56 manual (Allen et al. 1998) for maize and soybean. In addition, we evaluated the impact of the rooting depth value and the soil depletion factor without stress in the model estimates in terms of ET_a . Measured and modelled ET_a were compared for a range of p from 0.5 to 0.8, including the ranges of p proposed for the majority of crops. The rooting depth was varied in 50% with respect to the reference values for each crop and

management. For the assessment of ETa, the model was applied using daily time steps and actual irrigation data. In a secondary analysis, the model was applied in a predictive mode for the estimation of irrigation requirements to maintain the crop in optimal conditions during the whole growing season. In the model calculations, the crop suffers water stress when the water depletion in the root zone exceeds the “soil depletion fraction without stress”. Thus, working in this mode, irrigation was initiated to prevent water depletion from going beyond this threshold.

Table 2. About here.

3. RESULTS

3.1. Field data analysis: meteorological conditions, water use, irrigation management and crop development

Table 3 presents the maximum, minimum, and average annual temperatures, accumulated annual values of precipitation (Pp) and alfalfa reference evapotranspiration (ETr) recorded for the AWDN agro-meteorological station at the ARDC. Overall, temperatures were close to the historical average for the region. According to Table 3, 2012 had the lowest accumulated Pp (426 mm, 36.5% lower than the annual average) and highest accumulated ETr and average temperature. The highest annual Pp was 931 mm in 2008. Annual Pp showed high standard deviation (149 mm), influencing the irrigation management and the crop development in non-irrigated areas as indicated in the temporal evolution of the SAVI index, see Figure 1. Under irrigated conditions, with less dependence on precipitation, the soybean crop exhibited higher SAVI values, see Figure 1, but the seasonal ETa and the mean K_c (the ratio between seasonal ETa and ETr) is generally lower for this crop, see Table 4.

The total irrigation applied at the Mead 1 and Mead 2 fields varied greatly from year to year due to the variation of atmospheric demand and the effect of this parameter in crop ETa, see Table 4. In general terms, the sum of Pp plus applied irrigation is greater than the total ET measured during the growing season at Mead 1. Both amounts tend to be similar at Mead 2. For the rainfed field the difference between crop ETa and Pp varied greatly depending on the meteorological conditions. The observed differences between crop ETa and water inflow (Pp or Pp plus irrigation) should not be interpreted as water shortage in the fields. The differences encountered in some growing seasons, mainly 2009 and 2012, could be explained by the use

of the water stored in the root zone; thus a complete analysis of the water shortage must be based on the daily evolution of the water balance and not only in total seasonal amounts.

Table 3. About here.

Figure 1. About here.

Table 4. About here.

3.2. Selection of the effective cover dates based on observed data

To further assess the relationship between the point (date) of the maximum of the K_{cb} curve and the LAI and SAVI values, the three variables were plotted as a function of Growing Degree Days (GDD) for maize and soybean for the entire analyzed period (see Figure 2). GDDs were calculated using a base temperature (T_{base}) equal to 10°C. For maize, the K_{cb} data reached its maximum value (0.95) at a LAI of approximately 5.5 m²/m² and a SAVI of 0.68. The maximum K_{cb} for soybean (0.9) occurred for a LAI of 3.7 m²/m² and SAVI equal to 0.72, see

Figure 2. The minimum value of SAVI for both crops was 0.10.

Figure 2. About here.

3.3. Analysis and proposed modification of the relationship between VI and crop transpiration

The empirical relationships between K_t ($K_{cb}/K_{cb,max}$) and LAI for maize and soybean (Figure 3 a and b) indicates a non-linear relationship with saturation occurring for LAI values of 5.5 m² m⁻² for maize and around 3.7 m² m⁻² for soybean. The maximum K_{cb} values measured in the field resulted in K_t values around 1 for both canopies. The experimental datasets for both crops were fitted with the relation presented in Equation 1 in which the coefficient α resulted equal to 0.52 and 0.76 for maize and soybean respectively. The values of α were obtained for each data set by minimizing the RMSE comparing measured and modelled K_t values. The relationship obtained fits the experimental values with a relatively good agreement; the RMSE

