Revista Brasileira de Meteorologia, **v. 38,** e3823003023, 2023
DOI: http://dx.doi.org/10.1590/0102-7786381003023 rbmet.org.br

Article

Use of MODIS and OLI/TIRS to estimate TVDI and Surface Moisture in Agricultural Monitoring Programs

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Received: 5 June 2023 - Accepted: 19 October 2023

Abstract

One of the major challenges for effective agricultural activity monitoring systems is defining robust indicators of spatial and temporal variability for the main risk factors associated with crop production. In this context, this study aimed to analyze the potential of the Temperature-Vegetation Dryness Index (*TVDI*), obtained by terrestrial and orbital sensors from soybean production areas in southern Brazil, in generating spatial and temporal patterns of the main risk factor, surface moisture, to be incorporated in operational agricultural monitoring systems. For this purpose, MODIS Terra and Landsat-8 OLI/TIRS sensor images were used, as well as data from surface positioned sensors to serve as a reference. The study area encompassed one soybean crop area, soybean mapped crop areas near the experimental area, and the municipality of Carazinho-RS. The experimental area was analyzed during the soybean growing season. As the *TVDI* data estimated by OLI/TIRS and MODIS sensors were coherent and robust, both sensors can be used in conjunction for agricultural risk monitoring. Its main features are continuous monitoring of large production regions by $TVDI_{\text{MODIS}}$ and spatial distribution detailing by $TVDI_{\text{OLI/TIRS}}$ in critical periods to water deficit.

Keywords: agriculture, water deficit, remote sensing, surface temperature, NDVI.

MODIS e OLI/TIRS Para Estimar TVDI e a Umidade da Superfície em Programas de Monitoramento Agrícola

Resumo

Um dos importantes desafios para construção de sistemas eficazes de monitoramento agrícola é a definição de indicadores que representem a variabilidade espacial e temporal dos principais fatores de risco associados à produção. Neste contexto, se analisou a potencialidade de uso do *TVDI* (*Temperature-Vegetation Dryness Index*), obtido a partir dos sensores terrestres e orbitais em áreas de produção de soja no sul do Brasil, na geração dos padrões espaciais e temporais do principal fator de risco, a umidade da superfície, visando sua incorporação em sistemas operacionais de monitoramento agrícola. Utilizou-se imagens dos sensores MODIS Terra e OLI/TIRS Landsat 8, e dados de sensores posicionados na superfície que serviram como referência. A área de estudo abrangeu lavoura de soja, onde foi conduzido o experimento, lavouras de soja próximas e o município de Carazinho/RS. O período de análise foi o período de cultivo da soja. Dada a coerência e robustez do *TVDI* estimado pelos sensores orbitais, verificou-se que é possível o uso conjugado destes sensores em sistema de monitoramento de risco agrícola. A principal característica é o acompanhamento contínuo da umidade em amplas regiões agrícolas usando $TVDI_{\text{MODIS}}$ e detalhamento da distribuição espacial da umidade da superfície com $TVDI_{\text{OLI/TIRS}}$ nos períodos críticos à deficiência hídrica.

Palavras-chave: agricultura, déficit hídrico, sensoriamento remoto, temperatura de superfície, NDVI.

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1. Introduction

One of the major challenges for effective agricultural activity monitoring systems is defining robust indicators of spatial and temporal variability for the main risk factors associated with crop production (Fraisse *et al.*, 2016; Radin & Matzenauer, 2016). In the case of soybeans grown in southern Brazil, the most important risk factor is water deficit (Sentelhas *et al.*, 2015, Zanon *et al.*, 2016, Matzenauer *et al.*, 2020).

Surface moisture is therefore a key variable in this scenario and can be either measured by direct methods or estimated by indirect methods. Indirect estimation of surface moisture can be effective and convenient, as it reduces labor force, time, and expenses, especially for large agricultural areas (Uniyal *et al.*, 2017). One of the ways to estimate it indirectly and that has been gaining increased space in the agricultural context is through remote sensing techniques. Satellite images are considered one of the best technologies for systematic data collection in monitoring agricultural activities, from which data can be obtained using portable sensors, drones, or orbital sensors (Tsukahara *et al.*, 2016). The use of data from different sensors in a complementary way helps in monitoring; however, there is still a lack of specific studies for different proposed indicators.

Sandholt *et al.* (2002) proposed to estimate surface moisture using an empirical approach that relates, in a two-dimensional space, the Normalized Difference Vegetation Index (*NDVI*) and Surface Temperature (*Ts)*, resulting in the *TVDI* (Temperature-Vegetation Dryness Index). Studies have shown that TVDI is a robust indicator of surface moisture in both dry (Sandholt *et al.*, 2002) and wet (Holzman *et al.*, 2014, Uniyal *et al.*, 2017, Schirmbeck *et al.*, 2018) climates. This is because this index uses information on vegetation status and temperature changes, both determined by the moisture factor (Sandholt *et al.*, 2002, Chen *et al.*, 2015, Wang *et al.*, 2020). Schirmbeck *et al.* (2022a,b) demonstrated that specifically for soybean production regions in the Rio Grande do Sul State, TDVI is a robust index and has a significant correlation with several variables (storage, deficit, ETr, ETr/ET0, and moisture) associated with the water conditions in the soil-water-plant system.

