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TVDI as an indicator of water status in spring-summer crops in Rio Grande do Sul State, Brazil

Lucimara Wolfarth Schirmbeck[1(*)], Denise Cybis Fontana[1,2] and Juliano Schirmbeck[1]

[1]Universidade Federal do Rio Grande do Sul, Programa de Pós-Graduação em Sensoriamento Remoto – PPGSR, Centro Estadual de Pesquisa em Sensoriamento Remoto e Meteorologia – CEPSRM, Av. Bento Gonçalves, 9500 – Campus do Vale– Caixa Postal: 15044, CEP 91501-970 Porto Alegre, RS, Brazil. E-mail: lucimaraws@gmail.com and schirmbeck.j@gmail.com

[2]Universidade Federal do Rio Grande do Sul, Faculdade de Agronomia, Departamento de Plantas Forrageiras e Agrometeorologia, Av. Bento Gonçalves, 7712, Agronomia, Caixa-postal: 15100, CEP 91540-000 Porto Alegre, RS, Brazil. E-mail: dfontana@ufrgs.br

[(*)]Corresponding author

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ABSTRACT

This work aimed at evaluating the TVDI (Temperature-Vegetation Dryness Index) as an indicator of water status and characterizing water spatial and temporal variability for the spring-summer crops in Rio Grande do Sul. For this purpose, the surface temperature MODIS products (MOD11A2) and vegetation index (MOD13A2) with spatial resolution of 1,000 m and temporal resolution of 8 and 16 days, respectively, were used to obtain the TVDI. Data from meteorological stations were also used to determine the water balance. The period of analysis corresponded to the spring-summer crops of 2011-12, 2012-13, 2013-14, 2014-15 and 2015-16. The results show that the TVDI is a good indicator of water surface status and represented well the water deficit occurrence in the spring-summer crops. The spatial and temporal resolution of the images used to calculate the index allowed obtaining reliable data, both during the development cycle and between Ecoclimatic Regions. These characteristics show that TVDI can be used as an indicator of water status and can, therefore, be part of the agrometeorological monitoring programs in Rio Grande do Sul.

Introduction

The responsible management of water resources is essential for several branches of activities and is closely related to the sustainability of ecosystems. In the agricultural sector, water availability is crucial because it defines the accumulation rate of biomass that is transformed into either grain or fruit production and even to support animal weight gain.

The subtropical climate of Rio Grande do Sul, the amount and distribution of water supplied to the crop impose an upper limit to soybean yield, explaining an important part of the interannual yield variations (Zanon et al., 2016). In the state, soy crops occupy the largest cultivation area and are responsible for the highest production volume, followed by irrigated rice and maize crops. The highest water consumption of soybean crops is about 7.5 mm.day^{-1} and occurs in February and March, during the period of greatest biomass accumulation, the flowering and grain formation (Matzenauer et al., 2002). Therefore, this "critical" period for the soy crop regarding lack of water is when grain yield is defined and knowledge on water availability has been used to elaborate crop forecasting models (Krüger et al. 2007; Melo et al., 2008).

In Rio Grande do Sul, the average yield of soybean crops is about 2,500 kg.ha^{-1} (average from 2011 to 2015 crop-seasons - IBGE, 2016), mostly without irrigation. The average yields in the state are lower than the experimental values, indicating a possibility of increasing yields by adjusting management practices and improving adaptation to the climate (Zanon et al., 2016). The state average yields are also lower than the values obtained in the Brazilian Midwest, where Mato Grosso state, the largest soy producer in Brazil, reports average yields higher than 3,000 kg.ha^{-1} (average for the same period). The total annual rainfall (about 1,500 mm) is similar in both states, but with significantly different distribution. In the Brazilian Midwest, the soybean cultivation period coincides with the rainy season, when most of the annual precipitation occurs. However, in Rio Grande do Sul, water for the crop is frequently undersupplied during summer (Matzenauer et al., 2002) since the annual total rainfall is evenly distributed throughout the year (Matzenauer et al., 2011). In this context, Berlato & Fontana (1999) stated that rainfall is the fundamental meteorological element defining soybean yields. Despite the importance of knowing water conditions in agricultural production areas, there are difficulties in determining them with adequate spatial and temporal representation.

Remote sensing techniques appear as viable possibilities for supporting sustainable water management. The vegetation indices seem to be an appropriate tool to study the dynamics of agricultural crops and characterize their water status. The MODerate Resolution Imaging Spectroradiometer (MODIS) sensor provides several free products with high processing levels. The Normalized Difference Vegetation Index (NDVI) and Surface Temperature (T_S) data stand out as tools used for determining the water status of the vegetation on the surface.

