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Water deficit detection in sugarcane using canopy temperature from satellite images

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Abstract

Water deficit (WD) is the main yield gap for sugarcane in Midwest Brazil. Thus, WD detection is essential to quantify yield losses, but field detection requires measurement of soil water content over large areas. In this study, we tested leaf temperature (T_L) and land surface temperature (T_s) to detect WD in a commercial sugarcane area. The area is located in the central region of Goiás State, Brazil. According to Köppen classification, the climate of the region is Aw (humid tropical, with rainy summer and dry winter). The soil is a Ferralsol (clayey texture). T_L was measured by a portable infrared thermometer, and T_s was obtained using a spectral image from Landsat 8. Both T_L and T_s measurements occurred between 28 Jan and 24 Aug 2014 (298-506 DAP). The water balance identified periods of water deficit (WD) and surplus (WS). The difference between T_L-T_a was greater than zero (7.11 °C) in WD periods and lower than zero (-2.18 °C) in WS periods. The difference between T_s-T_a , in turn, ranged from -0.66 °C to 4.06 °C, but not following the tendency of WD or WS, which is associated with a relative error between T_L and T_s near 20% for some date. The T_s-T_a difference detected soil WD or WS when the relative error was low (362 and 410 DAP) and under higher WD (506 DAP) and WS (394 DAP). This way, T_L was able to detect WD and WS along sugarcane growth, while T_s showed limited application, requiring improvement based on surface properties to reduce the error in relation to T_L . Furthermore, bands 10 and 11 are recommended for surface temperature estimation. Calibration uncertainty increases when the band 11 is used alone, being this band more affected by the absorption of radiation by the atmospheric water vapor, which implies larger errors related to the atmospheric profile in the acquisition of surface temperature.

Keywords: Saccharum spp., Landsat-8, spectral image, remote sensing, drought.

Abbreviations: DAP _ days after planting; T_a _ Air temperature; T_s _ Land surface temperature; T_L _ Leaf temperature; TB10 _ band 10; TB11 _ band 11; WD _ Water deficit; WS _ Water surplus.

Introduction

Sugarcane was grown in 8.7 million ha in the 2017/18 crop season in Brazil. Of these, the Midwest region accounted for 1.8 million ha, and Goiás State accounted for near 1 million ha (CONAB, 2018). The Midwest region has a water deficit occurring mainly in the winter, with low rainfall during about 7 months per year (Alvares et al., 2013). In this region, there is a huge yield gap caused by water deficit in sugarcane crop due to the longer cycle. The yield gap by water deficit represents 68.6% of the total yield gap in the Midwest, while in Goiás State, this value reached 76.4% (Monteiro and Sentelhas, 2017).

The crop has a physiological mechanism to withstand a period of water deficit, e.g., the stomatal closure (Gilbert et al., 2011). Moreover, there are different levels of adaptation and yield reductions (Sousa et al., 2017). As a consequence

of that, the crop reduces transpiration and increases leaf temperature (Gerhards et al., 2016). Leaf temperature can be between 1 and 4 °C below air temperature if the crop is under no water limitation (López et al., 2009). Otherwise, under water deficit stress, the leaf temperature has a gradual increase, reaching between 4 and 6 °C above air temperature (López et al., 2009).

The difference between leaf and air temperature has been used as an index to detect water deficit and its level in many crops, e.g., potato (Gerhards et al., 2016), wheat (Mon et al., 2016), bermudagrass (Emekli et al., 2007), soybean (Sayago et al., 2017) and sugarcane (Brunini and Turco, 2016). Leaf temperature can be measured using infrared thermometers, obtaining its value from an exact point or small areas through an image. That approach shows limitation due to spatial heterogeneity in the soil water condition and labor time (Sayago et al., 2017). Such condition is highlighted for sugarcane, grown in expansive areas, and gets intensified at the beginning of the cycle, given the lower soil cover by the crop (López et al., 2009).

An alternative for spatial heterogeneity is measuring the difference between leaf and air temperature using satellite or aircraft image within the thermal infrared range, considering the spatial temperature variability in the surface (Clarke, 1997; Torrion et al., 2014). Torrion et al. (2014) used suborbital image to determine the difference between leaf and air temperature for cotton under three water supply levels. Leaf and air temperature were the same in plots without water deficit. When half of the water demand was applied, the leaf temperature was between 3 and 11 °C above air temperature, the maximum exceeded value when irrigation was not used.