is 0.07 for maize and 0.08 for soybean. The addition of the new term in the K_t -LAI relationship, as presented in the Equation 5, allows for a better fit of the K_t -LAI relationship (data not shown) reducing the RMSE to 0.05 for maize and 0.06 for soybean. The best fit between measured and modelled K_t values was found for $\alpha=0.45$ for maize and $\alpha=0.60$ for soybean when the $K_{cb,min}$ different from 0 is considered. The empirical relationships between LAI and SAVI for both crops (Figure 3 c and d) also indicate a non-linear relationship in both crops. The empirical relationships between LAI and SAVI were fitted for maize and soybean reducing the RMSE by varying the exponent β in the Equation 2. The resultant β coefficients using the SAVI index were 0.47 and 0.63 for maize and soybean respectively. The obtained relationships fit well with the experimental VI values with RMSE lower than 0.05 for both crops.

Figure 3. About here.

Figure 4 shows the K_{cb} -SAVI relationship for $\alpha/\beta=1.11$ (maize) and 1.21 (soybean) with a minimum $K_{cb}=0$ following the methodology proposed by Choudhury. In addition, we present the K_{cb} -SAVI relationship for $\alpha/\beta=0.96$ (maize) and 0.95 (soybean) with a minimum $K_{cb}=0.12$ for both crops following the modification proposed in this work. Both exponential relationships based on the SAVI index were compared with the experimental pairs of K_{cb} -SAVI, see Figure 4. The comparison of measured and modelled K_{cb} values results in a RMSE equal to 0.061 for maize and 0.092 for soybean using the Choudhury approach and the results indicate some discrepancies for SAVI values lower than 0.2 in both canopies. The modification proposed increases the linearity of the relationship, (see Figure 4) and fits the experimental data for the whole range of SAVI, reducing the RMSE when comparing measured and modelled K_{cb} to 0.048 for maize and 0.080 for soybean.

Figure 4. About here.

3.4. Analysis of the linear relationship between basal crop coefficient and SAVI

A simple linear relationship based on the K_{cb} and SAVI values for bare soil and at effective cover was used to reproduce the behavior of the K_{cb} -SAVI experimental values, as originally proposed by Neale et al. (1989) and Bausch (1993). The maximum K_{cb} values measured in the field were, on average, 0.95 for maize and 0.9 for soybean, the minimum K_{cb}

value in absence of crop was estimated to be 0.12. The SAVI values at effective cover were, on average, 0.68 for maize and 0.72 for soybean and the minimum values of SAVI were around 0.10 for both crops. The resulting linear equations were $K_{cb}=1.414*SAVI-0.02$ for maize and $K_{cb}=1.258*SAVI-0.006$ for soybean. Figure indicates a fairly good agreement with the experimental data. The RMSE comparing experimental and simulated values was similar to the RMSE obtained for the exponential relationship (RMSE=0.075 for maize and RMSE=0.068 for soybean). The lower values measured for soybean and maize were also adequately reproduced using the proposed relationship. Comparison of the linear relationship developed for maize with the work published by Bausch (1993) indicates little change in the K_{cb} -SAVI relationship for the new maize varieties. The two equations are nearly coincident predicting similar K_{cb} values of maize for SAVI values from 0.3 to 0.68, (Figure). Nevertheless, the linear relationship published by Bausch (1993) slightly overestimates the experimental K_{cb} values of maize during the initial stages of growth, when SAVI index is lower than 0.2.

Figure 5. About here.

3.5. Results of the soil water balance model

The K_{cb} -SAVI relationships developed and discussed in the previous sections, both exponential approaches and the linear equation for maize and soybean, were used to estimate water balance components by using a water balance model. The model was applied at a daily time step and the results were validated with the field measurements of ETa by the flux towers at the Mead 1 and Mead 3 sites. In a second step the soil water balance model was inverted to estimate irrigation water requirements to maintain the crop in optimum conditions. The model was operated in this manner during the analysis period for Mead 1 and Mead 2 and the results were compared with the actual irrigation applied. The application of the soil water balance model at a daily scale requires the interpolation of the SAVI data for the estimation of daily K_{cb} values. The methodology followed for the interpolation of discrete SAVI data is presented below.