These two datasets can be used to calculate another index, known as TVDI (Temperature-Vegetation Dryness Index) widely used to estimate soil moisture and water availability on a regional scale in several regions of the globe (Sandholt et al., 2002; Chen et al., 2011; Son et al., 2012; Gao et al., 2011; Holzman et al., 2014). However, the use of this index is still incipient in Rio Grande do Sul. Among the few studies available, Schirmbeck et al. (2016) verified that TVDI has a consistent vegetation response to water availability in the state, but emphasizes the need for further studies to understand better this index and its limitations. In this context, the present study aimed to evaluate the TVDI as an indicator of the water condition for spring-summer crops and to characterize its spatial and temporal variability as incorporate it into the monitoring programs in Rio Grande do Sul.

Material and Methods

The study area was the Rio Grande do Sul state, and the analyses were done regionally according to the eleven Ecoclimatic Regions (Figure 1). The daily meteorological data of the 2011-12 to 2015-16 crop-season years were obtained from thirteen stations (Figure 1) that belong to the National Institute of Meteorology (Instituto Nacional de Metereologia, INMET). The average air temperature, rainfall, insolation, relative humidity and wind speed data are available at the Meteorological Database for Teaching and Research (BDMEP, 2016).

The meteorological data were organized in 16-day periods, making them compatible with the data from the MODIS images. Evapotranspiration was calculated by the Penman-Monteith method (Allen et al., 1998) and, further, the meteorological water balance (Thornthwaite & Mather, 1955) was determined for a 75 mm water storage capacity of the soil. The study period covered spring-summer months, from November to May of the 2011-12, 2012-13, 2013-14, 2014-15 and 2015-16 seasons, according to the available meteorological data for each season (Table 1). The accumulated water deficit was plotted as a bar chart for each meteorological season and crop-season and used to characterize the water status.

The analyses used the data originating from the orbital images of the MODIS (MODerate Resolution Imaging Spectroradiometer) sensor on board the Terra satellite. Among several products, it offers the surface temperature (T_S) from the MOD11A2, and the NDVI from the MOD13A2, with 1,000 m spatial resolution corresponding to compositions of 8 and 16-day periods, respectively. To cover the study area, the products for the tiles h13v11 and h13v12 were downloaded from the database of the Land Processes - Distributed Active Archive Center (LP DAAC, 2016) and transformed from sinusoidal projection to WGS 84 geographical coordinates, from which the study area was cutout.

TVDI, the indicator evaluated in this study, is based on the characteristic triangular dispersion between T_S and NDVI (Figure 2). The upper and lower limits of this dispersion are used to normalize the model, considering that the model provides a stress index between 0 and 1 for each image. The opposite sides of this triangle correspond to the exposed soil (low NDVI and high T_S) and total vegetation cover (high NDVI and low T_S). Under partial coverage conditions, the lower the T_S, the more adequate is the water status and, therefore, the lower the TVDI index.

The slope of the linear regression line between T_S and NDVI characterizes the degree of deficiency, given the negative relationship between these two parameters, according to several studies (Wang et al., 2007, Holzman et

Figure 1. Map of the study area highlighting the used meteorological stations and the Ecoclimatic Regions of Rio Grande do Sul.

