

Water monitoring of soybean crops using the TVDI obtained from surface radiometric sensors






Abstract – The objective of this work was to evaluate the use of the surface moisture data generated by the temperature-vegetation dryness index (TVDI), obtained from sensors positioned on the surface of a soybean (*Glycine max*) agricultural field. The dry and wet limits of the index were obtained using Landsat-8 images covering the region around the crop. To assess the quality and consistency of the TVDI, a correlation analysis was carried out between the TVDI, the normalized difference vegetation index (NDVI), surface temperature (T_s), and the variables that are usually used to express surface moisture. The TVDI showed a significant correlation with soil moisture, water storage in the soil, water deficit, real evapotranspiration, and the real evapotranspiration/potential evapotranspiration ratio. The displacement of radiometric data measured on the surface (NDVI and T_s) within the evaporative triangle, adjusted with orbital data, consistently describes the variability of water conditions during the study period, being a tool to support decision-making in crop management.

Index terms: Landsat-8, NDVI, remote sensing, soil moisture, surface temperature.

Monitoramento hídrico de lavoura de soja com uso do TVDI obtido de sensores radiométricos de superfície

Resumo – O objetivo deste trabalho foi avaliar o uso dos dados de umidade da superfície gerados pelo índice “temperature-vegetation dryness index” (TVDI), obtido de sensores posicionados na superfície de uma área agrícola de soja (*Glycine max*). Os limites seco e úmido do índice foram obtidos com uso de imagens Landsat-8 que abrangem a região em torno da lavoura. Para avaliar a qualidade e a coerência do TVDI, foi realizada análise de correlação entre o TVDI, o “normalized difference vegetation index” (NDVI), a temperatura da superfície (T_s), e as variáveis usualmente utilizadas para expressar a umidade da superfície. O TVDI mostrou correlação significativa com umidade do solo, armazenamento de água no solo, déficit hídrico, evapotranspiração real e relação evapotranspiração real/evapotranspiração potencial. O deslocamento dos dados radiométricos medidos na superfície (NDVI e T_s) dentro do triângulo evaporativo, ajustado com dados orbitais, descreve de forma consistente a variabilidade das condições hídricas no período de estudo, sendo uma ferramenta para apoio à tomada de decisões no manejo de culturas.

Termos para indexação: Landsat-8, NDVI, sensoriamento remoto, umidade do solo, temperatura superficial.


Lucimara Wolfarth Schirmbeck⁽¹⁾ ,
Denise Cybis Fontana⁽²⁾ ,
Juliano Schirmbeck⁽³⁾ ,
Genei Antonio Dalmago⁽⁴⁾  and
José Maurício Cunha Fernandes⁽⁴⁾ 

⁽¹⁾ Universidade Federal do Rio Grande do Sul, Campus do Vale, Avenida Bento Gonçalves, nº 9.500, CEP 91501-970 Porto Alegre, RS, Brazil.
E-mail: lucimaraws@gmail.com

⁽²⁾ Universidade Federal do Rio Grande do Sul, Faculdade de Agronomia, Avenida Bento Gonçalves, nº 7.712, Agronomia, CEP 91540-000 Porto Alegre, RS, Brazil.
E-mail: dfontana@ufrgs.br

⁽³⁾ Universidade do Vale do Taquari, Centro de Ciências Exatas e Tecnológicas, Avenida Avelino Talini, nº 171, Universitário, CEP 95914-014 Lajeado, RS, Brazil.
E-mail: schirmbeck.j@gmail.com

⁽⁴⁾ Embrapa Trigo, Rodovia BR-285, Km 294, Caixa Postal 3081, CEP 99050-970 Passo Fundo, RS, Brazil.
E-mail: genei.dalmago@embrapa.br, mauricio.fernandes@embrapa.br

 Corresponding author

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Introduction

Information generated from remote sensing data, at different spatial scales, can serve as a basis for studies both for the identification of yield gaps and for the management of risks in the agricultural sector. In the state of Rio Grande do Sul, Brazil, the water condition is the main risk factor for the soybean (*Glycine max* L.) crop, which covers the largest area of cultivation in the country, around 5.8 million hectares in the 2020 harvest (IBGE, 2021). The normal water condition of the region, however, restricts obtaining higher soybean crop yields (Sentelhas et al., 2015; Zanon et al., 2016), besides causing a high interannual variability in grain production (Battisti et al., 2017; Matzenauer et al., 2020). In this scenario, indexes that characterize the water condition in soybean crops in a precise and accurate way are essential, but, although previously studied extensively, still need advances, especially in the spatial detail of information.

Surface-mounted radiometric stations in the field, with sensors to capture information analogously to orbiting satellites, are being used to follow the biophysical processes of local crops with more spatial and temporal details (Balzarolo et al., 2011). Field radiometric data can complement and assist the analysis of orbital data, since, besides characterizing in a greater detail the differences that occur over the phenological development of vegetation, they can also complement measurements during periods without data due to the presence of clouds or to any other factor that compromises image quality (Eklundh et al., 2011).