3.5.1. Operative functions to interpolate SAVI data

In order to determine the most adequate function to be used in the interpolation of the actual SAVI data in an operational scheme, we analyzed the values of SAVI and the

corresponding GDD obtained during 18 campaigns over irrigated maize and four campaigns over irrigated soybean as presented in Figure 2 a and Figure 2 b. The experimental data clearly indicate three different growth phases for both crops. The initial phase is characterized by a fast development of the SAVI values from bare soil conditions to the peak values of SAVI determined during the campaign. The second phase is a plateau period characterized by relative stability of the SAVI values although a slightly decreasing tendency is seen, more evident for maize data. The length of the plateau is different for both crops, being around 1000 GDD for maize and less than 500 GDD for soybean. After this phase, the SAVI values describe the crop senescence reaching minimum values corresponding to bare soil conditions. The greatest differences between the different varieties appear during the plateau and senescence periods, affecting the extent (duration) of these phases.

The initial phase can be reproduced for both crops with adequate precision using an exponential equation in the form: $SAVI = m \cdot \exp(c \cdot GDD)$ where m and c are constants for a given crop curve. The plateau and descending trend can be reproduced also for both crops using a Gompertz sigmoid function in the form: $SAVI = K \cdot \exp(-\exp(a - b \cdot GDD))$ where k is the maximum value of SAVI and a and b are constants for a given crop curve. Both equations can be easily linearized. The exponential equation can be linearized by the equation: $m \cdot GDD + c = \ln(SAVI)$ and the Gompertz function is linearized by the equation $a - b \cdot GDD = \ln(\ln(SAVI/k))$. Thus the necessary constants for each curve can be retrieved by correlating the experimental values of $\ln(SAVI)$ or $\ln(\ln(SAVI/k))$ versus the corresponding GDD data for each growing season. Both equations were applied individually for the SAVI curve obtained in each growing season and the daily values of SAVI were retrieved. The comparison of measured and modelled values indicated the good aptitude of both curves to reproduce the experimental data. The RMSEs were equal to 0.037 for maize and 0.044 for soybean, the RRMSEs were equal to 0.089 for maize and 0.113 for soybean. The methodology also allows estimation of the SAVI values during the change in the tendency from exponential growth to the plateau, which correspond to the time of the switch from the exponential to the Gompertz function. The error obtained during this period is lower than 15% of the measured values even if the proposed functions are fitted in absence of these values.

3.5.2. Evapotranspiration assessment

The comparison of measured and modelled ETa resulted in good agreement for every year analyzed in the study using both non-linear and simple regression equations (Table 5). In

general terms, the model based on the non-linear approach resulted in a better agreement for almost every year, although the precision of both approaches is similar. The agreement was also similar (similar RMSE) for both crops and management systems (rain-fed and irrigated). As presented in Table 5, the RMSE is lower than 1.1 mm day^{-1} for both crops for all growing seasons, with a mean value lower than 0.95 mm day^{-1} for every analyzed field using the analytical approach. The comparison of weekly mean ETa reduces the noise and improves the model performance, see Table 5 and Figure 5. However, despite the dispersion found in the comparison between measured and modeled values for some periods, the good agreement obtained for ETa values in every campaign analyzed reinforces the use of the proposed model for ETa assessment. In addition, these results open the possibility for the estimation of irrigation requirements based on the proposed approach.

A sensitivity analysis, varying the maximum value of Zr and p, indicates the low effect of the value of p in the ETa simulated by the model in rainfed (Mead 3) and irrigated fields (Mead 1 and Mead 2), see Table 6. Conversely, the analysis indicates that the model is more precise in terms of ETa for greater values of Zr in every analyzed field, see Table 6. These results should be considered in further analyses, and the selection of more adequate Zr values (or water holding capacity in the root zone) could improve the simulation of the processes governing the ETa in the analyzed crops. Nevertheless, the assumption of soil depth profiles explored by the roots in operational applications of this methodology, as is the case for irrigation assessment, must be analyzed as discussed below.

Table 5. About here.

Table 6. About here.

Figure 5. About here.