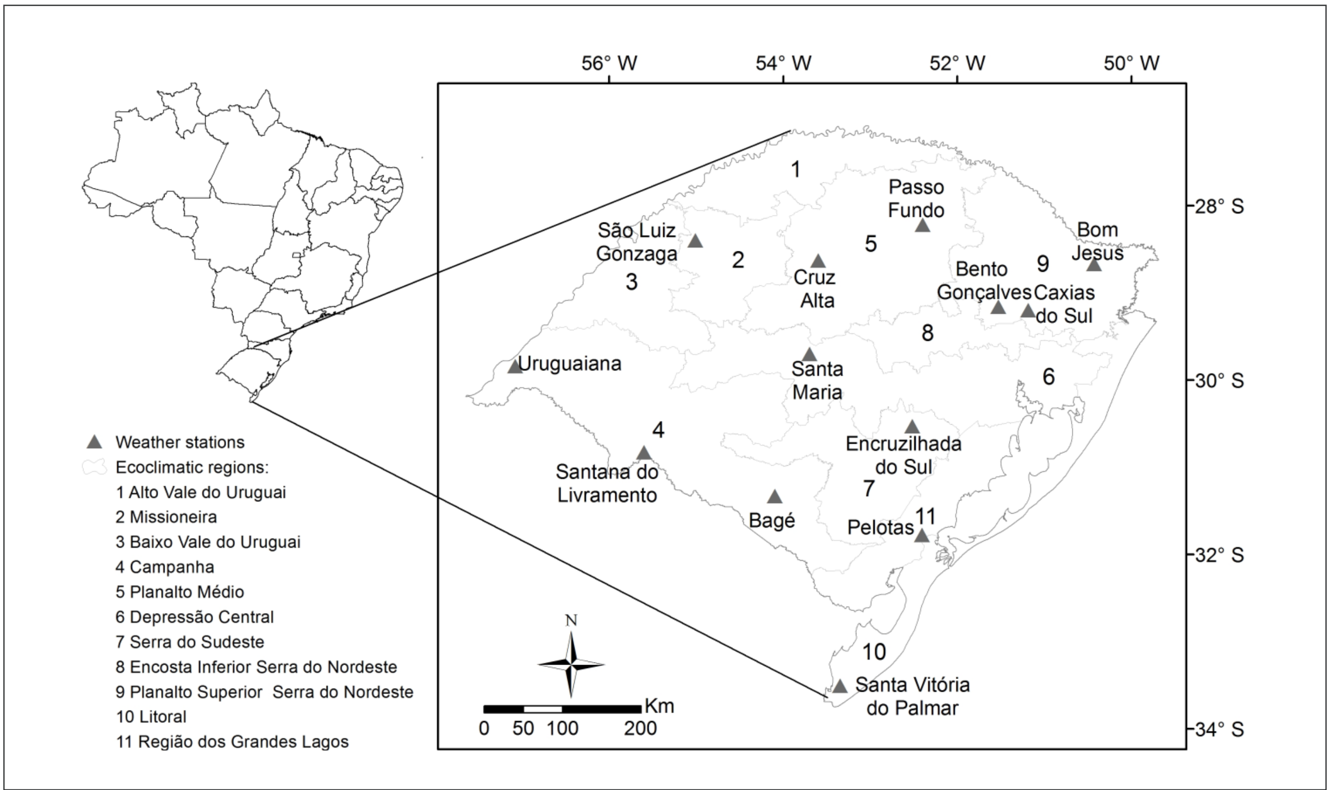


Table 1. Geographic coordinates of the meteorological stations, indicating the availability of data used in each crop.

Weather station	Lat (°)	Long (°)	Alt (m)	2011-12	2012-13	2013-14	2014-15	2015-16
Bagé	-31.33	-54.10	242.31	x	x	x	x	x
Bento Gonçalves	-29.15	-51.51	640.00	x	x			
Bom Jesus	-28.66	-50.43	1047.50	x	x	x	x	x
Caxias do Sul	-29.16	-51.20	759.60	x	x	x	x	x
Cruz Alta	-28.63	-53.60	472.50	x	x	x	x	
Encruzilhada do Sul	-30.53	-52.51	427.75	x	x	x		
Passo Fundo	-28.21	-52.40	684.05	x	x	x	x	x
Pelotas	-31.78	-52.41	13.00	x		x		
Santa Maria	-29.7	-53.70	95.00	x	x	x	x	x
Santa Vitória do Palmar	-33.51	-53.35	24.01	x	x	x		
Santana do Livramento	-30.83	-55.60	328.00	x	x			
São Luiz Gonzaga	-28.4	-55.01	245.11	x	x	x	x	x
Uruguaiana	-29.75	-57.08	62.31	x	x	x	x	x

al., 2014).

The TVDI was calculated by Equation 1, proposed by Sandholt et al. (2002):

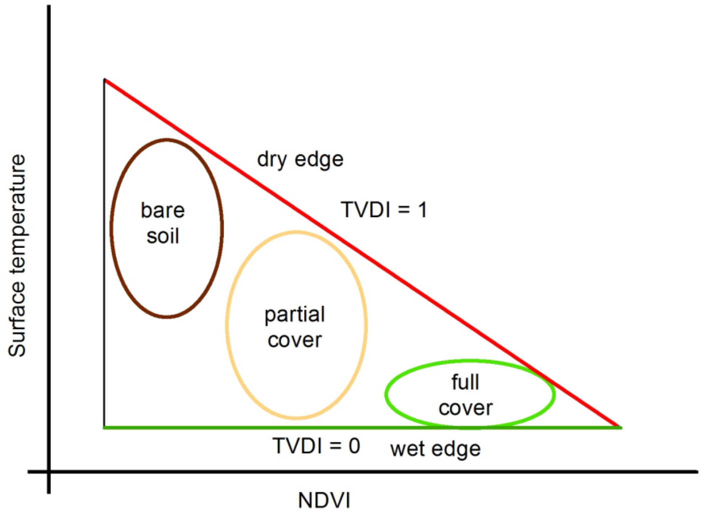
$TVDI = (T_s - T_s min) / (a + b * NDVI - T_s min)$ (1)

Where: T_s is the radiative temperature of the pixel (K); $T_s min$ is the minimum surface temperature (K) corresponding to the wet limit of the evaporative triangle (Figure 2 - green line); "a" and "b" are the linear and angular coefficients of the straight line representing the dry boundary.