TVDI can be calculated using data from different platforms if they have sensors capable of providing *NDVI* and *Ts* data, generating information at different spatial and time scales. The most common are studies with Landsat TM- and OLI-derived *TVDI* (Gao *et al.*, 2011, Chen *et al.*, 2015, Li *et al.*, 2016, Sayago *et al.*, 2017, Wang *et al.*, 2020) and MODIS-derived *TVDI*, from Terra (Chen *et al.*, 2011, Son *et al.*, 2012, Garcia *et al.*, 2014, Sun *et al.*, 2017). Despite this, the use of *TVDI* in operational systems for agricultural monitoring still lacks research characterizing similarities and differences between indexes arising from different sensors and their feasibility when coming from different platforms in a joint and complementary way, as well as establishing protocols for use.

Thus, this study aimed to analyze how the spatial and temporal patterns of *TVDI*, obtained in soybean production areas in southern Brazil, from terrestrial and orbital sensors (OLI/TIRS and MODIS), can be used efficiently in operational agricultural monitoring systems.

2. Material and Methods

The study was carried out at three scales: a soybean crop where the experiment was conducted, soybean crops mapped in areas surrounding the experiment, and the entire municipality of Carazinho-RS, located in the Pampa Biome, in southern Brazil (Fig. 1).

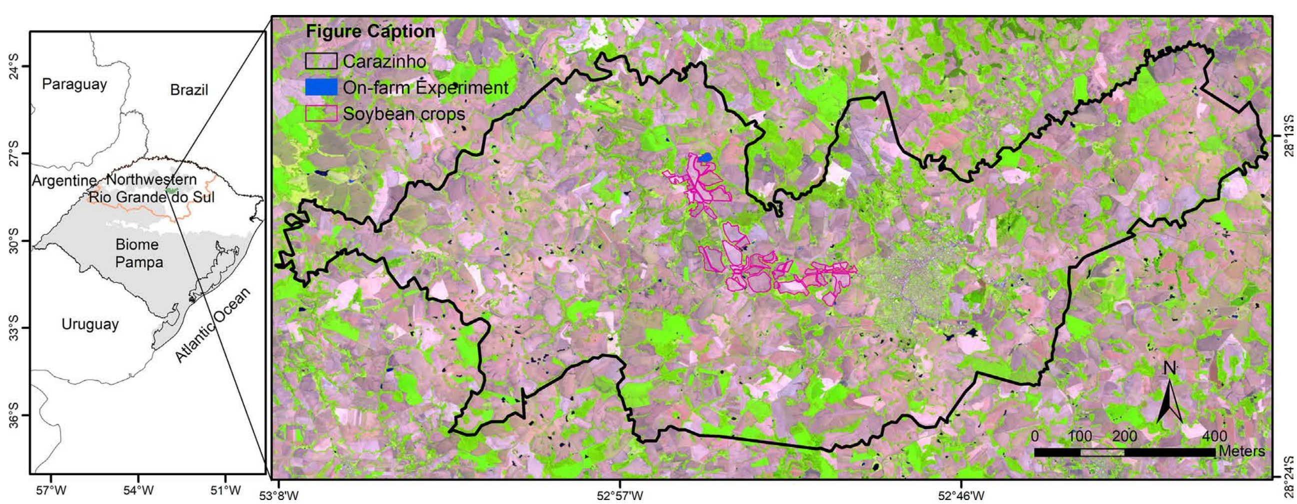

Figure 1 - Location of the study areas in northwestern mesoregion of the Rio Grande do Sul State and municipality of Carazinho/RS. Landsat-8 image from November 20, 2017, orbit/point (222/80).

Carazinho is in the northwestern mesoregion of Rio Grande do Sul State, which is responsible for more than 60% of the soybean production in the state (IBGE/SIDRA; May 12, 2021). Of the total 46,200 ha of cultivated area in the municipality, 40,400 ha are soybeans, mostly rainfed. According to Alvares *et al.* (2013), the local climate is *Cfa* type, which stands for humid subtropical, with hot summers and rainfall with regular distribution throughout the year, but with high interannual variability.

The experiment was carried out in an on-farm format, in a partnership among Embrapa Trigo from Passo Fundo, Granja Capão Grande, and the Faculty of Agronomy at UFRGS. The total area of the farm is 553.7 ha under intensive soybean production, with the experiment covering 27.4 ha. The experiment was analyzed from November 2017 to April 2018, with soybeans being sown on November 13, 2017, and harvested on April 3, 2018. Grain yield achieved 4,629 kg ha^{-1}. More details on farming practices are described in Schirmbeck *et al.* (2019).

2.1. Obtaining *TVDI*

As proposed by Sandholt *et al.* (2002), input data for calculating *TVDI* were T_S and *NDVI* (Eq. (1)), which were obtained from different sensors. T_S is the radiative temperature of the pixel (K); T_{Smin} is the minimum surface temperature (K) corresponding to the wet limit in the evaporative triangle dispersion; *NDVI* is the Normalized Difference Vegetation Index; "*a*" and "*b*" are the linear and angular coefficients of the line representing the dry limit obtained from the *NDVI* and T_S scatter plot, and are used for *TVDI* model standardization.

$$TVDI = \frac{(T_S - T_{Smin})}{(a + b\ NDVI - T_{Smin})} \qquad (1)$$

The evaporative triangle from two-dimensional space dispersion between *Ts* and *NDVI* defines different soil cover types and their respective moisture content. For points closer to the dry limit, represented by the slope of the T_S/*NDVI* line, *TVDI* equals 1 and indicates a water deficit. When *TVDI* equals zero, points are within the wet limit, which is given by the average minimum surface temperature over the analyzed period (Sandholt *et al.*, 2002).

