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Irrigation management with remote sensing: Evaluating irrigation requirement for maize under Mediterranean climate condition

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ABSTRACT

Water use control methods and water resources planning are of high priority. In irrigated agriculture, the right way to save water is to increase water use efficiency through better management. The present work validates procedures and methodologies using remote sensing to determine the water availability in the soil at each moment, giving the opportunity for the application of the water depth strictly necessary to optimise crop growth (optimum irrigation timing and irrigation amount). The analysis is applied to the Irrigation District of Divor, Évora, using 7 experimental plots, which are areas irrigated by centre-pivot systems, cultivated to maize. Data were determined from images of the cultivated surface obtained by satellite and integrated with atmosphere and crop parameters to calculate biophysical indicators and indices of water stress in the vegetation—Normalized Difference Vegetation Index (NDVI), Kc, and Kcb. Therefore, evapotranspiration (ETc) was estimated and used to calculate crop water requirement, together with the opportunity and the amount of irrigation water to allocate. Although remote sensing data available from satellite imagery presented some practical constraints, the study could contribute to the validation of a new methodology that can be used for irrigation management of a large irrigated area, easier and at lower costs than the traditional FAO recommended crop coefficients method. The remote sensing based methodology can also contribute to significant saves of irrigation water.

1. Introduction and objectives

For a sustainable irrigation management, crop evapotranspiration (ETc) should be determined, as precisely as possible. The weakest link in this weather-based approach to predict crop water use and irrigation requirement is the difficulty in reliably estimate the crop coefficient (Trout and Johnson, 2007). Crop coefficients are commonly estimated based on days since planting or (occasionally) growing degree days (Allen et al., 1998). For greater accuracy, in the place of a single Kc, dual crop coefficients may be considered as described in Allen et al. (1998): a basal Kcb, accounting for the dependence of ETc on the genetic characteristics of the crops, through transpiration; and a soil evaporation coefficient, Ke, which accounts for the degree to which the soil is covered by the crop, mainly referring to the evaporative component of ETc. A soil water balance will allow for the determination of the irrigation opportunity and crop water requirement (Allen et al., 1998). The best results with this methodology are achieved if on site determinations of soil water status are compared to the estimated values obtained from climatic data.

Relationships can be defined between these types of data – weather-based and *in situ* determined – and biophysical parameters derived from vegetation indices (VI) that can be obtained from multispectral images, through convenient empirical equations. These relationships will incorporate the eventual influences of local factors such as crop, soil, and topography. If such empirical equations are valid and reliable for a given crop in the region, they may be used for defining the crop water balance parameters from remote sensed data, instead of using the corresponding in situ parameters, which are harder and more expensive to obtain.

Research with maize has shown improvements in irrigation scheduling, due to better water-use estimation and more appropriate timing of irrigations, when Kcb estimates derived from remotely sensed multispectral vegetation indices were incorporated into irrigation-scheduling algorithms (Hunsaker et al., 2003). In the present work, remote sensing determined biophysical parameters are incorporated in the crop water balance of a maize crop in an irrigated region, in order to approach a new technology for definition of crop irrigation requirements for a wide irrigated area in that region.

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Nomenclature

CC	Field capacity
CE	Wilting point
CR	Capillary rise
Dr	Water deficit within the soil
DP	Deep percolation
ETo	Reference evapotranspiration
ETc	Crop evapotranspiration, crop water requirement
ETc*	Spectral crop evapotranspiration (from NDVI)
ETca	Actual crop evapotranspiration, crop water consumption
fc	Cover fraction
fc*	Spectral cover fraction (from NDVI)
h	Crop height
I	Irrigation depth
Kc	Crop coefficient
Kcb	Basal crop coefficient
Ke	Evaporative soil surface coefficient
Kc*	Spectral crop coefficient
Kcb*	Spectral basal crop coefficient
Ke*	Spectral evaporative soil surface coefficient
LAI	Leaf area index
LRO	Soil water content limit for optimal crop development
NIR	Near infrared radiation
NDVI	Normalized Difference Vegetation Index
NDVIs	Normalized Difference Vegetation Index for bare soil
P	Precipitation
R	Radiation in the red band
RMSE	Root mean squared error
VI	Vegetation Indices
θc	Soil moisture content calculated using satellite
θm	Soil moisture content measured using TDR
ρ_{NIR}	Observed reflectance in the near infra-red band
ρ_R	Observed reflectance in the red band

In this context, multispectral cameras installed on satellites provide images of the earth surface that are used to estimate the crop coefficient Kc and other crop parameters such as the fraction of land cover (fc) and the leaf area index (LAI). These crop parameters can be estimated from vegetation indices defined on the multispectral and thermal images obtained with cameras installed aboard the satellites or other vehicles. Vegetation indices (VI), computed as differences, ratios, or linear combinations of reflected light in the visible (blue, green, or red) and near infrared (NIR) spectra have been found to be closely related to several crop growth parameters (Heilman et al., 1982; Jackson and Huete, 1991; Moran et al., 1994).

