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Seasonal variation in canopy reflectance and its application to determine the water status and water use by citrus trees in the Western Cape, South Africa

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ABSTRACT

This study describes the diurnal and seasonal dynamics of the canopy reflectance, water use and water status of Midknight Valencia citrus trees under semi-arid conditions. Hyperspectral canopy reflectance data was collected on 30 trees at monthly intervals over a period of 16 months in a commercial orchard in South Africa. The mean canopy reflectance in the wavelength range 350–2500 nm followed a clear seasonal trend influenced by environmental conditions and tree phenology. Mean monthly reflectance peaked in summer (~22%) while the lowest value (~15%) was reached in winter with the seasonal changes in the sun's position accounting for a significant proportion of the variations. A sensitivity analysis of a Penman–Monteith transpiration model showed that water use by individual trees changed by up to 13% when the canopy reflectance was varied over the seasonal range of measured values. This suggested that the seasonal changes in tree water use influenced the seasonal trend of the canopy reflectance. Thus monitoring the canopy reflectance of citrus trees could offer information on the tree water status. To test this, sap flow data of water uptake and loss by the trees were compared with the canopy spectra. Sap flow data showed a heavy reliance by the citrus trees on the internally stored water with up to 25% of the daily total transpiration withdrawn from the trees' internal water storage pools when soil water was limited. This depletion of internally stored water, and hence the change in tree water status, was detected using spectral indices based on the first order derivatives of the canopy reflectance centered at two and, at most, four spectral bands. We conclude that even if citrus trees are evergreen, their canopy reflectance changes significantly throughout the year with a considerable impact on tree energy balance and water use. In addition, the contribution of the internally stored water to daily transpiration is a possible indicator of drought stress for citrus trees detectable from changes in canopy reflectance and it has potential applications in irrigation scheduling using canopy level spectral information.

1. Introduction

The development of precise irrigation scheduling tools in agriculture has received much attention in recent years. Such tools are quite important given the expected future increase in the frequency and severity of droughts in many parts of the world including Southern Africa (Makarau and Jury, 1997) due to the phenomenon of global climate change and the rising competition between water users. Conventional scheduling of irrigation is based on monitoring the plant's environment e.g. the microclimate (Allen et al., 1998) and the soil water conditions (Fares and Alva, 2000). However, since many aspects of the plant's physiology are dependent on the plant water status (Jones, 2004), much focus is now on scheduling irrigation using signals derived from the plants themselves (Cohen et al., 2005; Steppe et al., 2008).

One type of plant signal used as an indicator of drought stress is the plant water potential. Measurements of leaf water potential are taken either at predawn (Remorini and Massai, 2003) when the plant's transpiration stream is in equilibrium or at midday (Amèglio et al., 1999) when the stress conditions are most pronounced. The predawn leaf water potential approximates the soil water potential since the water potential gradient between the soil and the plant

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will be approximately zero. Numerous studies have shown that, for most plants, the midday leaf water potential is highly variable (Remorini and Massai, 2003; Jones, 2004) and instead the midday water potential of the stem's xylem is often preferred (Chone et al., 2001; McCutchan and Shackel, 1992; Dzikiti et al., 2010). Usually the water potentials are measured with pressure chambers or psychrometers and normally the measurements cannot be automated. Another drawback of this method is that only a few leaves can be sampled at a time presenting considerable spatial representativity problems.

The second type of plant signals that have been extensively investigated for irrigation scheduling is the use of sap flow (Cornelius et al., 1996) and the trunk diameter variation data (Fernández and Cuevas, 2010). Scheduling irrigation with these signals have mainly been evaluated on fruit trees (Goldhamer and Fereres, 2001) with each method either used singly or combined (Ortuño et al., 2005). Sap flow and trunk diameter variation signals have shown great potential for precise irrigation scheduling and these measurements can be automated. However, the high technical demands for maintenance and the intrusive nature of sap flow measurements diminish the usefulness of these methods in practice. In addition, many plants cannot be instrumented at the same time due to the high costs involved.

The third, and somewhat less developed, type of plant drought stress sensing involves the use of remote sensing tools to detect plant water deficit. Since the 1960s, the spectral properties of radiation reflected or transmitted by plants have been used to retrieve properties of the plants (Jacquemoud et al., 1995). These spectral methods are based on the principle that different plant conditions have unique spectral signatures from which information about the status of the plants can be retrieved e.g. via the use of spectral vegetation indices (Zarco-Tejada et al., 2005) or the inversion of radiative transfer models (Jacquemoud and Baret, 1990). Early spectral sensors measured the radiation reflected or transmitted by plants in a limited number of broad spectral bands. As such, the amount of information that could be extracted from these measurements was only limited to changes in these few bands.