This study was parameterized by crop-season, a single evaporative triangle for all the analyzed crop-seasons, since this approach is apt to represent the moment and frequency of water restriction events over time (Schirmbeck et al., 2016). The TVDI index was, therefore, used to characterize the water conditions prevailing in each crop for each Ecoclimatic Regions of the state. Graphs of the accumulated TVDI values and temporal profiles during crop-season were analyzed against the data on water deficits recorded in the surface meteorological stations.

Finally, a case study showing the images and frequency histograms of NDVI, T_s and TVDI values for the soybean and rice crops with the greatest water restriction was carried out for two distinct times of the crop cycle, crop implantation generally in October and maximum green biomass usually in February.

Figure 2. Schematic representation of the Evaporative Triangle, given by the relationship between surface temperature (T_S) and the normalized difference vegetation index (NDVI). Source: Adapted from Sandholt et al. (2002).



Results and Discussion

The crops of 2011-12, 2012-13, 2013-14, 2014-15 and 2015-16 (Figure 3) analyzed in this study characterized the water status in Rio Grande do Sul very well, showing high interannual variability that reflects on the highly variable grain yield obtained in the state (Berlato & Fontana, 1999). Among the analyzed crop-seasons, the 2011-12 season showed the greatest deficits for most meteorological stations. The water deficit was higher than 600 mm accumulated in the spring-summer period when the largest soybean crop develops (October to May). In contrast, the 2015-16 crop had the lowest deficit (less than 200 mm) while other years had intermediate water conditions. This high variability pattern between crops requires good indicators of the water status so they can be incorporated into crop monitoring systems in large production regions.

It is noteworthy that the water deficit in all analyzed crop-seasons occurred mainly in January and February when due to the subtropical climate prevailing in the state, the evaporative demand of the atmosphere is higher and often exceeds the water supplied by rainfall. The coincidence between water constraints and critical periods of crops is vital for defining grain yield (Cunha et al., 2001), the temporal characteristic of the sought indicator is important, i.e. the indicator should be able to provide continuous periodical information on water status throughout the development cycle of the spring-summer crops.

All analyzed crop-seasons showed important water status differences among the different sites, evidencing that the sought indicator should not only have the previously mentioned characteristics but also be able to provide an adequate spatial detail of the water status over the entire state area.

The water status indicated by the meteorological water balance (Figure 3), calculated from the surface meteorological stations, was coherent with the TVDI (Figure 4) obtained from the MODIS images. The accumulated TVDI values (Figure 4a) were higher in the 2011-12 season (8.58), lower in 2015-16 (7.25) and intermediate in the other seasons. Recalling that TVDI values are being accumulated throughout/over the images, and the index varies from 0 to 1 on each date; high TVDI (TVDI = 1) indicates water restriction while low TVDI (TVDI = 0) indicates favorable water condition. It should also be noted that the data from meteorological stations represent the information of the area near the measuring point while the data of the images are generated in a regular grid that covers an entire region of interest. This fact represents an important advantage of using orbital images derived indicators. In the case of TVDI obtained from MODIS images, the regular grid is 1x1 km, totaling more than 280,000 points in Rio Grande do Sul.

The continuous monitoring of water status throughout the crop-season, obtained from the average TDVI profile every 16 days, can be evaluated in Figure 4b. These temporal profiles allow relating the current water condition with crop susceptibility to water restrictions (critical periods). In soybean crop, the critical periods include especially flowering and grain filling (Farias et al., 2009). For most crop-seasons, the TVDI was higher in the period of maximum vegetative growth, associated with the beginning of the flowering, which occurs more frequently in January (Fontana et al., 2015), Julian days (JD) 1 and 17. However, noticeable differences were observed between crop-seasons during this period and high variability between dates in the same crop-season. Detecting these differences is essential, from the understanding of the variable water conditions, to model grain yield (Melo et al., 2008) or elaborate climatic risk zoning (Cunha et al., 2001).

The mean TVDI values ranged from 0.3 to 0.5 when establishing the crop, between 0.6 and 0.8 during high veg-

Figure 3. Accumulated water deficit measured by the meteorological stations in different Ecoclimatic Regions of Rio Grande do Sul, period (October to May) of 2011-12 to 2015-16 crop-seasons.

