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Water stress detection in potato plants using leaf temperature, emissivity, and reflectance

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ABSTRACT

Water stress is one of the most critical abiotic stressors limiting crop development. The main imaging and non-imaging remote sensing based techniques for the detection of plant stress (water stress and other types of stress) are thermography, visible (VIS), near- and shortwave infrared (NIR/SWIR) reflectance, and fluorescence. Just very recently, in addition to broadband thermography, narrowband (hyperspectral) thermal imaging has become available, which even facilitates the retrieval of spectral emissivity as an additional measure of plant stress. It is, however, still unclear at what stage plant stress is detectable with the various techniques.

During summer 2014 a water treatment experiment was run on 60 potato plants (*Solanum tuberosum* L. *Cilena*) with one half of the plants watered and the other half stressed. Crop response was measured using broadband and hyperspectral thermal cameras and a VNIR/SWIR spectrometer. Stomatal conductance was measured using a leaf porometer. Various measures and indices were computed and analysed for their sensitivity towards water stress (Crop Water Stress Index (CWSI), Moisture Stress Index (MSI), Photochemical Reflectance Index (PRI), and spectral emissivity, amongst others).

The results show that water stress as measured through stomatal conductance started on day 2 after watering was stopped. The fastest reacting, i.e., starting on day 7, indices were temperature based measures (e.g., CWSI) and NIR/SWIR reflectance based indices related to plant water content (e.g., MSI). Spectral emissivity reacted equally fast. Contrarily, visual indices (e.g., PRI) either did not respond at all or responded in an inconsistent manner.

This experiment shows that pre-visual water stress detection is feasible using indices depicting leaf temperature, leaf water content and spectral emissivity.

1. Introduction

Today, agriculture consumes about 80–90% of fresh water worldwide (Gonzalez-Dugo et al., 2010; Morison et al., 2008). Water-deficit stress, usually shortened to water- or drought-stress, is a phenotypic characteristic that exhibits dehydration in the plant due to the lack of available water required to keep cell concentrations at an acceptable and healthy level (Hopkins and Hüner, 2009). Water stress is one of the most critical abiotic stressors limiting plant growth, crop yield and quality concerning food production (Hsiao et al., 1976).

As a plant physiological reference, stomatal conductance measured by a porometer is the most sensitive reference measurement of plant water stress induced by water deficit (Jones, 2004a). A porometer measures the vapour concentrations at two different locations within a defined path using humidity sensors from which leaf transpiration is calculated. Knowing the leaf transpiration, stomatal conductance is directly calculated (Pearcy et al., 1989). However, the direct measure of leaf transpiration using porometry involves contact with the leaves and intervenes in the interactions between the leaf and the surrounding environment. Further, the method is labour-intensive, time-consuming, and only provides point measurements (Costa et al., 2013).

Imaging techniques open the possibility of fast and non-destructive spatio-temporal monitoring of many physiological and structural crop characteristics. The main remote sensing techniques for the detection of plant stress (water stress and other

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types of stress) are thermal imaging (thermography; 8–14 μm), visible, near- and shortwave infrared reflectance (VNIR/SWIR; 0.4–2.5 μm), and fluorescence (e.g., 0.76 μm). Thermal imaging takes advantage of the leaf energy balance equation, i.e. leaf temperature varies with transpiration from leaves (Jones, 1999; Tanner, 1963). The underlying concept is that a decrease in plant water status leads to a reduction in leaf transpiration as a result of active regulation of stomatal aperture, consequently increasing the leaf temperature due to a reduced evaporative cooling (Inoue et al., 1990). Conversely, a well-watered plant will have a lower temperature in comparison to the ambient air temperature. The stomatal regulation of a plant also highly depends on the actual meteorological factors, such as solar radiation, wind speed, ambient air temperature and vapour pressure deficit (VPD). VPD is the difference between the actual amount of water in the air and the maximum amount of water vapour in the air for a given temperature and therefore gives the capability of leaf transpiration. In general, the higher the VPD the higher the leaf transpiration rate for a healthy plant. In summary, leaf and canopy temperatures are a function of stomatal conductance and meteorological variables (Jones, 2004b). Stomatal closing is one of the first responses to water deficit and thus gives thermal imaging the possibility for detecting water stress pre-visual, i.e. before the change of leaf colour (Costa et al., 2013; Jackson et al., 1981; Jones, 2004b; Maes and Steppe, 2012).

The main problem of this temperature-based approach is constituted by the fact that the direct use of leaf or canopy temperature values alone cannot be an absolute estimator of the physiological status of crop plants (Inoue et al., 1990) since leaf temperatures measured under natural field conditions are very sensitive to highly fluctuating environmental factors. Thus, a variety of approaches were developed in the past to calibrate or normalize leaf temperature to estimate plant water stress more quantitatively. First corrections were done by the difference between leaf and air temperature (Idso et al., 1977). The popular Crop Water Stress Index (CWSI) (Jackson et al., 1981) not only corrects for air temperature but rather for all meteorological variables. In particular, the use of dry and wet artificial reference surfaces, which neglect additional meteorological data to describe the current environmental conditions, improved the usability of CWSI for thermal remote sensing (Jones, 1999).