Wet and dry limit delimitation and triangle-shaped dispersion are called index parameterization. This study covered the entire soybean cycle, as proposed by Schirmbeck *et al.* (2018). As *TVDI* is an index that provides moisture estimation relative to wet and dry limits, a parameterization per season, using all images available during the period of interest, is required to assess *TVDI* variations at different dates throughout the season. Aiming for integrated and complementary use as surface moisture indicators in crop monitoring systems, *TVDI* was determined at different spatial and time scales for data acquisition.

2.2. Surface-mounted sensors (reference)

A radiometric station was installed in the on-farm experiment to measure *NDVI* and T_S data on the surface. The station has technology like that of sensors aboard orbital platforms and thus served as a reference for analyzing orbital platform *TVDI* data. *NDVI* was measured by SRS - Meter Group sensors, while surface temperature (T_S) was measured by a model SI 421-Apogee sensor. The data were stored in a datalogger EM50 - Meter Group, with records every 15 minutes.

NDVI sensors were used to measure incident and reflected radiation flux within the red (0.6 to 0.7 µm) and near-infrared (0.805 to 0.815 µm) spectrum. A sky-facing hemispheric sensor was installed 1 m above the soybean canopy to measure incident electromagnetic radiation. The surface-facing directional sensor was used to measure reflected surface radiation (soybean/soil) and was restricted to a 20° field of view. T_S sensor measured surface-emitted radiation within the thermal infrared spectrum (8 to 14 µm) at a half-angle field of view of 18°. T_S and directional *NDVI* sensors were installed in pairs, with a 90° angle pointing to the same area.

2.3. Satellite images used

TVDI was determined from images using data from two orbital sensors with distinct characteristics, OLI/TIRS from Landsat-8 and MODIS from Terra.

For OLI/TIRS sensor, *TVDI* parameterization made use of 4 images referring to 11/20/2017, and 01/7, 02/8, and 02/24/2018, orbit/point 222/80. To do so, we used daily *NDVI* product from USGS - ESPA database (United States Geological Survey - Center Science Processing Architecture), with 30-m resolution within the red (band 4) and near-infrared (band 5) bands, and thermal bands 10 and 11, with 100-m resolution. T_S was estimated using the split-window algorithm proposed by Jiménez-Muñoz *et al.* (2014), which were previously tested by Schirmbeck *et al.* (2017, 2019). To calculate *TVDI*, an evaporative triangle was obtained from the 739k pixels in the municipality of Carazinho. Quality data were used to remove clouds and shadows from the OLI/TIRS images, as well as apply a mask to the urban area.

For MODIS sensor images, *TVDI* parameterization comprised images from 11/01/2017 to 04/23/2018 (12 images) from the LP DAAC database (Land Processes database Distributed Active Archive Center). The images were from the h13v11 and h13v12 quadrants and encompassed the entire Rio Grande do Sul State, which is required to cover different land covers and surface moisture levels for images with 1-km spatial resolution. *NDVI* images were obtained from the MOD13A2 product as 16-day maximum value images. For T_S, MOD11A2 product was used, with an image composition corresponding to the first 8 days obtained in the day and night, with no clouds, using the split-window method (Schirmbeck *et al.*, 2018, 2019). For *TVDI* calculation, an evaporative triangle was obtained using 309k pixels covering the entire area of Rio Grande do Sul State, due to the smaller spatial detail of the sensor.

2.4. *TVDI* data analysis

The analyses were organized in three stages to cover the main aspects of *TVDI* use in operational monitoring systems. In the first stage, evaporative triangle adjustment parameters were obtained using OLI/TIRS and MODIS sensors and compared, discussing procedures for their adjustment from three sensor types.

The second step evaluated the coherence of *TVDI* data from the different sensors. *TVDI*, *NDVI*, and T_S were estimated for the data collection point from the sensors: the plot where the experiment is being implemented, the surrounding soybean areas, and the entire municipality of Carazinho. Statistics were obtained in a sampling window of 3 x 3 pixels, for both satellites, covering 90 x 90 m for OLI/TIRS and 3000 x 3000 m for MODIS. These values were analyzed together with the data obtained on the surface at the radiometric station. Means and variability were calculated, and frequency distribution histograms were also made.

In the last stage, a proposal for *TVDI* use in an operational monitoring system was explored, integrating OLI/TIRS and MODIS data. For water condition characterization at a regional scale (to entire RS State), images and a plot of *TVDI* mean values throughout the soybean growing season, both from the MODIS sensor, were presented. Spatial detailing (municipality and producing crops) was carried out with the joint use of MODIS and OLI/TIRS images, which were temporally defined according to the critical period to water restriction for soybeans when there is the greatest risk of losses.

3. Results and Discussion

3.1. Evaporative triangle adjustment

OLI/TIRS and MODIS inherent characteristics show that evaporative triangles for parameterization during soybean growing season have a similar pattern. Therefore, both sensors were coherent but with differences in parameters to define dry and wet limits. If compared to OLI/TIRS, the MODIS triangle (Fig. 2a) had a lower T_{Smin} (293.6 K) and higher negative slope of the dry boundary line (-28.8), with the latter associated with surface evapotranspiration (Chen *et al.*, 2015; Silva-Fuzzo & Rocha, 2016). OLI/TIRS triangle had a higher T_{Smin} (296.7 K) and lower negative straight slope (-20.5). Dry and wet limits were different because they include water conditions at different dates and spatial and time resolutions between both orbital sensors evaluated. For MODIS, a larger number of images (November and April) and spatial coverage (RS State) were used in parameterization. As a result, MODIS had a greater negative slope, therefore, surface moisture conditions are more contrasting (Schirmbeck *et al.*, 2019).