From the discussion above, this study aimed: (1) to identify water deficit based on the difference between leaf and air temperature in comparison with soil water content; and (2) to evaluate the use of land surface temperature obtained from surface image within the thermal infrared from satellite Landsat_8 to determine leaf temperature in commercial areas cultivated with sugarcane.

Results and Discussion

Biometric measures

Leaf area is responsible for gas exchange, in which water vapor exits (H₂O_v) and carbon dioxide enters (CO₂). The area still receives the radiant energy used in photosynthesis. Stomatal closure inhibits gas exchange, promoting an increase in leaf temperature. LAI increase was marked up to 362 DAP in cane_plant, reaching the peak of 5.46 (Figure 1). Robertson et al. (1999) found maximum LAI values of 4.92 for irrigated crop and 4.11 for crop under water deficit. Keating et al. (1999), in turn, observed maximum LAI values around 7.0. The LAI of sugarcane (SP_79_1011) showed its maximum value in irrigated (6.48) compared to non_irrigated (6.33) system (Farias, 2001). Varela (2002) points out 7.08 as the maximum LAI of that crop, which can be reached at 288 days. Farias et al. (2007) detected maximum LAI between 3.5 and 4.0 for different irrigation levels and zinc rates.

Air, leaf and surface temperature

Plant transpiration is a component of the energy balance, which determines leaf temperature according to leaf anatomical factors (dimensions, pigmentation and mass), environmental factors (solar radiation, air speed, air temperature and air relative humidity) and biological factors (number and distribution of stomata) (Leuzinger et al., 2010). When water was limiting, transpiration decreased and leaf temperature increased (Wang and Gartung, 2010). In this study, the air temperature (T_a) ranged from 28.3 °C, at the beginning of the cycle, to 31.3 °C, from 442 days after planting (DAP) to the end of the cycle (Figure 2a). Leaf temperature (T_L), measured in the field, ranged from 27.1 °C at the beginning of the evaluation (298 DAP), to values above 35 °C from 442 to 474 DAP (Figure 2a). T_L was lower than T_a until 394 DAP, but after this date, the presence of a

water deficit leads to a T_L higher than T_a (Figure 2a). Land surface temperature (T_S) ranged from 26.5 °C, at 410 DAP, to a maximum value of 34.9 °C, occurring at 506 DAP. Brightness temperature (TB) for band 10 (TB10) and 11 (TB11) were lower than T_a , T_L , and T_S for all evaluated date (Figure 2a). In the absence and presence of water deficit, sugarcane plants reach average T_L values around 27 °C and 32 °C, respecively (Trentin et al., 2011).

The highest relative error occurred for TB10 and TB11 when T_L was used as a reference (Figure 2b). The relative error occurred at the end of the cycle, with _6.88% for band 10, and _10.7% for band 11. At 426 DAP, it was observed the maximum error of _42.2%, occurring for band 11 (Figure 2b). The use of T_S obtained from band 10 and 11, soil cover factor and vapor pressure at atmosphere reduced the relative error in comparison with T_L , wherein in most of the periods analyzed, the error was lower than 10% (Figure 2b). In three samples, T_S error was around 20% (Figure 2b). The moment at which T_L was higher than T_a indicates water deficit. The error associated with T_S compared to T_L can be related to the proportion of soil cover along the area, the surface energy balance, thermal properties of the surface, as crop albedo, weather conditions and surface roughness (García, 2012).

Water deficit detection

Leaf temperature (T_1) was lower than air temperature (T_a) from 298 to 394 DAP, period in which the water balance indicates a water surplus, supplying the total crop demand without water deficit (Figure 3a). With soil water deficit from 410 DAP, T_L becomes higher than T_a , with constant T_L increase from the difference of 1.86 °C. The maximum difference, of 7.11 °C, was reached at 474 DAP (Figure 3a). After this date, a 14_mm rainfall event occurred for the period 474_490 DAP (Figure 3b), which leads to a lower T_L and $T_{\rm a}$ difference. The two last samples had a continuous water deficit, but with decreased T_L and T_a difference, which can be caused by the ending of the cycle. In this moment, the crop reduced leaf area index to ~ 2 (Figure 3b). That is one of the first signs of continuous water deficit (Inman_Bamber, 2005), leading to increased crop albedo by less green leaves and lower crop maturity (Inman_Bamber et al., 2008; Pincelli and Silva, 2012). Sayago et al. (2017) observed an outlier for the relationship between temperature vegetation dryness index (TVDI) and relative evapotranspiration occurring after soybean reached maturity with leaf senescence, altering the surface energy balance.