3.5.3. Irrigation Water Requirements

The results of the comparison between actual irrigation amounts and irrigation requirements simulated by the model are shown in Figure 6. In general terms, the irrigation requirements are well correlated with the actual irrigation applications. Actual irrigation is, on average, greater than the irrigation requirement, with the differences being within 15% of

actual values. For the Mead 1 continuous maize field, the actual irrigation amounts were greater than requirements, except in 2012 when the crop suffered water shortage during some periods of the growing season. For the Mead 2 rotation field, the actual irrigation amounts are slightly lower than requirements in 2002 and 2006 (both soybean years) and in 2012 (a maize year). 2012 was the driest year in the time series analyzed and the increases in water demands in both fields were not satisfied by the irrigation applied, resulting in water stress conditions, mainly at the end of the growing season. In contrast, the differences between actual irrigation amounts and irrigation requirements do not strictly imply over-irrigation in the study plots. Actual irrigation must account for the unavoidable inefficiencies of an irrigation system, transport, application and uniformity and the applied depth must be greater than the irrigation requirements simulated by the model to account for application efficiency and maintain the crop in optimal conditions.

Figure 6. About here.

4. DISCUSSION

As pointed out in the introduction, the high values of LAI reached in the experimental maize fields resulted from an increase in plant density; high plant populations are possible because of the more erectophile leaf angle distributions of the new hybrid varieties and the adequate radiation distribution into the structure (Tian et al., 2011). This increase is exemplified by the comparison of the 73,500 plants ha⁻¹ reported by Neale et al. (1989) and the 84,500 plants ha⁻¹ obtained (on average) in the present study. The LAI values at effective cover obtained herein are considerably greater than the experimental data collected from the 1960s to the early 1980s (Cackett and Metelerkamp, 1964; Neale et al., 1989). Conversely, the value of $K_{cb,max}$ is similar to those maximum values of K_{cb} estimated for different maize varieties by Wright (1982) and other research in subsequent decades (e.g., Jovanovic and Annandale, 1999) when the appropriate conversion in the reference evapotranspiration is applied. Also, the values of the SAVI index for the new hybrid varieties do not differ from the maximum value at effective cover reported in previous studies (Bausch, 1993; Choudhury et al., 1994). The analysis of the effect of maize architecture and plant densities in K_{cb} , LAI and SAVI is pointing to the difficulty in simulating K_{cb} from LAI values because the relationship will change with the introduction of new hybrids and plant densities. Nevertheless, the use of SAVI for the assessment of K_{cb} seems to be more robust and less affected by changes in canopy architecture. Note that the values of K_{cb} and SAVI at full cover have not changed with respect

to the values obtained for old varieties but we detect a notable variation only in the value of LAI at effective cover.

For soybean, the value of LAI at effective cover is similar to the values reported in the literature for soybean (Odhiambo and Irmak, 2012; Irmak et al. 2013) and other crops like wheat (Duchemin et al., 2006). The value of $K_{cb,max}$ is lower than the maximum K_{cb} values proposed in the FAO-56 manual (Allen et al., 1998) even considering the conversion for the different reference crop surface. This difference has been previously reported for soybean growth in the central USA (Payero and Irmak, 2013) and in the North China Plain (Wei et al., 2015). Consequently, the maximum K_{cb} for soybean may need to be adjusted in future studies.

The values of α obtained for soybean was greater than those values reported by Choudhury et al. (1994) and the value for maize is in the bottom of the range proposed by these authors for multiple crops (0.5-0.7). In contrast with the narrow range of α values for multiple crops established by those authors, the data presented in this work clearly indicates the need for different values of α for the two crops. The values of β obtained in this work are close to those values reported by Choudhury et al. (1994) for the same crops. In addition, we analyzed the use of a relationship based on the normalized difference vegetation index (NDVI) for selected LAI-NDVI pairs corresponding to all plots. The best value of β using NDVI was 0.62 for both crops and the relationship presented in Equation 2 fits the experimental data with reasonable precision (RMSE<0.05 for both crops). Nevertheless, the LAI-NDVI relationship shows a clear saturation effect for LAI values over 4.0 in the case of maize. However, saturation is not clear for soybean because of the lower LAI values reached by this crop. The saturation at high LAI limits the application of NDVI for the assessment of K_{cb} in the new varieties of maize. The results in this study indicate that the K_{cb} values are still increasing at LAI values greater than 4; therefore, these values cannot be resolved using the NDVI index. The ratios between the exponents indicate a more linear relationship for both crops using SAVI instead of NDVI, in agreement with the work done by Choudhury et al. (1994). These results point to the advantage of a relationship based on SAVI; in addition, this index also reduces the effect of soil background reflectance changes due to wetting events or soil types and extends the analysis to larger values of LAI for maize.