When comparing surface moisture with the development cycles of annual crops, the evaporative triangle must be adjusted to cover the entire crop season (Schirmbeck *et al.*, 2018). Thus, when building a triangle, extreme water conditions for the entire period under analysis will be represented, making dry and wet limits fixed. This is critical for comparisons over time since *TVDI* is related to these limits. If adjustment is made on each date separately,

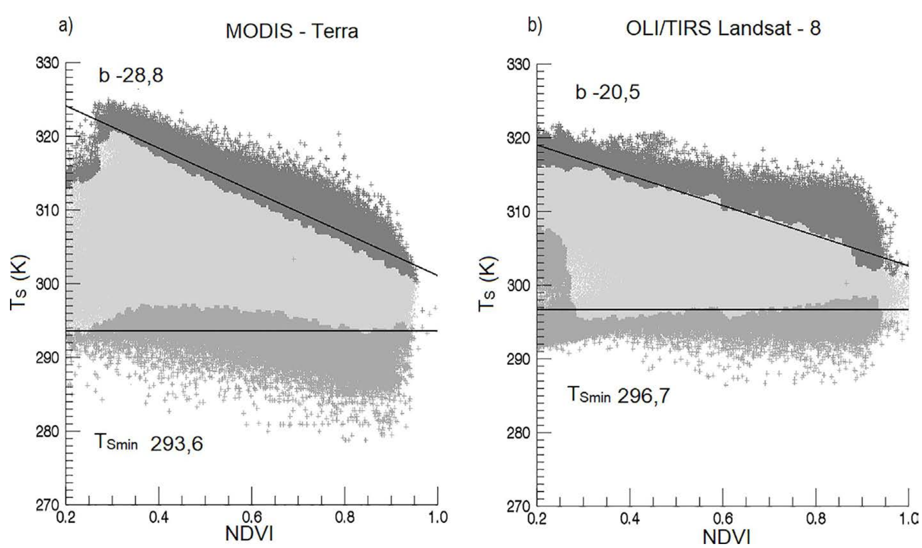

Figure 2 - Evaporative triangle obtained from: a) MODIS sensor - Earth for the Rio Grande do Sul State and b) Landsat-8 OLI/TIRS sensor for the municipality of Carazinho, 2017/18 soybean growing season.

the same *TVDI* value may represent different water conditions on different dates.

3.2. Coherence of *TVDI* from different sensors

Figure 3 shows that *TVDI* had a similar time variation pattern between sensors, with coherence in the magnitude of values on dates in which the acquisition coincided, despite known differences in sampled area size for each set of collected data. However, Fig. 3 also demonstrates some important differences between sensors, changing the usefulness of the index if incorporated in agricultural monitoring systems.

A *TVDI* dataset from a radiometric station ($TVDI_{sup}$) installed in a crop is analyzed to verify daily variability. This is because *NDVI* values are associated with green biomass (Monteiro *et al.*, 2012; Prabhakara *et al.*, 2015) and are quite stable from one day to another. High *TVDI* variability over days is due to its high sensitivity to surface temperature change (Schirmbeck *et al.*, 2017), which, in turn, may be associated with rainfall events. $TVDI_{sup}$ was determined using data from a sensor installation point in the field; however, in this study, it only served as a reference for orbital data analysis. This data has a positive point of high frequency over time, but with spatial representation restricted to the sensor view area (e.g., at 1 m high, it has 64 cm in diameter). In a precision agriculture context, these sensors, or similar ones, could be onboard terrestrial platforms, or even on drones, and generate *TVDI* maps with a detailed spatial distribution. *TVDI* obtained from OLI/TIRS sensor ($TVDI_{OLI/TIRS}$) also showed superior values to those from MODIS ($TVDI_{MODIS}$). Such difference can be attributed mainly to the sampled area. While OLI/TIRS sensor has a 90 x 90 m window, the MODIS sensor shows a wider context (3000 x 3000 m window). High values occurred at the beginning of the soybean growing season and, as expected (Silva-Fuzzo & Rocha, 2016; Uniyal *et al.*, 2017; Holzman *et al.*, 2018), they are associated with lower surface moisture. In this period, $TVDI_{OLI/TIRS}$ had higher values (0.77 on 11/20) than did $TVDI_{MODIS}$ (0.65 on 11/17). The following images, 01/07 and 01/19 for OLI/TIRS and MODIS respectively, showed a *TVDI* reduction as surface moisture increased by occasion of rainfall events (12/23 and 01/01, respectively), totaling 60 mm. In the following images 02/02 (MODIS) and 02/08 (OLI/TIRS), the index increases again due to a sequence of dry days before image capture. There was another index drop in the next pair of images [02/18 (MODIS) and 02/24 (OLI/TIRS)]. This can be associated with 4 significant rain events in the 8 days before image capture. Thus, the pattern obtained with data from both orbital sensors was coherent with surface moisture changes throughout the cycle. Therefore, *TVDI* datasets from both sensors can be used (Xu *et al.*, 2018).