The use of land surface temperature (T_s) to obtain the difference from air temperature showed to be less sensitive for water supply throughout the evaluation period. In the first evaluation, the difference ($T_s_T_a$) was of _0.66 °C, which continued to reduce until _4.06 °C, with an increase of water surplus from 7 mm to 61 mm (Figure 4). At 410 DAP, the temperature difference becomes positive in 1.2 °C, associated with water deficit (Figure 4). Continuous water deficit around 20 mm until 490 days after planting kept the $T_s_T_a$ difference negative. In the last evaluated date, in turn, with an increase of water deficit to 34 mm, the $T_s_T_a$ difference indicates a positive difference of 1.74 °C. Sayago et al. (2017) observed that the use of temperature vegetation dryness index (TVDI), obtained from T_s range, does not represent properly the soil water content



Fig 1. Leaf area index (LAI, m² m⁻²) of sugarcane as a function of days after planting and dates. Error bars: standard deviation.



Fig 2. Air temperature (T_a) (a), leaf temperature (T_L), land surface temperature (T_s) and brightness temperature for bands 10 (TB10) and 11 (TB11); relative error between T_s (estimate from TB10 and TB11) and T_L (b) measured from 298 to 506 days after planting for sugarcane. Error bars: standard deviation.



Fig 3. Leaf and air temperature difference measured at 13h ($T_{L}T_{a}$), water surplus and deficit (a), and rainfall and leaf area index (b) measured along the sugarcane growth from 298 to 506 days after planting. ^{*}Error bars: standard deviation.



Fig 4. Surface temperature (T_s) and air temperature (T_a) difference measured at 13h $(T_s_T_a)$; water surplus (WS) and deficit (WD) measured along the sugarcane growth from 298 to 506 days after planting.



Fig 5. Location of field experiment for sugarcane in Santo Antônio de Goiás, GO. Köppen's climate classification adapted from Alvares et al. (2013).

when under high vegetation cover. Moreover, these authors observed an improvement between TVDI and relative crop evapotranspiration when the vegetation covered over 60% of the soil. The use of surface temperature from satellite Landsat 8 for agricultural areas can show uncertainties associated with estimation and calibration approach based on band 10 and 11. Yu et al. (2011) obtained a root mean square error of 1.0 °C for four agricultural areas, where the error was associated with vapor pressure in the atmosphere. Besides that, LST was obtained from a pixel of 900 m², where surrounding conditions can affect the surface temperature and delay the response for the crop water deficit, resulting in a higher error (Moreira and Galvíncio, 2007; Sayago et al., 2017). This is evidenced when analyzing the error from $T_{s}T_{L}$ and $T_{s}T_{a}$ difference. When the relative error for T_{s} was lower (Figure 2b), as in 362 and 410 DAP, the crop clearly tended to be under limited and good water supply, respectively (Figure 4). Otherwise, when the water surplus and deficit were higher, respectively, at 394 and 506 DAP, even with a relative error around 8%, the $T_{S_}T_{a}$ difference correctly indicates the plant water status.

Materials and Methods

Experimental site

The field experiment was conducted in Santo Antônio de Goiás, Goiás State (16.4894° S; 49.3129° W; 769 m above sea level), in a commercial area with 194 ha (Figure 5). According to Köppen's classification, the climate of the region is Aw (Alvares et al., 2013). Mean annual air temperature was 23.0 °C, with the hottest (September) and coldest month (June) having, respectively, a mean air temperature of 31.7 °C and 14.4 °C. During the year, the rainy and dry periods are, respectively, from October to April and from May to September (INMET, 2018). Annual mean rainfall, relative humidity, and reference evapotranspiration were, respectively, 1498 mm year⁻¹, 70% and 1559 mm year⁻¹ (Silva et al., 2012). In the area, the soil was classified as Ferralsol, with clayey texture (Silva et al., 2014). The

cultivar grown was the CTC_4, which had excellent initial growth, with medium to late maturity and tolerance to drought (CTC, 2013).

