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Methodology for obtaining prediction models of the root depth of lettuce for its application in irrigation automation

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ABSTRACT

Irrigation scheduling and automation are usually conducted using models that are based on the measurement of the soil water content. In this sense, water balance has established itself as a good indicator of the growth and development of crops and is currently used in several automatic programming systems, primarily in intensive farming and microirrigation systems. This method analyses the gains and losses of water in a limited volume of soil to determine the water availability for crops and the soil water status. A parameter of great importance for the application of this method is the root depth, which limits the soil volume to be considered in the water balance. In most cases, the actual evolution of this parameter during crop development is not considered, using instead fixed tabulated values or values that have been proposed in the literature. However, during some periods of crop development, the soil profile that is considered for the water balance does not correspond to the profile that is actually explored by the root system, resulting in a mismatch in the water balance. A good relationship between the root depth and the percentage of ground cover in lettuce has been observed, the latter of which is associated with crop development and the evapotranspirative demand. Therefore, this paper presents a methodology for obtaining prediction models of the root depth of the 'Little Gem' lettuce crop from the percentage of ground cover. The implementation of this prediction model in an automated irrigation management system will permit the optimisation of water resources due to the adjustment of the water content to the actual volume that is explored by the roots.

1. Introduction

Water consumption is currently one of the major factors increasing agricultural productivity, albeit being a limited resource. In this context, irrigation is one of the most complex processes that are performed by the farmer due to the multitude of factors that are involved in water management. The technical information that permits the optimisation of irrigation includes a precise knowledge of both the water usage and crop performance (Hsiao et al., 2009; Domínguez et al., 2011). An alternative to classical empirical production functions is the use of crop simulation models for irrigation management (Griffin et al., 1993; Stöckle et al., 2003).

A model is a representation or abstraction, generally a mathematical one, of an actual system with the aim of predicting its behaviour (Mize and Cox, 1968; Mackerron, 2007; Steduto et al., 2009). The main advantage of models lies in their easiness and efficiency predicting of reality. The current processing power of computer systems has permitted the knowledge of the climate–soil–crop relationship to be expressed in dynamic models (explanatory models) that simulate growth and crop production (Whisler et al., 1986; Boote et al., 2010). This knowledge has led to the development of new models and methodologies that serve as support tools for the management and optimisation of water resources in agricultural systems, which are encompassed within the concept of *precision agriculture* (Haboudane et al., 2004).

These irrigation scheduling models are physically based on the water balance at the crop root zone (Eilers et al., 2007; Nishat et al., 2007; Panigrahi and Panda, 2003; Shang and Mao, 2006). In this sense, the depth of the root system is an important parameter of vegetative crop development, whose involvement in water

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balance is determined by the need to know the soil profile that is explored by the root system, as it is necessary to maintain the optimum moisture conditions for the proper development of the crop (Rincón, 2005). The root depth is directly related to the rate of root penetration, which is specific to each crop, and with soil texture, which determines the mechanical resistance of the soil to root growth (Taylor and Brar, 1991). Therefore, the root depth is an input variable in irrigation scheduling systems and is typically estimated using fixed tabulated values or values that have been suggested in the literature.

Knowing the precise value of the root depth at each instant of crop development enables the optimisation of existing methodologies for irrigation scheduling based on knowledge of the soil water status, as this knowledge permits the establishment of a water balance that is adjusted only to the root absorption area, demonstrating the need for new methodologies to obtain models of the evolution of the rooting depth at each stage of development (Sammis et al., 2012; Ma et al., 2013).

Another transcendent parameter that is an indicator of the crop status is the fraction of vegetation cover or percentage of ground cover (PGC), which is directly related to crop evapotranspiration through the crop coefficient Kc (Allen et al., 1998, 2007), whose relationship has been studied in various irrigation systems, having obtained successful results in tomato (Hanson and May, 2006), bean (De Medeiros et al., 2001) and onion (López-Urrea et al., 2009). PGC can be estimated with high accuracy by applying digital image-processing techniques of aerial photographs of the vegetation cover (Congling et al., 2005). Furthermore, the percentage of ground cover has also been correlated with plant height, generating successful results in ornamental shrubs (Grant et al., 2012), winter wheat (Xu et al., 2010) and constructed wetland plants (Xiao et al., 2011), among others, and producing fairly accurate mathematical models for the precise estimation of the lettuce crop coefficient Kc (Fernández-Pacheco et al., 2014).