Field-installed radiometric sensors, measuring at different wavelength ranges, can provide information on different plant processes. Sensors that measure red and near-infrared radiance provide data for calculating the normalized difference vegetation index (NDVI), widely and successfully used for biophysical parameters, to, for example, estimate actual evapotranspiration or even model grain yield estimates (Barbosa et al., 2019). Moreover, sensors that provide measurements in the thermal spectrum allow obtaining surface temperature (T_s), an indicator of plant water status (Wang et al., 2007).

Simultaneous T_s and NDVI data allow obtaining the surface moisture index, known as the temperature-vegetation dryness index (TVDI) (Sandholt et al., 2002), which is based on the evaporative triangle concept and used in various studies to monitor surface

water status (Wang et al., 2007; Holzman et al., 2014). Despite being widely used, most of the analyzes with this index were carried out in dry conditions, with few applications in humid subtropical conditions (Schirmbeck et al., 2017b, 2018). When the TVDI is obtained from orbital images, the responsiveness of the index to variations in plant water status highlights some uncertainties related to issues of the temporal adequacy of data acquisition, such as satellite transit time or even number of revisits. Radiometric issues can also lead to uncertainties, resulting from the spectral purity of the pixel, band position and width, and sensor degradation, among others. However, when the TVDI is obtained from radiometric sensors positioned on the surface, it is important to decide which methodology to adopt in order to determine the dry and wet limits of the evaporative triangle used to parameterize the index (Garcia et al., 2014; Schirmbeck et al., 2018). These limits define the possible conditions that may occur in a region and period of the year, relating the TVDI values at each moment to the set limits (Schirmbeck et al., 2018). For index parameterization, it is necessary to detect extreme water conditions, which commonly occur in large regions, but not likely in small areas, as in a field crop (Jackson et al., 1977).

The objective of this work was to evaluate the use of the surface moisture data generated by the TVDI, obtained from sensors positioned on the surface of a soybean agricultural field.

Materials and Methods

The experiment was conducted in the municipality of Carazinho, in the state of Rio Grande do Sul, Brazil (-28.228550°S, 52.905086°W, at 560 m of altitude) during 142 days in the spring/summer harvest of 2017/2018. The 27.4 ha crop area is located in a total area of 553.7 ha, where 450 ha of soybean are cultivated in the spring/summer period.

The climate, according to Köppen's classification, is subtropical humid, Cfa, with hot summers and regularly distributed rainfall throughout the year (Alvares et al., 2013), and the soil is a Rhodic Ferralsol (IUSS Working Group WRB, 2006).

The DM 5958 RSF IPRO soybean cultivar was sown on 11/13/2017 with a 45 cm spacing between rows and a density of 24 plants per square meter. The plants emerged on 11/21/2017 and were harvested on

4/3/2018. The soil analysis determined the adopted base fertilization, which was of: 300 kg ha⁻¹ N-P₂O₅-K₂O, 12 kg ha⁻¹ N, 60 kg ha⁻¹ P₂O₅, and 24 kg ha⁻¹ K₂O at sowing, besides 160 kg ha⁻¹ KCl the day before sowing. The crop field was monitored constantly to control pests, weeds, and diseases; when necessary, the products indicated for the crop were used (Reunião..., 2016).

After the soybean plants emerged, phenology was monitored weekly throughout the crop cycle. For this, biometric data were collected to obtain the leaf area index (LAI) and root depth according to Dourado-Neto et al. (1999). At each evaluation time, the plant phenological stages were checked and determined by Yorinori (1996). The LAI measurements consisted of collecting four plant samples (replicates) from 1.0 m of the row segment, also weekly. The data were collected by simple sampling (surveys) of the transects located in the central area of the plots. The central point of the transects was at least 100 m in radius relative to the crop border, ensuring the representativeness of the micrometeorological conditions of the soybean field.

The reference evapotranspiration (ET₀) was estimated following the FAO Penman-Monteith method (Allen et al., 2006), and the meteorological water balance was calculated daily using the Thornthwaite & Mather (1955) methodology (Pereira, 2005). The soybean crop coefficient (K_c) between 0.4 and 1.15 was used according to Allen et al. (2006), while soil water storage capacity (SWSC) was assumed to vary during the cycle as a function of plant and root growth over the experimental period (Dourado-Neto et al., 1999). The thermal sum was used to calculate root growth and obtained as described in Rosa et al. (2009) for a 10°C base temperature.

Grain yield was determined at the harvest maturity stage. Samples were collected from the central area, on previously determined transects, with four replicates of two 10 m rows collected in each replicate, totaling a 9 m² area. Grain yield was corrected to 13% moisture.