Up to now, most studies regarding temperature based plant water stress detection used handheld broadband infrared cameras (Grant et al., 2006; Jones et al., 2009). The temperature retrieval using these 1 channel camera systems underlies the assumption of a constant emissivity (e.g. $\varepsilon = 0.97$ for vegetation), which in nature does not exist (Ullah et al., 2012). Thus, neglecting the spectral emissivity of the leaves themselves limits the accuracy of temperature estimation. For example, an error in the assumed emissivity of 1% results in absolute temperature errors of about 1 K (Jones, 2004b). Thermal hyperspectral imaging systems such as Telops HyperCam, Itres TASI-600, Specim AisaOWL have recently become available. The great advantage of these devices is the ability to measure the emitted radiance in many narrow bands, which compared to broadband thermal cameras allows a very stable temperature emissivity separation (TES) and very accurate temperature retrievals (Schlerf et al., 2012).

Besides temperature, these hyperspectral thermal infrared (TIR) imagers also have the ability to derive spectral emissivity by using a solid TES. Emissivity is defined as the ratio of radiative energy from the surface of an object of interest to the radiation from a blackbody following Planck's law depending on the wavelength at the same surface temperature. Until recently, emissivity spectra have not been exploited in vegetation studies for the following reasons: (1) low and complex spectral emissivity variations originate from plant physiological and biochemical processes as well as from plant structural effects; (2) low signal-to-noise ratio as well as low spatial and spectral resolution of airborne or satellite remote sensing TIR sensors fail to detect minor variations in plants' TIR spectral fingerprint; (3) to retrieve exact emissivity spectra accurate atmospheric correction and temperature emissivity separation (TES) methods are needed. Thus, only few authors studied plant properties in TIR mainly focusing on species discrimination (e.g., Ribeiro da Luz and Crowley, 2010, 2007; Salisbury, 1986; Ullah et al., 2012). Concerning plant stresses in the TIR, just very recently Buddenbaum et al. (2015) and Buitrago et al. (2016) demonstrated the ability of stress detection using the spectral emissivity. Buitrago et al. (2016) revealed the detection of water and cold stress at two different points in time based on the spectral emissivity of both European beech (*Fagus sylvatica*) and rhododendron (*Rhododendron cf. catawbiense*) leaves. They used a directional hemispherical reflectance (DHR) Bruker Vertex 70 FTIR laboratory spectrometer, equipped with an integrating sphere (Hecker et al., 2011). In comparison to passive emissive measurement devices, this non-imaging method is destructive, very time-consuming and limited to single leaves. On the contrary, Buddenbaum et al. (2015) were able to clearly differentiate water stressed and non-stressed European beeches (*Fagus sylvatica*) based on spectral emissivity using a passive emissive imaging spectrometer, the Telops HyperCam. No conclusions were drawn at which stage water stress can be detected using spectral emissivity in comparison to other stress sensitive methods (e.g., plant temperature, stomatal conductance), since this study was conducted during one diurnal course. Nevertheless, spectral emissivity facilitates new possibilities to detect water stress in contrast to the hyperspectral VNIR/SWIR spectral domain. Spectral radiation in the VNIR/SWIR is dominated by overtones and combination modes of fundamental vibrations, which originate from the interactions of solar radiation and leaf contents (e.g., leaf pigments). In comparison, spectral emissivity as the capability of emitting thermal radiation has large potential for the quantification of vegetation stresses, since it may be directly linked to leaf physiology and biochemistry (Ribeiro da Luz and Crowley, 2007).

Water stress not only changes leaf temperature and spectral emissivity but also leaf and canopy water content, pigment content, and structure. These leaf and canopy parameters are driving leaf and canopy reflectance in the solar reflective spectral range of the electromagnetic spectrum (VNIR/SWIR). Especially hyperspectral data opened the opportunity for the development of narrowband vegetation indices (VIs), which simplify the complex vegetation reflectance signatures and are indirectly related to plant physiological and structural parameters (Govender et al., 2009). Numerous studies make use of (VIs) for water stress detection such as the Water Index (WI, Peñuelas et al. (1997)), the Normalized Difference Vegetation Index (NDVI, Rouse et al. (1974)), and the Photochemical Reflectance Index (PRI, Gamon et al. (1992)). Suárez et al. (2009) observed robust relationships of PRI against canopy temperatures for various crops (e.g. $R^2 = 0.72$ for maize). Furthermore, Panigada et al. (2014) observed PRI as a more sensitive indicator for early plant water stress, when only plant physiological parameters are affected, than traditional VIs (e.g. NDVI). Additionally, VNIR fluorescence imaging is a good indirect estimator of water stress (Lang et al., 1996).

From the above discussion we derived the following aims for this study: (1) to evaluate in a controlled experiment the ability of temperature based indices and VNIR/SWIR reflectance based indices for detecting water stress in comparison to plant physiological measurements, (2) to compare hyperspectral and broadband imaging systems for deriving temperatures as a basis for water stress detection and (3) to examine the abilities of detecting water stress using the spectral emissivity of plant leaves.