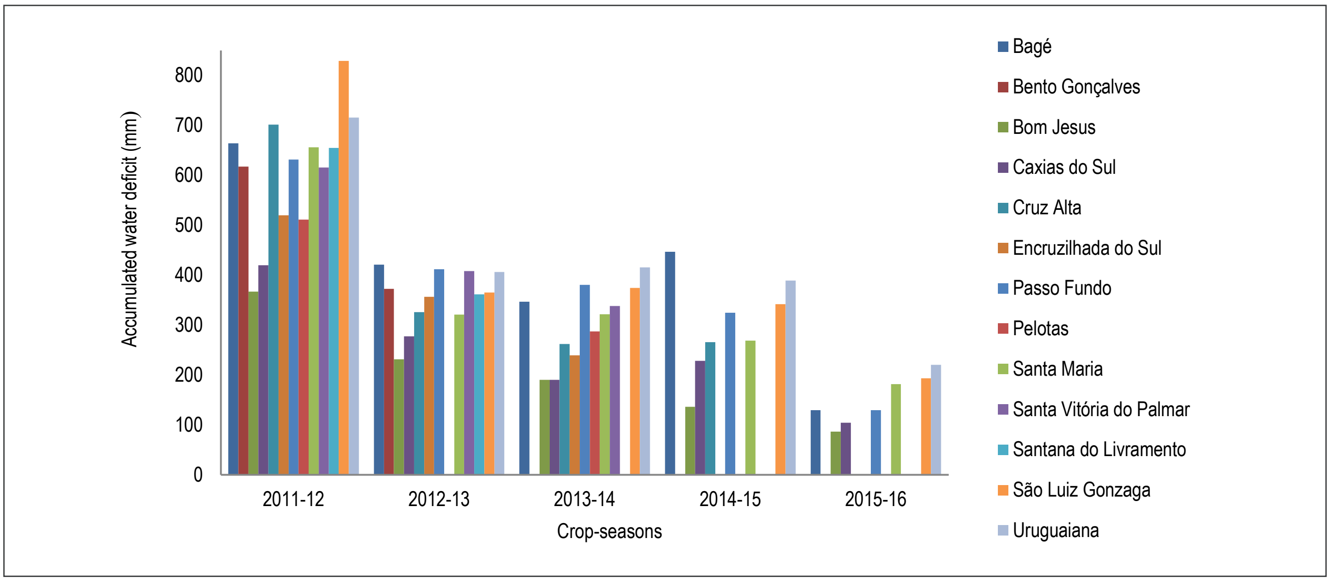
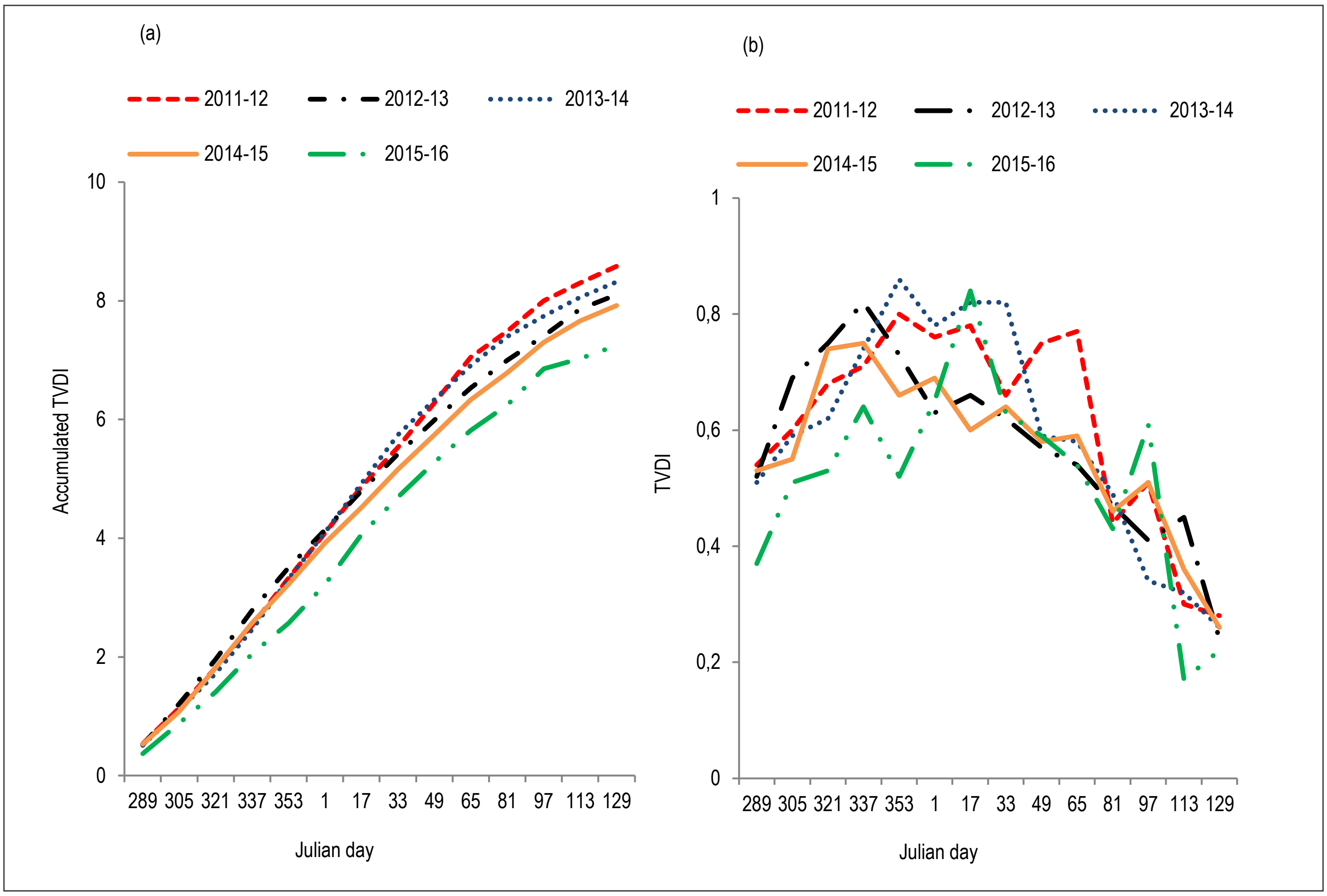