The Choudhury approach assumes a K_{cb} value equal to 0 for the minimum VI values obtained over bare soil surfaces; however, the results from this study clearly indicate the effect of residual soil evaporation on the VI- K_{cb} relationship for small values of SAVI. According to the references presented in the methodology review and the data analyzed herein, a relationship with a minimum K_{cb} value greater than 0 for bare soil conditions is more suitable

for ETa assessment and irrigation scheduling purposes. The addition of the new term in Equation 5 allows for a better fit of the K_t -LAI relationship, increases the linearity of the K_t -SAVI relationships and improves the accuracy of this relationship in reproducing the field data. In addition, the present study confirms the ability of the simple regression to reproduce the ETa behavior in maize and soybean, though the non-linear approach derived from the analytical model reproduced the measured values and tendencies more precisely. Both relationships are valid for the estimation of crop ETa, and the model precision is improved when weekly values are compared. The consideration of weekly values is not cosmetic and reasons for this improvement are various. In a detailed analysis of mean K_c values for olive trees, Martínez-Cob and Faci (2010) discuss the effect of meteorological conditions on daily K_c data, and propose the use of mean values obtained during longer time periods. In addition, Torres and Calera (2010) highlighted the inaccuracies of the soil evaporation model for daily values and demonstrate the coherency of the model for periods longer than a week. The sensitivity analysis indicated that the value of p had a small effect in the estimates of ETa while the model results in better estimates of ETa for rooting depths of about 1.5 m in irrigated fields and 2.0 m in the rainfed field. For irrigation assessment purposes and working in operational scenarios, we strongly recommend the selection of the most reliable rooting depth, reproducing the actual conditions for the plant and the soil. At the same time, this rooting depth must be conservative, allowing maintenance of the plants in well watered conditions during the whole growing season. For the irrigated field analyzed in this work, 1.0 m coincides with both premises and can be considered as the management rooting depth.

Finally, we propose the use of different interpolation procedures considering the necessity of a function that represents the actual pattern of crop development even in the absence of experimental data or remotely sensed inputs during some periods. The most critical periods are the inflexion points because it is difficult to pinpoint these values using a series of discrete satellite images. We consider that linear interpolations between existing points are adequate for dense time series, but this interpolation approach underestimates and overestimates the actual values for convex and concave tendencies respectively. Polynomial approaches allow for a very precise interpolation of the experimental data, but result in aberrant tendencies when used in predictive schemes.

5. CONCLUSIONS

The experimental data and model analyses presented in this paper point to the fact that with the new hybrid varieties, K_{cb} reaches a maximum at LAI values of 5.5 for maize and around 3.7 for soybean. The values of SAVI corresponding to the maximum K_{cb} were 0.68 and 0.72 for maize and soybean. Practical use of the relationships must consider that the maximum value of K_{cb} is around 0.95 for maize and 0.9 for soybean for an alfalfa reference crop. These values are obviously affected by the measurement precision, but higher K_{cb} values are not expected even though the SAVI values could be greater than the SAVI values at effective cover reported in this study.

The analysis of the field data reinforces the importance of K_{cb} obtained for minimum SAVI values. This concept should be considered in the formulation of the K_{cb} -VI relationship for a better agreement with field measurements. In addition, the results obtained in this work demonstrate that a simple linear formulation is valid to reproduce the experimental K_{cb} -SAVI relationships and the use of exponential approaches is an improvement, allowing a more precise estimation of the K_{cb} values during intermediate crop development stages. These relationships are the key for the assimilation of remote sensing data into soil water balance models and allow for an operational assessment of K_{cb} in the analyzed canopies.

Based on the proposed relationships, the remote sensing soil water balance model was applied at a plot scale and the results indicate an adequate model performance in terms of crop ETa. These results reinforce the utility of this model for ETa assessment and open the possibility for the estimation of irrigation requirements. The analysis of irrigation requirements indicated that the crop water requirements were not met during some growing seasons mainly during the seasons with low precipitation and high water demand.

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