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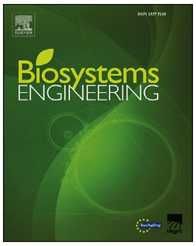

Research Paper

Linking thermal imaging and soil remote sensing to enhance irrigation management of sugar beet

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The use of reliable information and data that are rapidly and easily acquired is essential for farm water management and appropriate irrigation strategies. Over the past decade, new advances have been made in irrigation technology, such as platforms that continuously transmit data between irrigation controllers and field sensors, mobile apps, and equipment for variable rate irrigation. In this study, images captured with a thermal imaging camera mounted on an unmanned aerial vehicle (UAV) were used to evaluate the water status of sugar beet plants in a plot with large spatial variability in terms of soil properties. The results were compared with those of soil moisture measurements. No direct relationship was observed between the water status of the soil and that of the crops. However, the fresh root mass and sugar content tended to decrease when higher levels of water stress were detected in the crop using thermal imaging, with coefficients of determination of 0.28 and 0.94 for fresh root mass and sugar content, respectively. Differences were observed between different soil types, and therefore different irrigation strategies are needed in highly heterogeneous plots.

1. Introduction

Farmers, cooperatives and agricultural consultants are facing radical changes regarding the methods employed to collect, analyse, and use information to add value to their production outputs. Over the past 20 years, we have observed increasing interest in farm- and block-level precision agriculture (Blackmore, Godwin, & Fountas, 2003; Zude-Sasse, Fountas, Gemtos, & Abu-Khalaf, 2016); however, the next 20 years will give rise to canopy-, branch-, and even fruit-level production practices that will demand a new farming mentality (Krishna, 2016, chap. 5). Field sensors will provide terabytes of quantitative and qualitative information about crops, such as nutrients levels and plant and soil moisture status, and about orchards, such as the three-dimensional canopy shape, the mass and size of each fruit, as well as the number of fruits per plant. Amassing this information into a coherent database that can be rapidly and easily used to make informed decisions on what, when, where, and how to plant, irrigate, prune, thin, treat and harvest each crop will soon be one of the

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fundamental challenges for farmers to address (Cox, 1996). This scenario allows farmers to move from intuitive decision making to analytical decision making.

Irrigation accounts for 70% of the freshwater (watercourses and groundwater) used worldwide, which is three times more than 50 years ago. During recent droughts, such as those in California (from 2013 to 2015) or Spain, continuous water deficits have increased from 15 to 60 months (Lopéz-Moreno et al., 2009); these droughts highlight the need for precision irrigation techniques to improve water use efficiency so that the resource is applied exactly at the right location, time and rate. The possibilities introduced by the use of remote sensing include precise water management within a plot. Therefore, different irrigation strategies can be followed based on the spatial variability of the soil and crop conditions. Because of this variability, the actual water requirements of crops may change within the same plot. In this case, the challenge for precision irrigation is the development of methodologies to acquire the required information that will allow uniform management within demarcated areas in the plots and the validation of protocols that enable precise irrigation in various sub-units.

Soil moisture monitoring through instruments placed in a few locations in a field has been argued to have important disadvantages that are primarily related to representativeness and the fact that crop water status depends on other factors in addition to soil moisture content (Jones, 2004). The water status of plant tissues, which is commonly measured in terms of water potential (Jones, 1992), can be used as a precise indicator for irrigation scheduling (Jones, 2004). Pressure chambers (Scholander, Hammel, Bradstreet, & Hemmingsen, 1965) have been widely employed to measure leaf water potential for water deficit determination and irrigation scheduling. Although this method is a reliable measure of plant water status, it is highly time consuming and labour intensive, which results in inadequate sampling (Cohen, Alchanatis, Meron, Saranga, & Tsipris, 2005). Moreover, this method is not feasible for measuring the water potential of certain leaf types, such as those of sugar beet.