In recent years advances in sensor technology have led to spectroradiometers that can detect the reflected radiation in tens (multispectral sensing) and even hundreds of spectral bands (hyperspectral sensing). The development of the higher spectral resolution sensors has resulted in intense research on the possibility of predicting water use in agricultural and natural ecosystems and detecting subtle drought stresses using spectral-based methods. For example, remote sensing based models such as the surface energy balance algorithm for land (SEBAL) (Bastiaanssen, 2000) and the surface energy balance system (SEBS) (Su, 2002) are increasingly being used to estimate the evapotranspiration of various agro-ecosystems including orchards. However, the seasonal variations in the canopy reflectance of perennial crops e.g. citrus trees are largely unknown and thus limiting the accuracy of prediction of the exact crop water requirements. In addition, spectral-based devices for predicting commonly used drought stress indicators for irrigation scheduling such as the plant water potential are not yet fully developed.

Recent studies (Eitel et al., 2006; Rodríguez-Pérez et al., 2007; Dzikiti et al., 2010) revealed that the various plant water potential stress indicators are not detectable from the plant's spectral signature except when the plants are under severe drought stress. This is possibly because of the non linearity between the plant water content, which directly influences the plant spectral signature, and the plant water potential (Zweifel et al., 2000) which is a measure of the energy status of the plant. This study thus seeks, firstly to describe and interpret the seasonal dynamics of the canopy reflectance spectrum of Midknight Valencia orange trees in the Western Cape Province of South Africa and, secondly to quantify how the canopy spectral changes impact on the tree water use. Thirdly we develop a drought stress indicator based on the dynamics of water uptake and loss by the citrus trees using sap flow measurements. We demonstrate that this indicator is readily detectable from canopy reflectance data over a wide range of drought stresses. While the hyperspectral spectroradiometers are expensive, and often not automated (Garrity et al., 2010) the information presented in this study is potentially useful for developing cheap and accurate (Ryu et al., 2010) canopy spectral-based tools for use in precise scheduling of irrigation in orchards.

Table 1
Soil physical properties in the root zone of the Midknight Valencia orange trees at Sand Rivier Estates, Wellington. TAW is the total available water.

Depth (mm)	Soil property				
	TAW (mm/m)	Bulk density (kg m^{-3})	Texture		
			%Clay	%Silt	%Sand
100	120	1795	4.30	27.21	9.5
200	115	2050	11.13	15.33	10.8
300	126	1955	11.78	18.14	9.3
400	128	1850	26.18	9.16	8.9
500	148	1860	44.13	8.98	5.4
600	157	1805	34.78	21.41	4.8

2. Materials and methods

2.1. Experimental site and plant material

Experiments to monitor the seasonal dynamics of the canopy reflectance and how the canopy reflectance relates to the tree water status and water use were conducted in a 1.0 ha commercial orchard at Sand Rivier Estate, Wellington in the Western Cape Province of South Africa (33°56′S, 18°52′E, 113 m mean height above sea level). Plant material was the late maturing Midknight Valencia orange trees [*Citrus sinensis* (L.) Osbeck] budded on Carrizo citrange rootstock [*Citrus sinensis* × *Poncirus trifoliata*] planted in 2001. The trees were planted on ridges approximately 40 cm high in rows oriented in a north–south direction. Between row tree spacing was approximately 4.0 m wide while the spacing of the trees within the rows was approximately 2.0 m. Average tree height was about 3.8 m with a mean base area of approximately 4.7 m^2. The trees were hand pruned after harvest in September each year mainly by removing old branches and opening the middle of the canopies to maximize radiation interception. The soils at the trial site were shallow belonging to the Kroonstad soil form (Albic Luvisols) (Somers et al., 2010) and with a high clay content. Detailed physical properties of the soils are shown in Table 1. The trees were irrigated with a microjet system beneath the canopies delivering an equivalent of approximately 3.2 mm of water per hour.

2.2. Spectral measurements

Within the orchard, 30 healthy trees of similar canopy dimensions were selected and monitored from September 2008 to May 2010. During this period a time series of irrigation events, phenology and the corresponding canopy spectra was established. Five canopy reflectance spectra were measured at the top of each of the 30 trees around midday from 1200 to 1400 (Local time = GMT + 2 h) at least once a month only on cloudless days. Spectral measurements were however, not taken in December 2008, November and December 2009, respectively. An ASD FieldSpec Pro spectroradiometer (Analytical Spectral Devices Inc, Boulder, CO, USA) that detects reflectance in the 350–2500 nm spectral range was used to measure the canopy reflectance. The spectroradiometer is characterized by a spectral resolution of 3 nm (full-width-at-half-maximum, FWHM) and a 1.4 nm sampling interval across the