By using $TVDI_{OLI/TIRS}$, variability within the experimental crop could be seen with a detail level like the spatial resolution of a temperature sensor (i.e., 90 m). It is useful for detailing large crops or even large production regions, but with a limited number of images due to the revisit and cloudiness, which in the evaluated soybean growing season was 4 images throughout the cycle. Yet, for $TVDI_{MODIS}$, as it uses a 16-day composition (different from instantaneous data), it has as positive a continuous representation throughout the season, identifying temporal patterns throughout the season; in the soybean cycle under

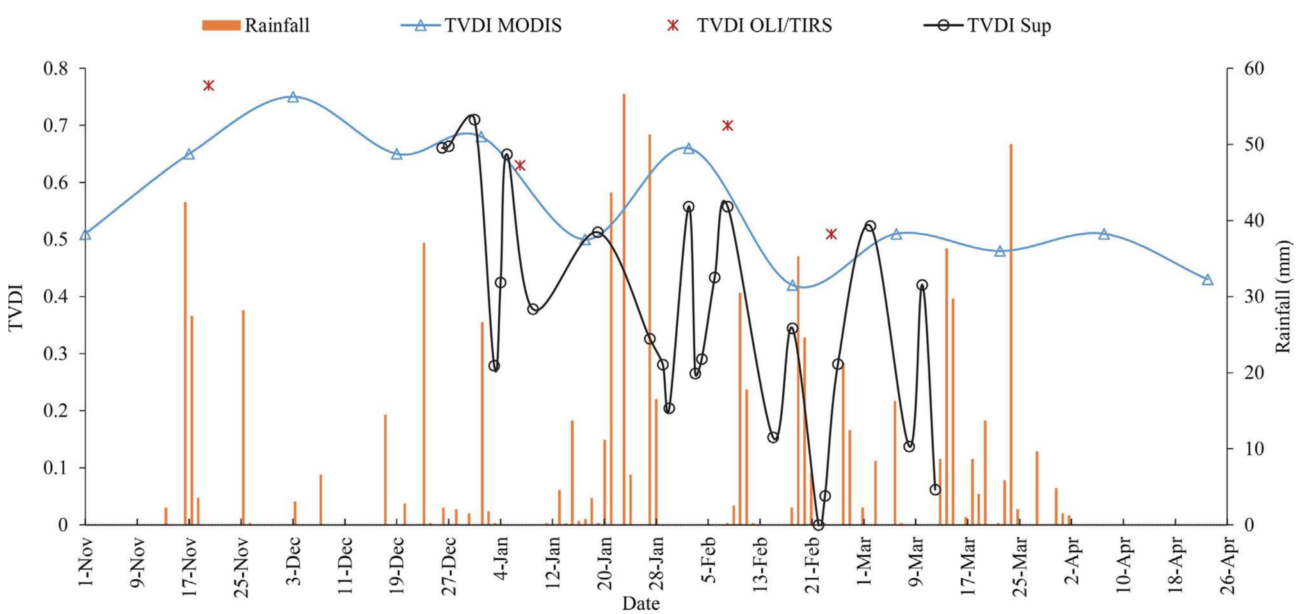

Figure 3 - Time profile of the surface moisture index (*TVDI*) calculated using sensors installed on the surface ($TVDI_{sup}$) for the pixels composing a 3 x 3 window obtained by the MODIS sensor ($TVDI_{MODIS}$), and by the OLI/TIRS sensor ($TVDI_{OLI/TIRS}$), and daily rainfall data throughout the 2017/18 soybean growing season. Carazinho-RS.

analysis, there were 12 images. In this case, the scale for obtaining information is 1000 m, which is suitable for monitoring large areas, and at a regional scale.

By expanding the study scale to the entire municipality of Carazinho, we confirmed coherence between *TVDI* values from OLI/TIRS and MODIS orbital sensors throughout the soybean growing season (Fig. 4). Just as seen in the experimental area (Fig. 3), $TVDI_{OLI/TIRS}$ values were slightly above those from $TVDI_{MODIS}$. Even so, the trend of the $TVDI_{MODIS}$ is also observed in the $TVDI_{OLI/TIRS}$ data. It is important to note that $TVDI_{OLI/TIRS}$ describes moisture conditions on a specific day, while $TVDI_{MODIS}$ reflects a 16-day condition from the *NDVI* product; thus, it carries somewhat distinct information, which may explain part of the magnitude differences in the data. Also, the mean *TVDI* on each date, from both sensors, for selected crops around the experimental area and crops throughout the municipality of Carazinho were similar. This is because soybean cultivation occupies about 60% of the municipality area (IBGE, SIDRA 2021), and the fact that farmers in the region may have adopted similar crop management practices. This ends up impacting *NDVI* and *Ts* in a similar way, as well as *TVDI* both in crop areas and in the entire municipality. These characteristics facilitate monitoring and integrating information from different sensors in this region.

Variability in mean values (Fig. 5 and Table 1) could be assessed by analyzing the dataset from all orbital-image pixels. The region showed deficit at the beginning of the crop cycle until mid-February. Afterwards, water condition was adequate, with a reduction in *TVDI* in virtually the entire region. In the pairs of images Nov 17 and Nov 20, as well as Feb 02 and Feb 08, higher mean *TVDI* was observed, greater variability with the occurrence of values close to 1, which indicates that surface moisture condition can be worrying in the period. On the other hand, in the

