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Research Paper

Leaf thickness to predict plant water status

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Plant-based techniques to measure crop water status offer advantages over soil-based methods. The objective of this study was to quantify the relationship between leaf thickness measurements, as a promising plant-based technique, with leaf relative water content (RWC) and assess the model across different species and leaf positions. The relationship between RWC and relative thickness (RT) was determined on corn (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench), soybean (*Glycine max* (L.) Merr.), and fava bean (*Vicia faba* L.). RWC was calculated as measured leaf water content/leaf water content at full turgor, and RT as measured leaf thickness/leaf thickness at full turgor. Two leaves from the top, middle, and bottom of five plants of each species were collected at 60 days of age. Leaf samples brought to full turgor were left to dehydrate in a lab. Leaf thickness was measured using a magnetic field sensor and water content using weight loss. The RWC-RT relationship showed a distinct breakpoint, which we hypothesise coincides with the turgor loss point. Linear piecewise modelling was used to regress RWC versus RT, resulted in models explaining 86–97% of the variations. The precision was improved by including leaf position on the plant in the model. The piecewise model parameters were related to salt tolerance of the species, which is also an indicator of drought resistance. Generally, the species with greater drought and salinity tolerance had a larger RT at the breakpoint.

1. Introduction

Improvements in water use efficiency can be achieved by precision irrigation timing to avoid early or late irrigation, which may lead to water or yield loss. Ideally continuous measurements of plant water status would be the optimum means to determine the best irrigation timing. Common methods of plant water status estimation for practical applications tend to range from the simple visual wilting approach to measurement intensive evapotranspiration models, or soil moisture measurements (Jones, 2004). Irrigation scheduling based on plant measurements merits consideration as an alternative to soil measurements and/or water balance computations. There are plant-based alternatives for estimating plant water needs, such as pressure chamber, psychrometer, thermal sensing, and sap-flow sensors (Jones, 2004). We propose a simple measurement method based on leaf thickness as suggested by Seelig, Stoner, and Linden (2011).

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Nomenclature

a	The intercept of the piecewise linear model of leaf relative water content versus leaf relative thickness for where relative thickness is equal or smaller than the breakpoint
b_1	The slope of the piecewise linear model of leaf relative water content versus leaf relative thickness for where relative thickness is greater than the breakpoint
b_2	The slope of the piecewise linear model of leaf relative water content versus leaf relative thickness for where relative thickness is equal or smaller than the breakpoint
c	The leaf relative thickness at the breakpoint of the piecewise linear model of leaf relative water content versus leaf relative thickness
EC	Soil electrical conductivity
TLP	Turgor loss point
RT	Leaf relative thickness
RWC	Leaf relative water content

Instead of improving soil moisture measurement methods or evapotranspiration models, we suggest it may be better if the critical water stress points at which irrigation should start could be directly measured on the crops grown. Plant-based approaches may offer a more reliable plant water status estimation by reducing the need for complex calculations and data sets associated with soil-plant-atmosphere water relationship (Jones, 2004; Kramer & Boyer, 1995). In this study, we set out to determine if leaf thickness could be a reliable indicator of water status of a plant.

Bachmann (1922) was the first to report that leaf thickness decreases upon dehydration and increases upon rehydration. Subsequently, Meidner (1952) determined that there is a strong correlation between leaf thickness and relative water content (RWC). Búrquez (1987) reported a strong correlation between RWC and leaf thickness in *Brassica napus* L., *Mirabilis jalapa* L., *Phaseolus vulgaris* L., and *Impatiens parviflora* DC. These researchers measured leaf thickness using different types of callipers and micrometers. Meidner (1952) used a gear-wheel micrometer and Búrquez (1987) used a spring-loaded gear-wheel. These devices were bulky and hard to automate to enable continuous plant water stress sensing. Transducer-based techniques were explored to enable automated leaf thickness measurement (Dongsheng, Manxi, Huijuan, & Ziqian, 2007; Li & Song, 2009; Malone, 1993; Marenco, Antezana-Vera, & Nascimento, 2009; McBurney, 1992; Rozema, Arp, Diggelen, Kok, & Letschert, 1987; Syvertsen & Levy, 1982; Vile et al., 2005; White & Montes-R, 2005). Most of these sensors are relatively bulky linear variable displacement transducers (LVDT).