Figure 4. TVDI profile for Rio Grande do Sul in the 2011-12, 2012-13, 2013-14, 2014-15 and 2015-16 crops. (a) accumulated TDVI profile of each crop; (b) TDVI profile during each crop-season.



etative development, and between 0.2 and 0.3 at the end of the cycle. Therefore, a lower TVDI trend was observed at the beginning and end of the crop cycle, as well as a smaller index difference between crop-seasons. The lower TVDI values result from lower NDVI values, associated with low biomass at the beginning and end of the cycle of annual spring-summer crops (Santos et al., 2014), and on the other hand, to high T_s associated with the lower soil cover during crop establishment and senescence and crop-season periods at the end of the cycle.

In the 2011-12 crop-season, the TDVI values were higher during a longer period of time while the data/crop analysis showed that the values were never lower than 0.5 over the entire cycle, indicating a more persistent unfa-

Table 2. Mean and coefficient of variation of the TVDI for the Ecoclimatic Regions of Rio Grande do Sul in the 2011-12, 2012-13, 2013-14, 2014-15 and 2015-16 crop-seasons, from November to May.

	2011-12	2012-13	2013-14	2014-15	2015-16	Average
Litoral	0.460	0.470	0.470	0.460	0.410	0.454
Grandes Lagoas region	0.520	0.530	0.550	0.530	0.460	0.518
Plan. Sup.Serra do Nordeste	0.550	0.530	0.530	0.510	0.490	0.522
Enc. Inf. Serra do Nordeste	0.590	0.570	0.590	0.560	0.490	0.560
Serra do Sudeste	0.580	0.560	0.580	0.570	0.510	0.560
Depressão Central	0.620	0.580	0.610	0.570	0.510	0.578
Campanha	0.640	0.600	0.620	0.600	0.540	0.600
Planalto Médio	0.660	0.620	0.620	0.580	0.560	0.608
Alto Vale do Uruguai	0.690	0.630	0.640	0.610	0.590	0.632
Baixo Vale do Uruguai	0.700	0.630	0.670	0.620	0.570	0.638
Missioneira	0.740	0.670	0.690	0.650	0.600	0.670
Average	**0.614**	**0.581**	**0.597**	**0.569**	**0.521**	**0.576**
CV (%)	**13.7**	**9.8**	**10.6**	**9.4**	**11.1**	**10.8**

vorable water condition (consistent with the highest accumulated values). It was also verified that especially in the second half of January, in February and early March, a critical period for defining grain yield (Cunha et al., 2001), TVDI was higher, with mean values between 0.66 and 0.78. In 2015-16, when the lowest deficits occurred, TVDI was lower most of the time compared to the other studied crop-seasons, ranging from 0.52 to 0.64 from December until the first half of March, TVDI (0.84) was high only at the end of the crop-season.

In the state, TVDI spatial variability can also be evaluated by the average index of each Ecoclimatic Region (Figure 1 and Table 2). The average of all regions shows that the highest mean TVDI and variability (Mean = 0.614 and CV = 13.7%) was observed in the 2011-12 crop-season. The regions with the highest average TVDI over the five crop-seasons were in the southwestern region of the state: Missioneira, Baixo and Alto Vale of Uruguay, Planalto Medio and Campanha. Especially in the southwestern, lower rainfall, higher temperatures, and soils with lower capacity for water retention result more frequently in unfavorable water status. The Depressao Central region had an intermediate pattern, marking the transition to regions with the highest TVDIs, located near the ocean (Litoral and Grandes Lagoas Region) and higher altitude areas (Planalto Superior da Serra do Sudeste, Encosta Inferior da Serra do Nordeste and Serra do Sudeste). Both climatic factors, greater proximity to water bodies and higher altitude, are associated with lower evaporative demand from the atmosphere and higher rainfall which, in general, favor water conditions.