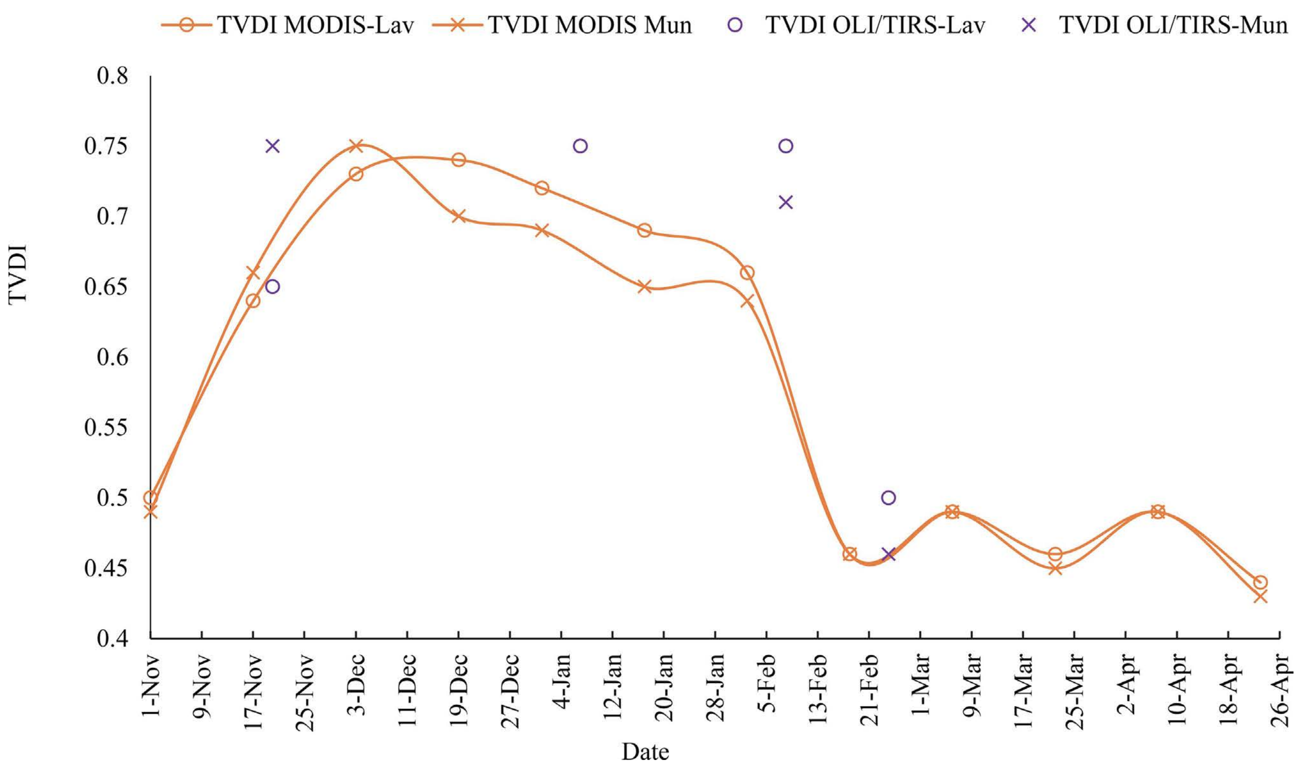

Figure 4 - Time profile of the surface moisture index (*TVDI*) from OLI/TIRS ($TVDI_{OLI/TIRS}$) and MODIS ($TVDI_{MODIS}$) sensors for selected crops (SCrop) and the entire municipality (Mun) of Carazinho.

Table 1 - TVDI mean values and standard deviation for the municipality of Carazinho, obtained by the OLI/TIRS sensor ($TVDI_{OLI/TIRS}$) of the Landsat-8 satellite and by the MODIS sensor ($TVDI_{MODIS}$) of the Terra satellite.

TVDI	Nov 20	Nov 17	Feb 08	Feb 02	Feb 24	Feb 18
	$TVDI_{OLI/TIRS}$	$TVDI_{MODIS}$	$TVDI_{OLI/TIRS}$	$TVDI_{MODIS}$	$TVDI_{OLI/TIRS}$	$TVDI_{MODIS}$
Mean	0.732	0.655	0.660	0.644	0.414	0.458
Standard deviation	0.194	0.093	0.172	0.072	0.156	0.072

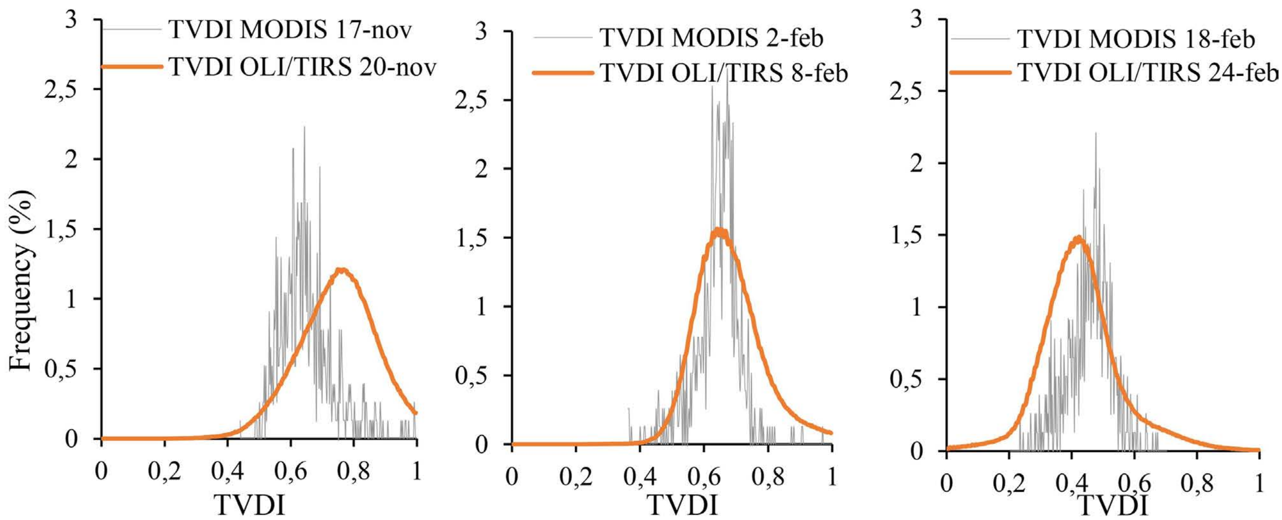

Figure 5 - Histograms of the frequency of *TVDI* occurrence for soybean crops in the municipality of Carazinho, obtained by the OLI/TIRS sensor ($TVDI_{OLI/TIRS}$) in orange, and by the MODIS sensor ($TVDI_{MODIS}$) in gray, between November/2017 and February/2018.

pair of images of Feb 18 and Feb 24, lower mean values and variability were observed, farther from 1, indicating a satisfactory moisture situation (Sandholt *et al.*, 2002, Holzman *et al.*, 2018).