Three sets of radiometric sensors mounted on separate masts were installed in the area, to enable the continuous monitoring of incident and reflected radiation in the red (0.6 to 0.7 μm) and near-infrared (0.805 to 0.815 μm) spectra using the NDVI spectral reflectance sensor (Meter Group, Pullman, WA, USA). Incident radiation was measured with the sensor facing upwards to provide the reference values, whereas the radiation reflected by the soybean crop was measured

with the sensor facing downwards, restricting the field of view to 20°, in order to monitor plant growth and development. The canopy radiation emitted in the thermal spectrum (8 to 14 μm) was also measured using three sets of the SI-421 radiometric temperature sensor for T_s (Apogee Instruments, Inc., Logan, UT, USA), with an 18° field of view. The NDVI and T_s sensors were installed in pairs in a weather tower at approximately 1.0 m above the canopy top, pointing at the same area at 90°. Both sensors monitored continuously, recording, every 15 min, data that were collected by and stored in the Em50 series data logger (Meter Group, Pullman, WA, USA).

The NDVI and T_s sensors have an imaging technology analogous to that of the operational land imager/thermal infrared sensor (OLI/TIRS) onboard the Landsat-8 satellite, with a 30 m spatial resolution in the near-infrared and red spectra, and a 100 m resolution in the infrared thermal spectrum by the TIRS sensor. Landsat-8 OLI/TIRS data were used to determine the wet and dry limits/edges of the TVDI triangle, as described by Schirmbeck et al. (2017c).

The images used to define the TVDI limits/edges were from 11/20/2017, 1/7/2018, 2/8/2018, and 2/24/2018, collected under clear skies with no clouds over the soybean crop (in a single evaporative triangle). The images were obtained from the United States Geological Survey database (USGS, 2021).

After collecting the NDVI and T_s from both field and satellite data and defining the dry and wet limits, the TVDI was estimated using the equation proposed by Sandholt et al. (2002):

$$TVDI = (T_s - T_{smin}) / (a + b Vi - T_{smin})$$

where T_s is the surface radiative temperature (K); T_{smin} is the minimum surface temperature (K) corresponding to the wet limit in the evaporative triangle dispersion; Vi is the NDVI; and a and b are the linear and angular coefficients of the line representing the dry limit obtained from the Vi and T_s scatter plot, used for normalizing the TVDI model.

Soil moisture was determined using a soil volume moisture sensor. The CS616 time domain reflectometer (Campbell Scientific, Inc., Logan, UT, USA) was installed vertically and used to measure the average moisture between 0 and 30 cm in the soil profile. The analysis used moisture data obtained daily at 9 a.m., in thermodynamic equilibrium with the previous day.

Data were recorded using the CR1000 datalogger (Campbell Scientific, Inc., Logan, UT, USA).

A weather station was also installed at the center of the experimental area. Temperature and relative humidity were measured using the HC2S3-L probe (Campbell Scientific, Inc., Logan, UT, USA), whereas incident global solar radiation was obtained by the SP-110-L-10 pyranometer (Apogee Instruments, Inc., Logan, UT, USA). Wind speed was calculated using the WINDSONIC1-L34 bidirectional sonic anemometer (Campbell Scientific, Inc., Logan, UT, USA), while rainfall was determined with the TB4-L rain gage (Campbell Scientific, Inc., Logan, UT, USA). All weather sensors were installed at 1.5 m from the ground and connected to the CR1000 datalogger (Campbell Scientific, Inc., Logan, UT, USA); the readings were taken every 30 s, and averages and/or totals were stored every 15 min depending on the variable.

The data from 25 sunny days were chosen for analysis. The selection criterion consisted of global solar radiation data measured in the period coincident with the passage of the Landsat-8 satellite from 10:15 a.m. to 10:45 a.m. For these days, graphs showing crop growth and development and surface water condition were plotted. In addition, the TVDI and components were expressed as a function of time. Pearson's correlation analysis was performed between the TVDI, NDVI, T_s , and the other variables that express surface moisture, i.e., soil moisture, water storage in the soil, water deficit, real evapotranspiration, and the real evapotranspiration/potential evapotranspiration ratio. Finally, the NDVI and T_s measurements were plotted to evaluate their evolution throughout the soybean cycle within the evaporative triangle constructed using the Landsat-8 images.

Results and Discussion

During the growing season, both soybean shoots and root system presented a rapid growth, while root depth stabilized in stage R3 (beginning of fruiting) at about 70 cm and at 71 days after sowing (DAS) (Figure 1). The LAI increased exponentially until full flowering (R2) at 64 DAS and continued to increase at a lower rate until 99 DAS at the end of grain filling (R5.3), when it reached values close to 8. Usually, roots and leaf area stabilize when flowering begins in R1. In this case, however, the plants continued to grow, following the species indeterminate growth habit

(Machado Júnior et al., 2017). After that, as leaves turned yellow, the LAI dropped sharply beginning the end-of-cycle decline. The pattern of evolution over time of the LAI and root depth showed that there were no environmental limitations significantly altering the growth and development of the plants.