Plant measurements

Ten points were sampled in the experimental area. Each point corresponded to two rows of eight linear meters. The plant data were obtained from January to August 2014, between 281 and 506 DAP, which corresponded to the end of the stem growth phase, i.e., the maturity phase. The procedure occurred in ten dates coincident with the passage of the satellite. The biometric indices evaluated were: i) Number of tillers per m² (Nassif, 2012); ii) Number of green leaves: by counting the number of fully expanded green leaves; iii) Leaf area per tiller: obtaining the leaf area according to Hermann and Câmara (1999):

$$LA = L \cdot W \cdot 0.75 \cdot (N+2)$$
[1]

in which LA is the leaf area per tiller (cm²), L is leaf length +3 (cm), W is leaf width +3 (cm), 0.75 the correction factor for sugarcane leaf area, and N the number of open leaves with at least 20% green area; iv) Leaf area index (LAI, $m^2 m^{-2}$), estimated by equation [2]:

$$LAI = \frac{NT \cdot LA}{S}$$
[2]

Where NT is the number of tillers per m^2 (NT, m^{-2}), LA the leaf area per tiller (m^2) and S the land surface (m^2).

Leaf temperature measurement

Plant leaf temperature was measured in the field, using a portable infrared thermometer (Minipa MT_330), with a resolution of 0.1 °C within the $_{60}$ °C – 550 °C range, and precision of ± 2 °C. Measurements were done in the field at the same day satellite Landsat 8 took the image from the area, starting on 28 Jan 2014, 298 days after planting, until 24 Aug 2014, 506 days after planting, with a temporal resolution of 16 days. The cloud between 309 and 336 days after planting (Feb_Apr) limited the comparison of satellite images with field measurements.

The spectral image was obtained from the satellite, in infrared bands 10 (10.60 – 11.19 μ m) and 11 (11.5 – 12.51 μ m), using four windows with a resolution of 100 x 100 m over the sugarcane field. Each window was set to three pixels (30 x 30) and used to determine land surface temperature (T_s). Bands 4 (0.630 – 0.680 μ m) and 5 (0.845 – 0.885 μ m) were obtained to determine the normalized difference vegetation index (NDVI) for the sugarcane target area, using a 30 x 30 m window. In the field, five plots with 12 plants were determined in each pixel area to measure leaf temperature and sugarcane growth. Leaf temperature was measured at a distance of 3 cm in four points along the leaf surface. In the initial evaluation, sugarcane was at the maximum growth rate, while the final evaluation corresponded to the maturity phase.

Land surface temperature

Land surface temperature $(T_S, °C)$ was estimated using the Split_Window algorithm (Rozenstein et al., 2014), which considers the brightness temperature of bands 10 and 11 from TIRS sensor, analyzing the mean and the difference of target surface emissivity, based on Eq. [3].

$$T_{S} = TB_{10} + C_{1} \cdot (TB_{10} - TB_{11}) + C_{2} \cdot (TB_{10} - TB_{11})^{2} + C_{0} + (C_{3} + C_{4} \cdot W) \cdot (1 - \varepsilon) + (C_{5} + C_{6}W) \cdot \Delta \varepsilon$$
[3]

where: TB_{10} and TB_{11} are the brightness temperatures of bands 10 and 11 (°C); C_0 , C_1 , C_2 , C_3 , C_4 , C_5 , and C_6 are parameters of the Split_Window algorithm, being, respectively, _0.268; 1.378; 0.183; 54.3; _2.238; _129.2; and 16.4 (Rajeshwari and Mani, 2014); ε is the mean emissivity of bands 10 and 11; W is the vapor pressure in the atmosphere at the moment the image was taken from the satellite; and $\Delta \varepsilon$ is the emissivity difference between bands 10 and 11.