Among the analyzed histograms, November images were the ones with the greatest differences between both sensors (histograms, Fig. 5 and mean values, Table 1). This can be attributed to a greater spectral mixture between soil and vegetation at the beginning of the crop cycle, which is detected distinctly by MODIS and OLI/TIRS sensors. Furthermore, the histograms of MODIS images showed peaks and depressions in frequencies, which is attributed to the spatial resolution of these images.

3.3. Proposal for *TVDI* use in monitoring systems

Coherence between the results of both sensors, whether in restricted areas (cropland) or wider ones, supports the combined use of MODIS and OLI/TIRS sensors for agricultural monitoring purposes. After defining the index temporal profile throughout the growing season by $TVDI_{MODIS}$, regional water conditions can be characterized for a given period. This result is important since robust indices that allow a clear view of the occurrence and variability in some conditions are essential in monitoring systems (Fraisse *et al.*, 2016; Ravelo *et al.*, 2016). In subsequent analysis, $TVDI_{OLI/TIRS}$ index can be used to detail spatial distribution in risk areas, improving understanding of impacts that variability in moisture conditions can cause when it occurs in critical phenological phases of crops, thus helping in decision-making and minimizing risks (Fraisse *et al.*, 2016).

In this conception, Fig. 6 shows *TVDI* use as a surface water indicator in a monitoring system, especially on detailing and mapping of risk areas. These are fundamental especially during the critical period of the crop to water restriction. This information is useful for decision making, increasing resource use efficiency, and ensuring agricultural production stability (Fraisse *et al.*, 2016; Romani *et al.*, 2016).

A first monitoring component could be generating 16-day images for the entire RS State using large-scale $TVDI_{MODIS}$ products continuously throughout the whole soybean cycle. From these images, the average *TVDI* values for different cities could be extracted, generating a profile with the time course of the index. For the crop under analysis, the index varied a lot over time and, on some dates, between regions within the RS State. $TVDI_{MODIS}$ images with a greater presence of red areas occurred at the beginning of the crop cycle, especially on December 3rd. On this data, after extracting data from the municipality of Carazinho, the highest *TVDI* in the profile was observed. Afterwards (images from Dec 19 to Feb 2) yellow and green tones predominated, consistent with high profile values. At the end of the crop cycle, from Feb 18 to Apr 23, colors in shades of blue were prevalent and coincided with the low values of $TVDI_{MODIS}$ in the profile.

A second component can be inputting phenological data to be able to infer the effects of moisture restriction on grain yield (Romani *et al.*, 2016). When water deficit coincides with a critical soybean period, the largest losses will be observed since water shortage directly impacts the formation of yield components (Matzenauer *et al.*, 2020). In this study, phenology was observed during the experiment, and the crop was at flowering and grain filling stages in January and February. For this component, the data collected by EMATER-RS, GeoR Package could also be used and made available in an Economic Newsletter, in which crop evolution is monitored every 8 days in different