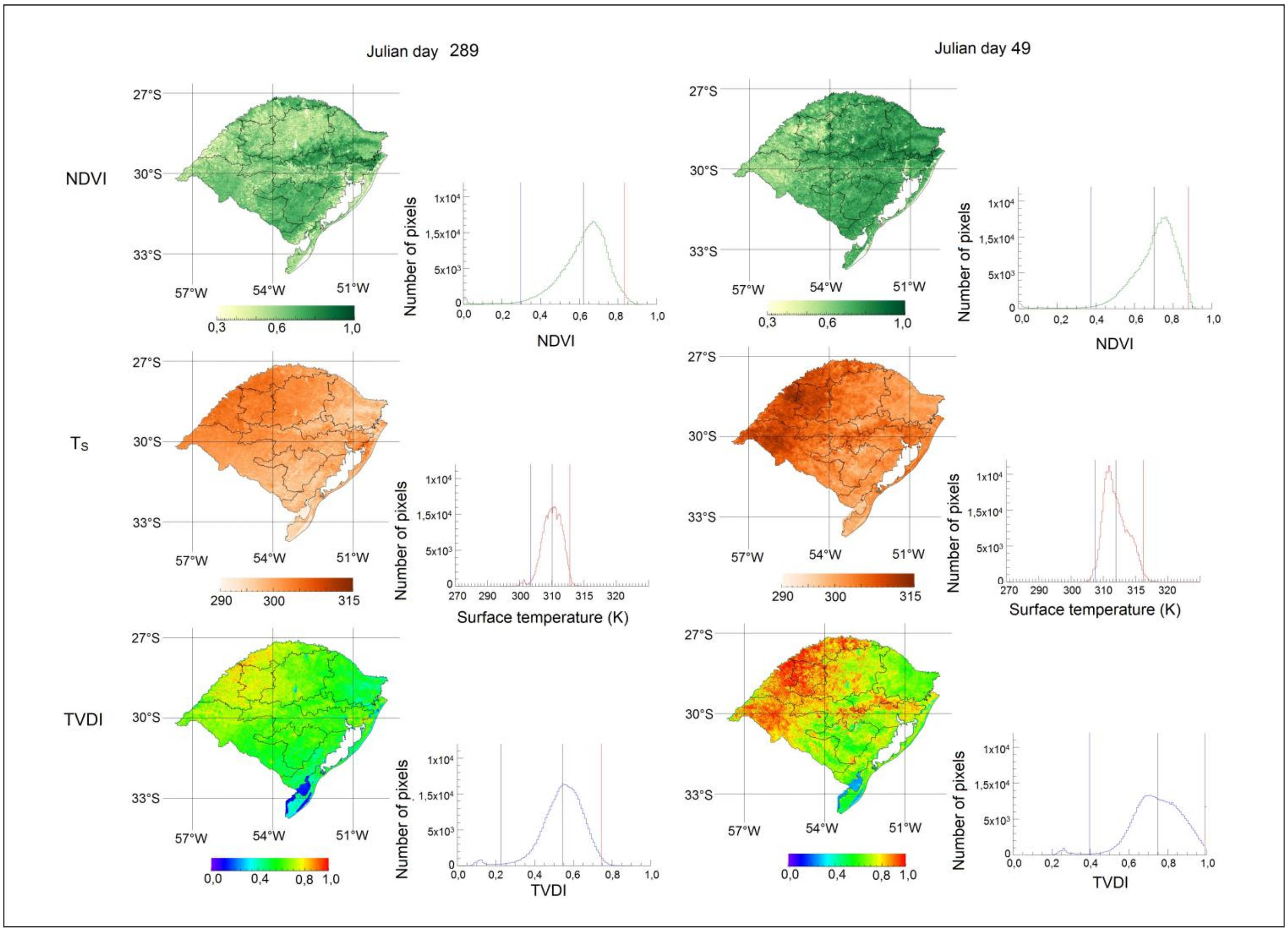
In terms of annual spring-summer crop production, the largest areas without irrigation, especially soybeans, are concentrated exactly in regions where average TVDIs are the highest (Planalto Médio, Missioneira, and Baixo and Alto Vale do Uruguay). More than 65% of the 4.3 million hectares of soybean planted in Rio Grande do Sul (last 10 years average - IBGE, 2016) are concentrated in these regions, being highly dependent on favorable water status to obtain high yields. Therefore, especially in this large producing region, TVDI can be extremely useful and contribute to planning and risk management, and real-time monitoring of agricultural activity.

In the Litoral and Grandes Lagoas regions, the predominant crop is rice, which is produced with flood irrigation in Rio Grande do Sul. The TVDI had lower pattern and values for an irrigated rice-producing region since the water supply of the springs is vital for the cultivation, but in general, higher availability of solar radiation and lower rainfall favor higher yields (Klering et al., 2016).