Sharon and Bravdo (1996) and Seelig et al. (2011) developed tiny leaf thickness sensors to optimise irrigation scheduling. Sharon and Bravdo (1996) compared irrigation scheduling using continuous leaf thickness monitoring with four conventional drip irrigation regimes based on timetables and water depletion. In this 4-year study, the sensor-based drip irrigation treatment resulted in the highest yield and greatest water use efficiency of grapefruit cv. Oroblanco (*Citrus x paradisi* Macfad). Similarly, Seelig et al. (2011) were able to improve water use efficiency of irrigated cowpea 25–45% by an automated irrigation system based on a leaf thickness sensor compared with timed irrigation scheduling. These studies show that irrigation scheduling based on the automated leaf thickness sensing has the potential to improve water use efficiency and conserve irrigation water.

The relationship between leaf thickness and RWC depends on plant and leaf characteristics and is affected by environmental variables. Leaf thickness is determined by plant anatomy, including the number, size, and arrangement of leaf cells that differ among species (Carpenter & Smith, 1979; Nicotra et al., 2011; Taiz & Zeiger, 2006; Vogelmann, Bornman, & Yates, 1996). Giuliani et al. (2013) have reported a significant difference in leaf anatomy among species of the genus *Oryza*. There is a significant variation in the structure of leaf mesophyll even between leaves located at different positions on the same plant (Eames & MacDaniels, 1925). The number and arrangement of the palisade parenchyma, as well as the overall morphology of a leaf, vary between species. They also depend on environmental variables such as light exposure, temperature, age, and irrigation regimes (Abrams & Kubiske, 1990; Búrquez, 1987; Carpenter & Smith, 1979; Gausman, 1974; Gausman, Allen, Cardenas, & Richardson, 1970; Hanba, Miyazawa, & Terashima, 1999; Nicotra et al., 2011; Taiz & Zeiger, 2006).

Leaf thickness changes not only as a result of RWC fluctuations but also due to environmental and physiological factors (Blum, 2011; Scoffoni, Vuong, Diep, Cochard, & Sack, 2014; Taiz & Zeiger, 2006). Some of these are rapid. For example, leaf thickness shows a diurnal-nocturnal dynamic. Under well-hydrated conditions, leaf thickness is almost constant during night hours but decreases during the day (Búrquez, 1987; Meidner, 1952; Rozema et al., 1987; Seelig et al., 2011; Syvertsen & Levy, 1982). Leaf thickness was negatively correlated with air temperature and light and positively with ambient relative humidity (Búrquez, 1987; Rozema et al., 1987; Syvertsen & Levy, 1982). These environmental factors affect leaf thickness variations through their role in transpiration (Búrquez, 1987; Giuliani et al., 2013; Rozema et al., 1987). Vapour loss and water supply as the discharge and charge sources of the leaf water content result in varying leaf thickness (Búrquez, 1987). Soil salinity increases leaf shrinkage during the day and the time of thickness recovery at night (Rozema et al., 1987). This may be explained by the water shortage-induced condition which causes plants to reduce water uptake from a saline medium (Blum, 2011; Parida & Das, 2005; Rozema et al., 1987). On the other hand, wounding, for example by insects, causes rapid leaf swelling (Alarcon & Malone, 1994).

Leaf thickness has been shown to affect photosynthesis (Smith, Bell, & Shepherd, 1998; Taiz & Zeiger, 2006). Varieties with thicker leaves show enhanced photosynthesis, a character trait used by plant breeders to improve yields (Peng & Ismail, 2004; Takai et al., 2013). Physiological changes that affect leaf thickness can have a long-lasting effect. Smith et al. (1998) found that a decrease in precipitation and an increase in leaf inclination were associated with thicker leaves. In addition, there is a positive correlation between leaf thickness