Satellite imagery from Landsat 5 was of broad utility in the present work, although spatial and temporal resolutions present severe limitations. Alternative satellites have had similar problems, not providing great help in this context. However, the next future is much more promising, as some countries have recently launched or are planning to launch a new generation of satellites that can overcome most of such limitations by frequently providing quality images highly suitable for precision agriculture, inclusive the irrigation scheduling (Mulla, 2013). Special relief is due to the NASA Sentinel 2 satellite, with multispectral high resolution images (up to 10 m), with a relatively short recurrence interval (5 days), quite suitable for irrigation management purposes.

Several authors (Neale et al., 1989; Choudhury et al., 1994; Bausch, 1995; González-Piqueras, 2006) have observed that NDVI is well related to the water use and transpiration of the plants. Therefore, the definition of reliable relationships between NDVI and Kcb and Kc became of main concern. Reginato et al. (1985), Neale et al. (1989, 1996, 2003, 2005), Jackson et al. (1980), Heilman et al. (1982), Bausch and Neale (1987), Michael and Bastiaanssen (2000), Jochum et al. (2002), Anderson et al. (2007), Hunsaker et al. (2005), Zhang and Wegehenkel (2006), Gonzalez-Dugo et al. (2009), Droogers et al. (2010), and Allen et al. (2011a,b) are some of the authors that have defined relationships for deriving crop coefficients from NDVI and other indices based on the reflectance of the crop surface, determined from multispectral images. It is clear that the authors are looking for the most reliable possible relation between the indices and the crop parameters.

Correlation equations have been defined to relate biophysical crop parameters, such as land cover fraction fc and leaf area index LAI, with NDVI and other vegetation indices (Bausch and Neale, 1987; Neale et al., 1989; González-Piqueras, 2006; Calera-Belmonte et al., 2005; González-Dugo and Mateos, 2008).

The present work is a first step in a research program with the general objective of testing and validating procedures for obtaining information on crop water status and growth stages, estimating crop coefficients, evapotranspiration and crop irrigation requirement using satellite images. This information can be extremely useful to elaborate, over short term intervals, GIS maps of crop water status and irrigation requirements in any large irrigation area, in order to serve as basis for an irrigation advisory system. In the present case, the study was applied to seven experimental plots in the irrigated area of Divor, close to Évora, south Portugal. The objective is to get relations between NDVI and crop parameters (basal Kcb and global Kc crop coefficients, land cover fraction fc, leaf area index LAI) that could be used in the referred regional irrigation management system. A first attempt is done to validate equations in Table 1 against locally determined data, looking for the possibility of adapting them for use in the regional context.

The specific objectives of this work can therefore be enumerated as:

- Use of Landsat 5 satellite multispectral images for determination of crop water requirements pertinent to the maize crop in the specific Mediterranean context, through the determination of vegetation indices and estimation of crop coefficients.
- Validation of equations to calculate basal (Kcb) and global (Kc) crop coefficients from a vegetation index (Normalized Difference Vegetation Index, NDVI).
- Validation of the empirical relation between Kcb and the vegetation index, through the determination of biophysical parameters leaf area index (LAI) and soil cover fraction (fc).
- Validation of all estimations from remote sensing with on-site monitoring of soil water content, water applied with irrigation, and water balance.

2. Methods and experimental conditions

2.1. Experimental design

The experiment area, the irrigation district of Divor, Évora, Portugal (38°44′N; 7°56′W, 309 m), has about 500 ha of irrigated land (Fig. 1). In 2007, seven experimental plots were prepared, cultivated to maize, and irrigated with centre pivot systems. Maize is the main irrigated crop of the region, with more than 50% of the total irrigated area (245 ha in the seven experiment plots).

The climate is Mediterranean, with 50% or more of the 550 mm average annual precipitation falling during winter (November to February) and next to zero during summer (mid-June to mid-September). Average monthly temperatures vary from 10 °C in January to 24 °C in August. Sunshine hours reach 2800 h a year,

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