Rainfall, the only water source available for the plants, was well distributed, totaling 771.9 mm throughout the soybean cycle (Figure 2). Grain yield was 4,629 kg ha⁻¹ for the crop season, a value consistent with the maximum average grain yield for soybean crops (Tagliapietra et al., 2021). Zanon et al. (2018) found that, for high yields, it is necessary to have a LAI greater than 6.3, ideally close to 8.0. The water conditions, therefore, were adequate for soybean crop development, since the total water required, on average, for soybean to reach maximum grain yield varies from 450 to 800 mm per cycle, depending on climatic conditions, crop management, and cycle length of the cultivar (Bergamaschi & Bergonci, 2017). The field data on soil moisture showed a variation pattern coincident with the soil water storage estimated from the water balance for the crop cycle. As expected, soil moisture varied according to the changing soil water storage. The storage values increased due to the use of the SWSC variable, estimated as a function of root

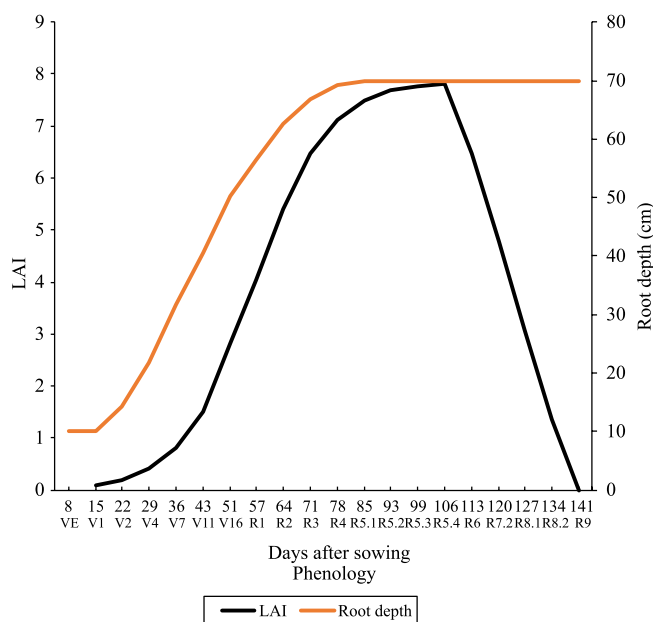


Figure 1. Leaf area index (LAI) and root depth of soybean (*Glycine max*) throughout the crop cycle in the 2017/2018 harvest.

depth. Soil moisture and water storage variations were associated with rainfall periods, increasing soon after rainfall and decreasing days after rainfall had stopped. Water restriction for the crop was observed between 50 and 60 DAS, coinciding with the end of the growing season, and between 77 and 87 DAS, representing the beginning of grain filling; smaller water deficits were observed in other shorter periods. Although total rainfall was suitable for the crop, there was an alternation of periods with higher and lower humidity in the soil throughout the cycle, which is important for subsequent analyzes related to the quality of the TVDI in characterizing the water condition of the surface.

The TVDI value on each date is associated with the dry and wet limits established in the parameterization of the index (Garcia et al., 2014). For this reason, a parameterization per crop was assumed, as proposed

by Schirmbeck et al. (2018), because the goal was to use the TVDI to monitor moisture throughout the soybean cycle. In this case, it is imperative that the set limits be invariant in time. Moreover, since the sensors positioned on the surface do not generate the variability of water conditions necessary to obtain the dry and wet limits of the evaporative triangle, the alternative proposed in this work was to use orbital data. Therefore, the evaporative triangle (Figure 3) was generated with the Landsat-8 OLI-TIRS images available throughout the cycle, and the NDVI and T_s data collected in the field were positioned within it. The distribution of points in the NDVI and T_s space reflects the water conditions (Zhang et al., 2014; Holzman et al., 2018). In addition, the use of regional data to generate the evaporative triangle allows obtaining a greater variability of water conditions

