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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.

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

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(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 (ETr) 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}*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 1930–1990 for representative hybrids grown in Iowa (Duvick et al., 2003) 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.