The brightness temperature (TB) of bands 10 and 11 (°C) was obtained based on the spectral radiation (L λ) (Eq. [4]) of the sensor and converted through the reverse of Planck's function (Eq. [5]):

$$L\lambda_{i} = M_{Li} \cdot Q_{cal} + A_{Li}.$$
 [4]
$$TB_{i} = \frac{K_{2i}}{ln(\frac{K_{1i}}{L\lambda} + 1)} + 273.15$$
 [5]

where: M_{Li} is the multiplicative factor of resizing for band i; Q_{cal} is the digital pixel number; A_L is the specific additive scaling factor for band i; TB_i is the brightness temperature from satellite in band i; K1 and K2 are calibrated constants for band i; L\lambda is the spectral radiation of the sensor in band i (W m⁻² sr⁻¹ μm^{-1}); and 273.15 is the constant to convert absolute temperature from Kelvin to °Celsius (°C).

The mean emissivity (ϵ) and emissivity difference ($\Delta\epsilon$) in bands 10 and 11 were obtained from Eq. [6] and [7] using land surface emissivity (LSE) for each band. Land surface emissivity was quantified using reference values (Eq. [8]) and the soil:vegetation ratio, determined by soil cover factor (SCF) (Eq. [9]):

 $\begin{aligned} \varepsilon &= \frac{(LSE_{10} - LSE_{11})}{2} \quad [6] \\ \Delta \varepsilon &= LSE_{10} - LSE_{11} \quad [7] \\ LSE_i &= \varepsilon_s (1 - SCF) + \varepsilon_s \cdot SCF \quad [8] \\ SCF &= \frac{NDVI - NDVI_s}{NDVI_v - NDVI_s} \quad [9] \end{aligned}$

where: LSE₁₀ and LSE₁₁ are, respectively, the emissivity of bands 10 and 11; $\varepsilon_s \in \varepsilon_v$ are, respectively, parameters for soil and vegetation emissivity for bands 10 ($\varepsilon_s = 0.971$; $\varepsilon_v = 0.987$) and 11 ($\varepsilon_s = 0.977$; $\varepsilon_v = 0.989$); NDVI is the

normalized difference vegetation index for the sugarcane target area (NDVI), from uncovered soil (NDVI_s), and from a natural forest (NDVI_v). NDVI was obtained from bands 4 and 5 from OLI sensor for sugarcane, soil and forest. The NDVI was used to estimate sugarcane leaf area index (Pereira et al., 2016).

The atmosphere's vapor content (w, g cm $^{-2}$) was obtained from the Leckner equation (Iqbal, 1983), shown in Eq. [10]:

$$w = 0.493 \cdot RH \cdot \frac{c_s}{T_a}$$
[10]

where: RH is the relative humidity (absolute value); e_s is the water vapor pressure in the saturation (hPa); and T_a is the air temperature (K).

Soil water deficit

Water deficit was quantified according to Thornthwaite and Mather's (1955) water balance, using 100 mm as a maximum soil water holding capacity. Reference evapotranspiration was obtained from the method proposed by Hargreaves and Samani (1985), using maximum, mean and minimum air temperature, in addition to extraterrestrial solar radiation, obtained based on the day of the year and latitude. These weather variables, along with rainfall, used as input in the water balance, were measured near the area of the field experiment.

Correlation and error analyses

Temperature values from satellite image using bands 10, 11 and land surface temperature (T_{s}) were quantified by the relative error (RE%) (Eq. [11]) in comparison with leaf temperature measured in the field.

$$RE\% = \frac{I_S - I_L}{T} \cdot 100$$
 [11]

where T_S represents the surface temperature, quantified based on bands 10, 11; and T_L is the leaf temperature measured in the field.

Conclusion

This research found that the difference between leaf and air temperature can be used to identify water deficit in commercial sugarcane areas, with the index being sensitive to the variation of soil water content. In contrast, the higher error between land surface temperature (obtained from brightness temperature) and leaf temperature limited the application of this approach to identify water deficit for sugarcane, except in the moment of higher water deficit or surplus. Further investigation is needed to estimate land surface temperature based on satellite image with higher spatial and temporal frequency, considering the crop stage, soil cover proportion, weather conditions and surface properties.

It is important to emphasize that T_s uses in its algorithm the estimation of brightness temperature from bands 10 and 11, since when only band 11 is applied, T_s values tended to be smaller. Furthermore, calibration uncertainty was more closely associated with the data of band 11, since this band is more affected by the absorption of radiation by the atmospheric water vapor, which implies larger errors related to the atmospheric profile in the acquisition of surface temperature.

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