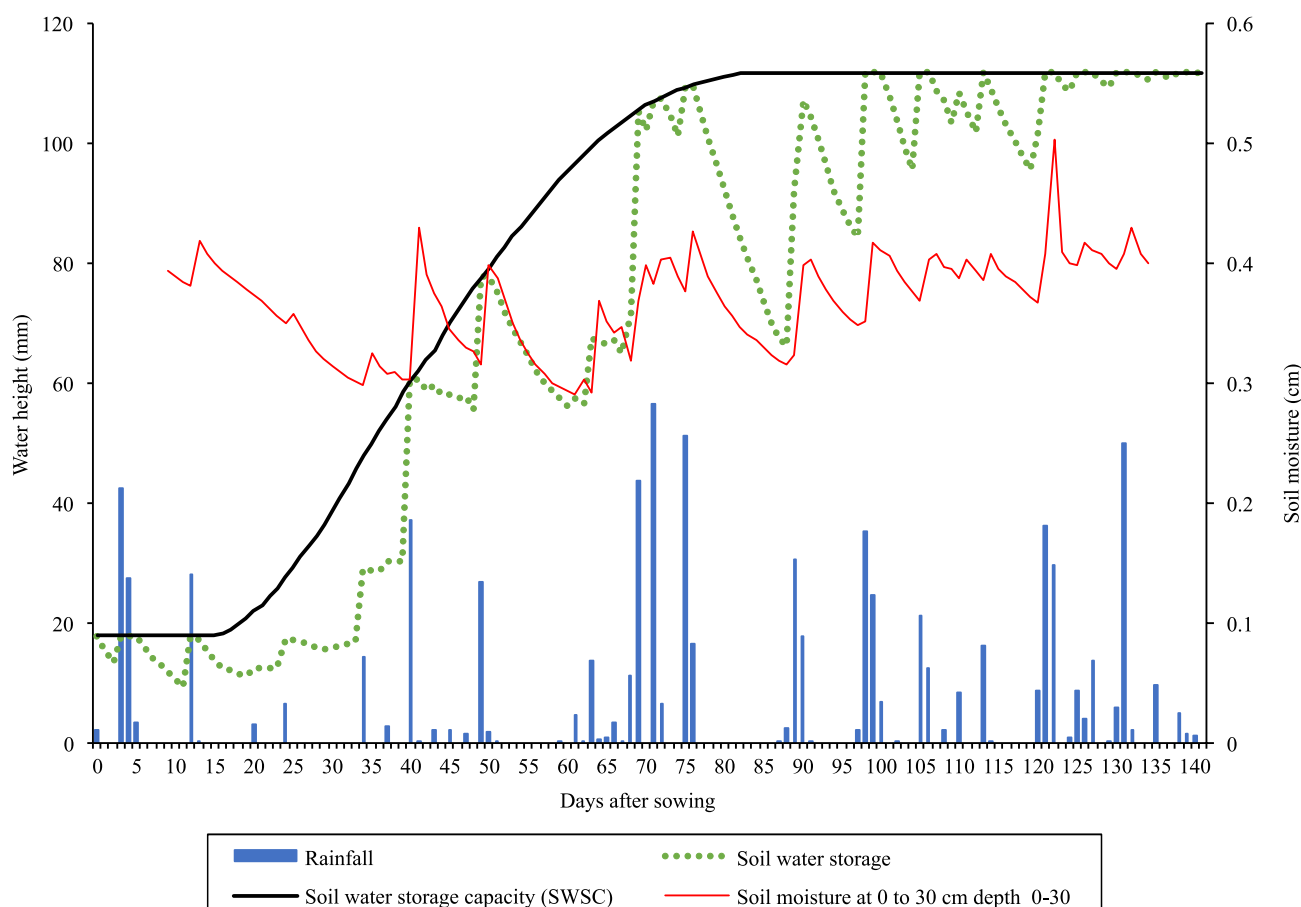


Figure 2. Soil water storage capacity, water storage, moisture at 0 to 30 cm depth, as well as rainfall, during the soybean (*Glycine max*) growth and development cycle in the 2017/2018 harvest.

(Sandholt et al., 2002), that is, a greater distribution of values in the NDVI and T_s space, covering the water conditions measured in the field.

The initial low and increasing NDVI values observed at the beginning of the cycle, when the crop was not fully covered by soil and the LAI was below 5, were above 0.9 and remained stable during flowering and grain filling, when the LAI reached between 6.0 and 8.0 (Figure 4). Stabilization at high values is a known NDVI characteristic, referred to as the saturation index. At saturation, the increases or decreases in the LAI do not correspond to NDVI variations; the index loses sensitivity and does not represent the LAI variations any longer. Therefore, it can be inferred that, from the moment the NDVI saturates, its contribution to the differentiation of water surface conditions using TVDI is reduced, which has already been pointed out by other authors (Holzman et al., 2014; Zhang et al., 2014; Schirmbeck et al., 2017c). The highest T_s occurred at the beginning of the cycle, when the greater availability of solar radiation coincided with exposed soil, without vegetation cover to help control the T_s via the evapotranspiration process (Allen

et al., 2006; Silva-Fuzzo & Rocha, 2016). T_s also tended to gradually decrease as the cycle advanced and solar declination decreased. However, this trend was interrupted several times by the rise in T_s , which occurred markedly at 53, 67, 81, 87, 97, 109, and 117 DAS. The elevation of T_s in these days was possibly due to either the higher amount of solar radiation or the reduction of surface moisture, altering the partition of energy balance (Garcia et al., 2014).

The TVDI presented a significant correlation with the different variables measured or estimated in the experiment (Table 1), which are usually used to indicate crop water condition (Allen et al., 2006; Bergamaschi & Bergonci, 2017). The higher the soil moisture, the soil water storage, the ET_R/ET_o ratio and the ET_R , the lower the TVDI, evidencing their inversely proportional relationship. For water deficit, however, the relationship was directly proportional: the higher the water deficit, the higher the TVDI. These correlations show that, despite the conceptual differences inherent in each of the surface moisture indicators used in the correlation analysis, the TVDI reached the expected result, showing the robustness of this remotely obtained index (Garcia et al., 2014; Holzman et al., 2018). When the TVDI is calculated using orbital images, the surface moisture conditions are mapped to a detail degree that is not possible using other forms of measurement or estimation.

It was also possible to quantify the association of the TVDI with the two parameters used in the NDVI and T_s calculations. There is a directly proportional and more intense correlation with the T_s of 0.87, which, as previously mentioned, is related to temperature control by the evapotranspiration process (Allen et al., 2006). When stomatal closure occurs due to the lack of water in the soil, the T_s of the vegetation increases and the TVDI also increases, whereas the relationship with the NDVI is inverse and less intense, with a value of -0.54 (Schirmbeck et al., 2017c).