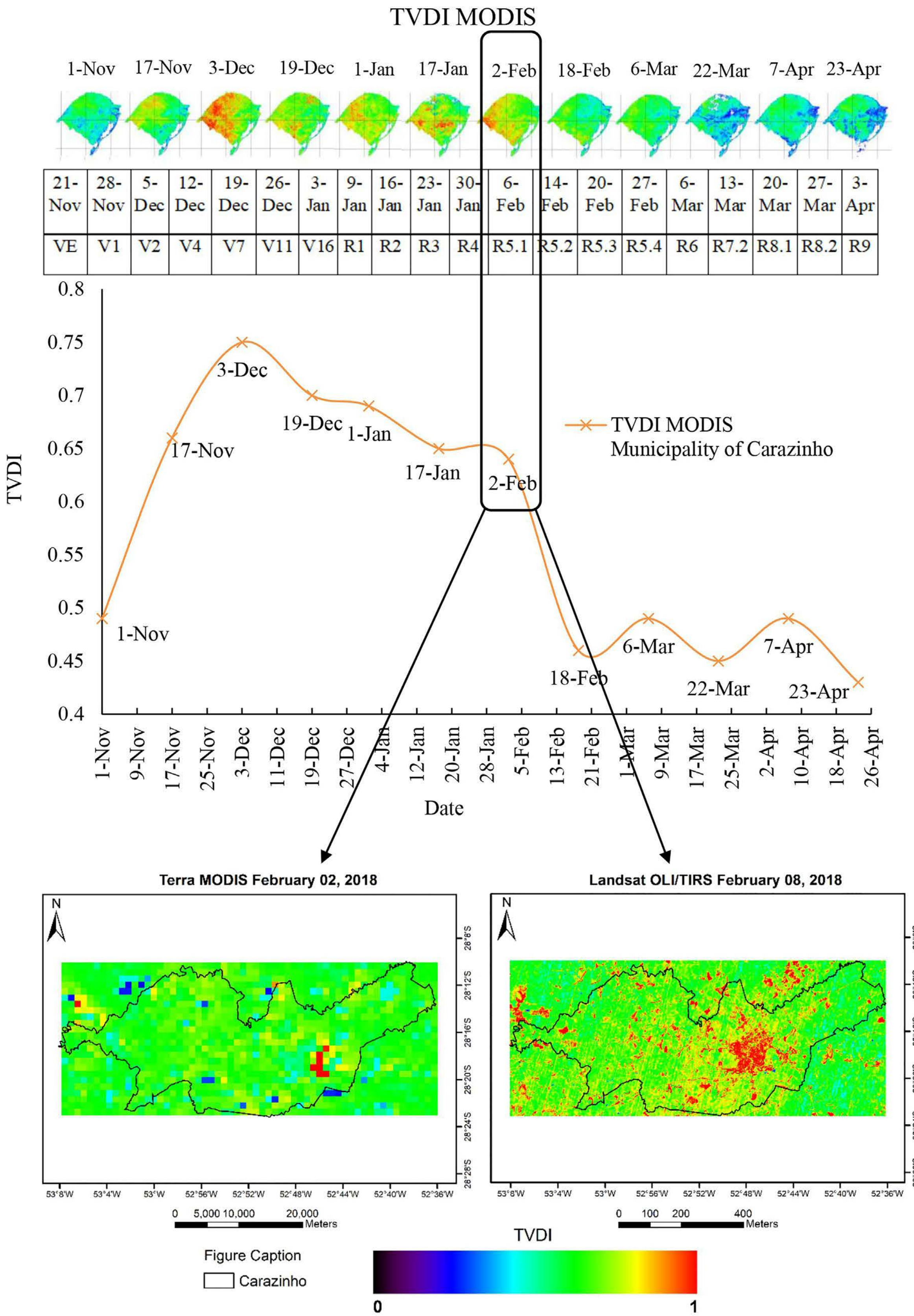

Figure 6 - Operating scheme of a monitoring system: $TVDI_{\mathrm{MODIS}}$ images for the RS State, the phenological scale of the crop and $TVDI_{\mathrm{MODIS}}$ profile for the municipality of Carazinho-Mun. Image detail $TVDI_{\mathrm{MODIS}}$-Mun for Feb 02 and $TVDI_{\mathrm{OLI/TIRS}}$-Mun for Feb 08.

regions within RS so that the critical period could be identified. By opting for orbital data only, *NDVI* can be used to estimate phenology (Fontana *et al.*, 2015) and define critical periods.

A third component is spatial detailing during the critical period, using $TVDI_{\mathrm{OLI/TIRS}}$ product. In the crop under review, the critical date was February 2, when high *TVDI* values, R5.2 stage (critical), and OLI/TIRS image availability occurred simultaneously. On this date, by expanding the municipality of Carazinho, we could understand the importance of using the sensors together. In $TVDI_{\mathrm{MODIS}}$, spatial resolution enabled us to detect a homogenization of values (predominance of green tones and some yellow dots). Yet in $TVDI_{\mathrm{OLI/TIRS}}$, *TVDI* spatial distribution could be seen with a greater distinction between plots, thus identifying areas with greater water deficits (in red).

The original proposal for a monitoring system still lacks studies and analyses to define *TVDI* thresholds able to identify critical water conditions and moments for soybeans and thus define a methodology for locating and classifying risk areas. Another aspect to be considered is that the evaporative triangle in these operating systems could be adjusted using different growing season, with extremely good or bad water conditions. Thus, an evaporative triangle characteristic of the production region could be obtained, which could be suitable for any growing season and in real-time. Such a feature is fundamental in operational agricultural monitoring since, as highlighted by Massignam *et al.* (2016) and Sivakumar (2016), when specific and appropriate to the characterization of limiting factors for a given crop, the products of these systems generate information both for agrometeorological planning and real-time monitoring, which is the case of *TVDI* for soybeans in the RS State.

In addition to using *TVDI* for monitoring, its continuous series of several years could also allow analyzing risk related to moisture factor statistically. Although other indexes have been used for this purpose, for example, the Water Need Satisfaction Index (ISNA in Portuguese) (Cunha *et al.*, 2001), *TVDI* has the advantage of generating risk data with high spatial detail, which is impracticable using data from weather stations.

4. Conclusions

Evaporative triangles adjusted using OLI/TIRS and MODIS sensor data show similarities, but with differences in magnitude for parameters defining the dry and wet limits, which are associated with radiometric, spectral, spatial, and temporal resolution.

TVDI index data obtained from surface and orbital sensors were coherent and complementary between them for spatial and time information.

As *TVDI* proved to be robust and there was coherence between data from the different sensors tested, the combined use of these sensors enables a proposal for an agricultural monitoring system. The main feature of the system is continuous monitoring of moisture in large production regions, using $TVDI_{\mathrm{MODIS}}$ and detailing of surface moisture spatial distribution using $TVDI_{\mathrm{OLI/TIRS}}$ for soybean phenological phases critical to water deficit.

Acknowledgments

This study was carried out with the support of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Financing Code n° 001 and by the Embrapa Trigo, through the SEG project. 02.15.07.003.00.00. The team also thanks to the employees of the Embrapa Trigo, Elisson S.S. Pauletti and Cristian M. Plentz, who helped in conducting the experiment and data collection, and the Granja Capão Alto for the partnership in the work.

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