Measurement of canopy temperature has been proposed as an alternative method of determining water potential (Bellvert et al., 2016). As water stress is induced, the stomata close, transpiration rates decrease and evapotranspirative cooling is reduced, causing leaf temperatures to increase (Maes & Steppe, 2012). Idso, Jackson, Pinter, Reginato, and Hatfield (1981) and Jackson, Idso, Reginato, and Pinter (1981) suggested the use of the crop water stress index (CWSI) as an indicator of plant water stress. Sensing the canopy temperature using infrared sensors or imaging has shown good potential for calculating the CWSI and estimating the plant water status for irrigation scheduling in cotton, corn, sunflower, grapevine, and pistachios (Gonzalez-Dugo, Moran, Mateos, & Bryant, 2006; Payero, Tarkalson, & Irmak, 2006; Möller et al., 2007; Testi, Goldhamer, Iniesta, & Salinas, 2008; Taghvaeian, Comas, DeJonge, & Trout, 2014). Although a non-water-stressed baseline, i.e., a wet reference, to calculate the CWSI was reported for sugar beet (Idso, 1982), the upper baseline, i.e., a water-stressed baseline or dry reference, contains some uncertainty, with most studies assuming a rather arbitrary fixed temperature increment above air temperature to represent the temperature of non-transpiring leaves; values approximately 5 °C above air temperature are often used. Alternatively, the degrees above non-stressed (DANS) index, which is a simplified version of the CWSI that is based only on the difference between the stressed and non-stressed canopy temperatures, can be used (Taghvaeian et al., 2014; DeJonge, Taghvaeian, Trout, & Comas, 2015). However, to the best of our knowledge, thermal sensing has not been applied to optimise sugar beet irrigation. Sugar beet is considered a highly water-consuming crop (Fabeiro, Martin de Santa Olalla, Lopez, & Dominguez, 2003), and its future in drought-prone areas with limited water resources could be compromised if crop productivity is not maintained under expected reductions in available irrigation water. To attain this objective, farmers are obliged to implement precision irrigation tools, such as thermal-based crop stress sensing, which may overcome the drawbacks of soil moisture and leaf water status monitoring, especially when remotely monitoring large areas of crops.

The earth-emitted thermal energy is a function of the surface temperature (Ts) and the surface emissivity, where emissivity is a material property that ranges in value from 0 to 1 (Snyder & Zhengming, 1998). Since remote sensors can detect and quantify the heat emitted from the earth, the surface temperature can be easily determined. Thermal images captured using micro-unmanned aerial vehicles (UAVs) have considerable advantages over manual infrared thermometers, which require considerable effort and provide limited representation of the whole field, and thermal imaging satellite data in which the spatial and temporal resolution is not sufficient for most irrigation applications. For small- and medium-sized plots, UAVs have a competitive advantage over large, autonomous aerial platforms, such as manned aircraft carrying considerable amounts of remote sensing equipment.

The goal of this study was to evaluate the use of thermal images captured using a micro-UAV to predict variations in crop water use due to soil variability and irrigation management. This method can subsequently be used as a decision support tool for the efficient irrigation management of sugar beet.

2. Materials and methods

2.1. Field description and experimental conditions

Field tests were conducted in a commercial sugar beet field (*Beta vulgaris* L., ssp. *vulgaris* var. *altissima*) during the 2014/2015 growing cycle (i.e., from October to July). The field was located in Cadiz, SW Spain (Latitude, 36.6965397° N; Longitude, 6.3184375° W). The experimental field covered an area of approximately 12 ha and was irrigated with a sprinkler system consisting of a triangular arrangement of emitters spaced 12 m apart along the laterals; the laterals were also spaced 12 m apart. The sprinkler wetting radius was approximately 12 m at a working pressure head of 30 m. In southern Spain, sugar beet is sown in autumn. In the experimental field, the crop was planted in mid-November at a depth of 25 mm with 120 mm between plants and 500 mm between plant rows. The climate of the study area is Mediterranean, with rainfall

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