The TVDI, estimated from the radiometric surface data, also allowed to analyze the displacement pattern (NDVI x T_s) of the data within the evaporative triangle during the soybean cycle (Figure 5), migrating between the wet and dry limits/edges obtained from the orbital data (Figure 3). The data labels in the figure allowed identifying the DAS that correspond to each point, facilitating the coherence and consistency analyses of the TVDI values. At the beginning of the season at

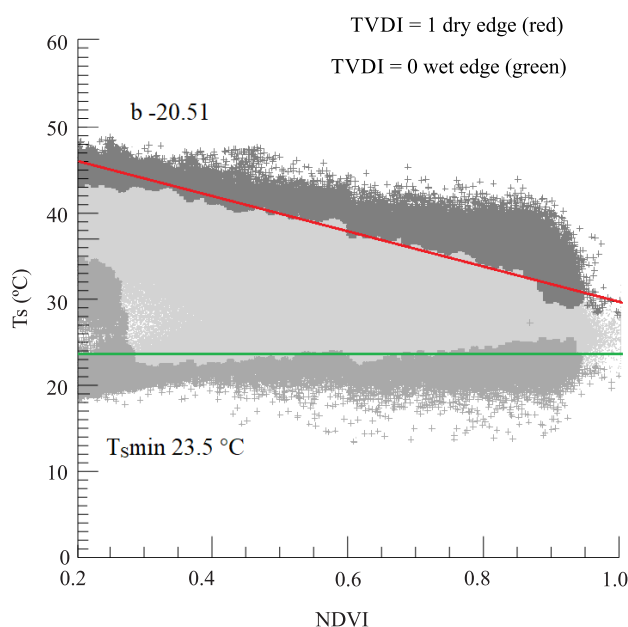


Figure 3. Evaporative triangle defined by the normalized difference vegetation index (NDVI) and surface temperature (T_s) data obtained from images of the Landsat-8 satellite. TVDI, temperature-vegetation dryness index.

43, 44, and 48 DAS, the points migrated from left to right within the triangle, given by the NDVI increase, associated with the LAI increase from 1.9 to 2.8 in the period (Figure 1). On these three dates, the distance from the points to the dry boundary was similar, which may indicate an equally similar but restricted water condition. There was also a low rainfall on these three dates (Figure 2), with reduced soil moisture; however, soil water storage remained constant due to the increased SWSC, given the estimated increased depth of the root system. Throughout the cycle, the points within the evaporative triangle were all very close because the NDVI stabilized at high values, between 0.7 and 0.9.

The zooming into the rightmost part of the evaporative triangle (black rectangle) reveals three situations that

show coherence between the TVDI and the surface water condition of the crop. At 77 and 75 DAS and also at 101 and 102 DAS (highlighted in the blue circle), the data approached the wet limit (Figure 5). The rainfall observed in both situations increased soil storage and moisture (Figure 2). However, contrarily, the data at 81 and 87 DAS were closer to the dry boundary (higher TVDI), indicating water restriction caused by the lack of rainfall and reduced soil storage and moisture.

The obtained results add to previous researches (Garcia et al., 2014; Silva-Fuzzo & Rocha, 2016; Uniyal et al., 2017; Holzman et al., 2018) that have been showing the quality of the TVDI in characterizing surface humidity. The contributions of the present work are mainly related to issues of spatial scale and climate. In terms of scale, it was shown that it is possible