This paper describes the design and validation of a new methodology for creating prediction models of the depth of the root zone of lettuce crops (*Lactuca sativa* L. cv 'Little Gem') from the PGC that was obtained by digital image processing. This PGC is the first to be calculated from the computer processing of digital photographs of the vegetation cover and then correlated with the root depth. The proposed methodology has been evaluated considering the accuracy of the estimation that was obtained by the mathematical equations that were provided by the method.

2. Materials and methods

2.1. Experimental plots

For the development of this research, four commercial lettuce crops of variety Little Gem, with low vigour (*Lactuca sativa* L. cv 'Little Gem'), were monitored in 2011 and 2012 and grouped into two seasons: two crops in the spring (from April to June) in a plot of an approximate area of 20.4 ha located in Pozohondo (latitude 38°39′20″ N, longitude 1°47′14″ W and altitude 869 m) in the province of Albacete, Spain; and two crops in the autumn (from October to December) in another plot of 8.3 ha located in San Javier (latitude 37°47′04″ N, longitude 0°49′34″ W and altitude 15 m) in the province of Murcia, Spain. The lettuce seedlings were obtained in a seedbed and transplanted at a density of 16.5 plants m^{-2}.

In both of the plots, the soil was classified as "Calcic Petrocalcids" (Baillie, 2001), and the average depth was approximately 40 cm, limited by the existence of a petrocalcic horizon that was more or less fragmented. The predominant texture was clay–loam with an average stoniness in both cases. The two plots were equipped with automated drip-irrigation systems. With the purpose of obtaining the same pluviometry, an emitting pipe was placed for each paired line of plants with drippers each 30 cm, with a flow rate of 2 L h^{-1} unitary discharge in single paired line and 1 L h^{-1} unitary discharge in double-paired lines.

In the plot of Pozohondo, the climate of the zone was continental Mediterranean (Papadakis, 1966). During the crop seasons, the average temperatures in this plot were 15.9 °C and 13.6 °C in 2011 and 2012, respectively. The average maximum temperatures were 22.8 °C and 19 °C, and the average minimum temperatures were 8.9 °C and 7.3 °C, respectively. The total rainfall that was recorded during the spring season was 48.9 mm in 2011 and 111.1 mm in 2012.

In the plot of San Javier, the climate of the zone was subtropical Mediterranean (Papadakis, 1966). During the crop seasons in this plot, the average temperatures were 16.1 °C and 16.7 °C in 2011 and 2012, respectively. The average maximum temperatures were 20.9 °C and 22.2 °C, respectively, and the average minimum temperature was 11.5 °C in both years. The total rainfall that was recorded during the autumn season was 75 mm in 2011 and 58 mm in 2012.

2.2. Data gathering

During the experimental crop seasons of each plantation, four sample subparcels with an area of 1.8 m^2 (1.8 m × 1.0 m) were delimitated by frames in each plot, being representative of the culture and randomly distributed, avoiding the edge of the plot to avoid the edge effect. From the first day of transplantation and at intervals of two to three days, plant growth was monitored by measuring the average root depth of lettuce plants and the PGC for each sample subparcel.

Because lettuce plants have a tap root system, several perforations were performed in the terrain for each plot to identify the primary root and measure its length, considering this value as the root depth. To determine the PGC for each sample plot, the vertical canopy was photographed using a digital compact camera (Coolpix S3300, Nikon, Japan) that was equipped with a charge-coupled device (CCD) sensor (resolution 16.0 megapixels; focal length 27.6 mm). This camera was mounted on a tripod at a fixed height of 1.40 m above ground level. To match the PGC, photographs were always taken at solar noon. It was recommended to take several photographs of each subparcel and to later select the best shot (i.e., a photograph that does not show luminosity defects or concavity and is correctly framed).

After recording photographs of the four sample subparcels and selecting the best shots, the images were digitally preprocessed such that only the interior of the frame was left. For this purpose, any commercially available photo editing software can be used. Because the method proposed here calculates the green cover as a percentage (rather than the number of pixels), the final resolution of the images will not affect the results; this method is therefore scale-invariant. In other words, because the percentage divides the number of vegetation pixels by the total number of pixels in the image, this proportion will remain the same if the image is scaled.

The preprocessed images were later processed using ENVI® (Environment for Visualising Images) software (Research System Inc., Boulder, CO, USA), which provides an easy-to-use environment to display and analyse images of any size and any type of data.

The first phase was the segmentation of the image to discriminate between the soil (beige) and the vegetation (green) (see Fig. 1). The software permitted to define these two classes and select the regions of interest (ROIs) in the image that pertained to the same class. Once these ROIs were defined, the image was segmented using a maximum likelihood supervised classification of the image based on the defined ROIs. After segmentation, the number of pixels corresponding to the vegetation (V), soil (S) and totality (T) of