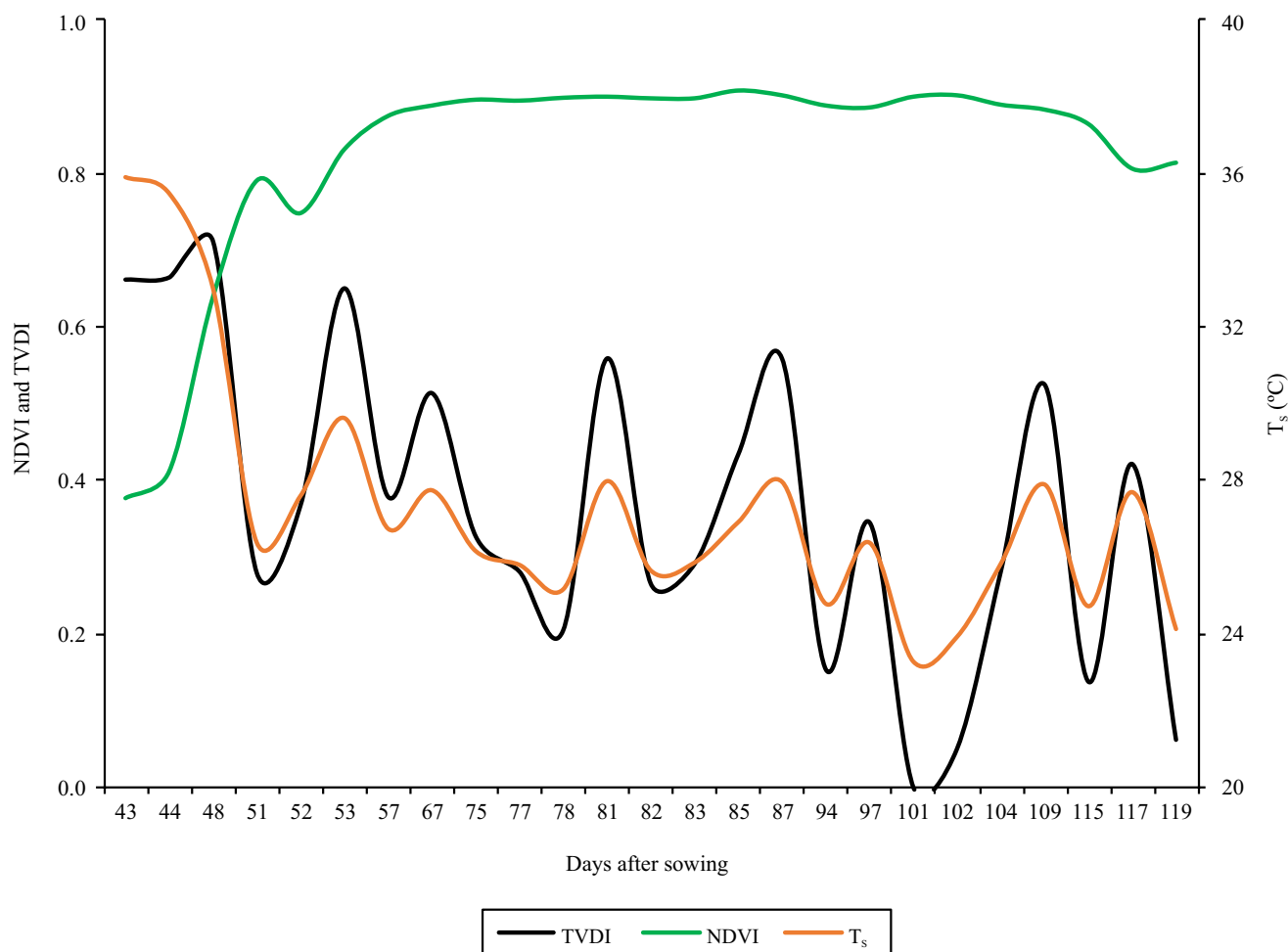


Figure 4. Normalized difference vegetation index (NDVI), surface temperature (T_s), and temperature-vegetation dryness index (TVDI) for surface moisture on sunny days in the 2017/2018 soybean (*Glycine max*) harvest.

Table 1. Pearson's correlation coefficients for the temperature-vegetation dryness index (TVDI), the normalized difference vegetation index (NDVI), surface temperature (T_s), and the variables that express surface moisture (soil moisture and storage), rainfall, water deficit and excess, real evapotranspiration (ET_R), potential evapotranspiration (ET_o), and the ET_R/ET_o ratio, obtained for the 2017/2018 soybean (*Glycine max*) harvest.

	TVDI	NDVI	T_s	Moisture	Storage	Rainfall	Deficit	Excess	ET_R	ET_o	ET_R/ET_o
TVDI	1										
NDVI	-0.54**	1									
T_s	0.87**	-0.88**	1								
Moisture	-0.49*	0.02	-0.29	1							
Storage	-0.72**	0.55**	-0.71**	0.74**	1						
Rainfall	-0.03	0.08	-0.05	0.08	0.28	1					
Deficit	0.57**	-0.20	0.43*	-0.70**	-0.83**	-0.25	1				
Excess	-0.04	0.10	-0.07	0.08	0.29	1.00**	-0.24	1			
ET_R	-0.50*	0.54**	-0.57**	0.49*	0.71**	0.26	-0.68**	0.25	1		
ET_o	0.36	0.13	0.13	-0.49*	-0.50*	-0.20	0.82**	-0.18	-0.21	1	
ET_R/ET_o	-0.55**	0.40*	-0.51**	0.60**	0.78**	0.32	-0.87**	0.31	0.93**	-0.55**	1

* and ** Significant at 5 and 1% probability, respectively.

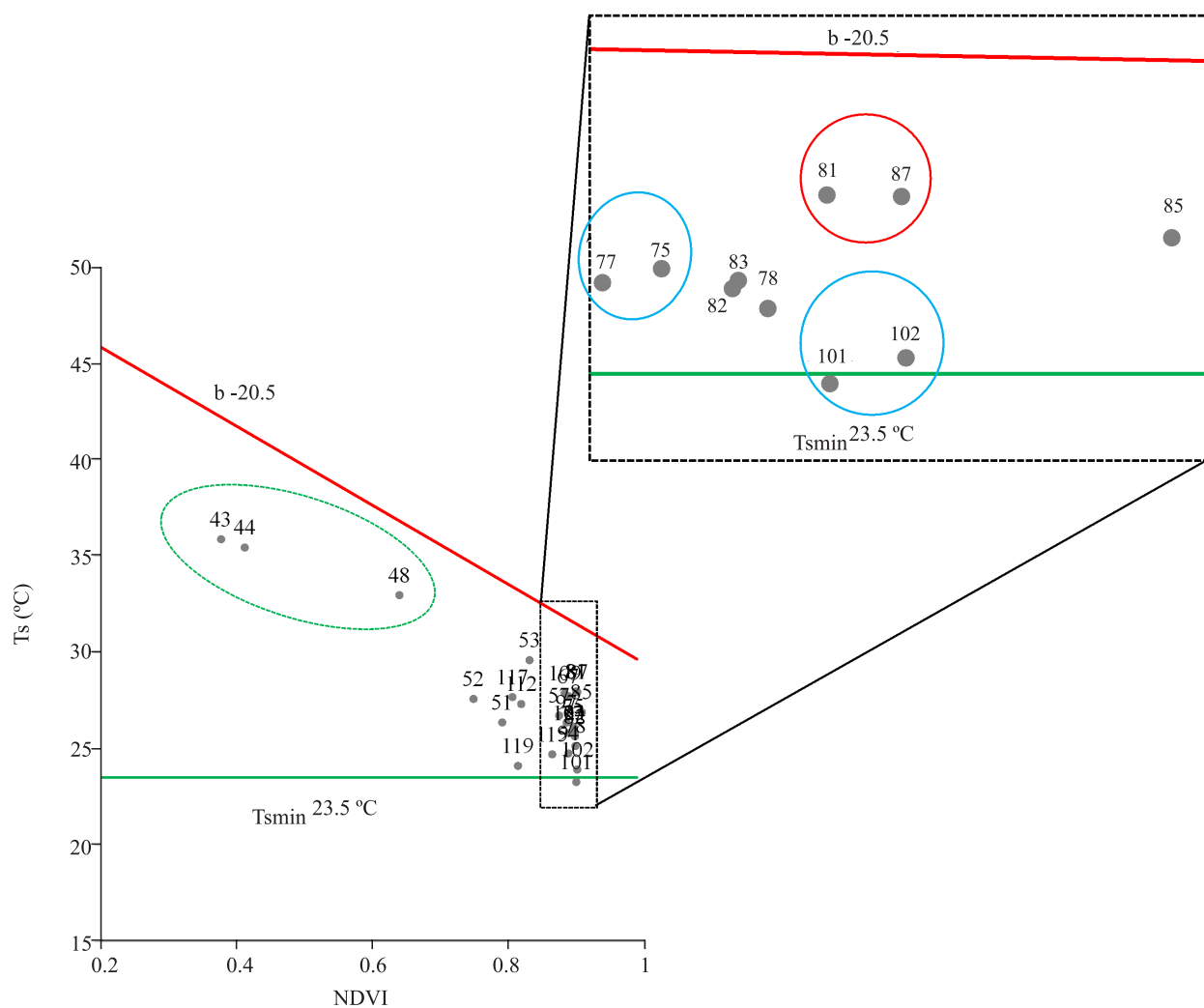


Figure 5. Evaporative triangle showing the wet and dry boundaries obtained from images of the Landsat-8 satellite, in the 2017/2018 soybean (*Glycine max*) harvest. T_s , surface temperature; and NDVI, normalized difference vegetation index.

to reconcile data obtained from sensors positioned on the surface and on orbital platforms. Orbital sensors are necessary to parameterize the TVDI. In relation to surface sensors, there are many possible applications. In the present study, the NDVI and T_s sensors were positioned in towers, generating data from a very restricted area, which is suitable for calibration studies. However, there is also the possibility of shipping the radiometric sensors in drones or similar equipment, which allows the formation of TVDI images with the most convenient spatial resolution. This is a potential to be explored by the precision farming community (Oliveira et al., 2021).

Regarding the climate issue, it should be noted that the TVDI was initially proposed for use in arid regions. For the humid subtropical climate, which predominates in the state of Rio Grande do Sul, Schirmbeck et al. (2017a) had already found that it is possible to use the index by differentiating the surface moisture conditions in extensive regions of production. The present work contributes by adding the information that, even for a crop with small water restrictions, located in a production region with humid subtropical climate, the TVDI has sensitivity to differentiate humidity over time.

Conclusions

1. The temperature-vegetation dryness index (TVDI) is precise and accurate in determining the surface moisture conditions in a soybean (*Glycine max*) agricultural field, as shown by the significant correlations with the usually used indicators.

2. The TVDI can be determined using surface-mounted sensors that capture information from radiometric measurements, but the dry and wet boundaries of the evaporative triangle need to be adjusted from orbital images of the region and study period, to make it possible to detect variations in water conditions throughout the soybean cycle.

3. The displacement of radiometric data measured on the surface—normalized difference vegetation index and surface temperature—, within the evaporative triangle adjusted with the orbital data, shows a pattern that consistently describes the variability of water conditions during the analysis period, expressing variability even in a humid climate and low water restriction.

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