In the southern portion of the state, the Campanha and Serra do Sudeste regions, animal production is more relevant, especially cattle and sheep, whose food base are the natural fields of the Pampa Biome. The forage supply to the animals varies greatly throughout the year since it is highly dependent on the thermal and water conditions (Wagner, 2013). The TVDI can indicate favorable or unfavorable situation for animal weight gain, leading to management actions that are more appropriate.

Figure 5 shows the NDVI, T_S and TVDI images for the crop that presented the highest water deficit (2011-12) for two different moments of the cycle, at the beginning (JD 289 - 10/16/2011) and in the greater development period (JD 49 - 02/18/2012) of the spring-summer crops. These images show high spatial (over the state area) and temporal (Table 2) variability. It should be highlighted that the comparisons of TVDI between dates are only possible when the parameterization is done by crop-season, i.e., taking into account extreme conditions for establishing the dry and humid seasonal limits, as proposed by Schirmbeck (2016).

Figure 5. Spatial distribution and histograms of NDVI, TS, and TVDI on two dates (10/16/2011- JD 289 and 02/18/2012 - JD 49). Rio Grande do Sul.



This was observed in the present analysis.

In the state, the average NDVI was 0.62 on JD 289 (October – crop establishment), lower than the 0.70 on JD 49 (February - high vegetative development), and the histogram was more asymmetric toward the high values. On the first date, the index was especially lower in regions where agriculture occupied the largest area (Ecoclimatic Regions of the Planalto Médio, Missioneira, Campanha, Depressão Central and Grandes Lagoas), associated to the preferential establishment period of spring-summer crops. In these areas, the spatial distribution of temperature showed higher values than the rest of the state. Lower NDVI and higher T_s resulted in higher TVDI in northwestern Rio Grande do Sul.

In this same region, a substantial change is observed on JD 49 (February - high vegetative development). Again, this was the portion of the state that presented the highest TDVI values, but now with values much higher than those verified on the previous date, contrasting even more with the rest of the state. The unfavorable water status at this time was associated with high tem p eratures and lower green biomass in the northwest.

Conclusions

The TVDI is an indicator of the water status on the surface able to show the occurrence of water deficiencies estimated by the water balance in spring-summer crops, such as soybean, rice. Given the spatial and temporal resolution characteristics of the images used to calculate the index, it is possible to obtain reliable data both during the development cycle and among the RS Ecoclimatic Regions. These characteristics allow using the TDVI as an indicator of the water status in the monitoring agrometeorological programs in Rio Grande do Sul.

Acknowledgements

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Índice de umidade do solo TVDI como indicador da condição hídrica em culturas de primavera-verão no Rio Grande do Sul

Lucimara Wolfarth Schirmbeck[1(*)], Denise Cybis Fontana[1,2] e Juliano Schirmbeck[1]

[1]Universidade Federal do Rio Grande do Sul, Programa de Pós-Graduação em Sensoriamento Remoto – PPGSR, Centro Estadual de Pesquisa em Sensoriamento Remoto e Meteorologia – CEPSRM, Av. Bento Gonçalves, 9500 – Campus do Vale– Caixa Postal: 15044, CEP 91501-970 Porto Alegre, RS. E-mail: lucimaraws@gmail.com e schirmbeck.j@gmail.com

[2]Universidade Federal do Rio Grande do Sul, Faculdade de Agronomia, Departamento de Plantas Forrageiras e Agrometeorologia, Av. Bento Gonçalves, 7712, Agronomia, Caixa-postal: 15100, CEP 91540-000 Porto Alegre, RS. E-mail: dfontana@ufrgs.br

[(*)]Autor para correspondência

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RESUMO

Este trabalho teve como objetivo avaliar o índice de umidade do solo TVDI como um indicador da condição hídrica para culturas de primavera-verão e caracterizar sua variabilidade espacial e temporal no Estado do Rio Grande do Sul. Foram utilizados os produtos MODIS de temperatura de superfície (MOD11A2) e de índice de vegetação (MOD13A2) com resolução espacial de 1.000 m e temporal de 8 e 16 dias, respectivamente, para a obtenção do TVDI (do inglês *Temperature-Vegetation Dryness Index*). Também foram utilizados dados de estações meteorológicas de superfície para cálculo do balanço hídrico. O período de análise correspondeu às safras primavera-verão para as culturas da soja e do arroz de 2011-12, 2012-13,2013-14, 2014-15 e 2015-16. Os resultados mostraram que o TVDI é um indicador da condição hídrica da superfície, capaz de representar a ocorrência de deficiências hídricas destas culturas indicadas pelo balanço hídrico. Dadas às características de resolução espacial e temporal das imagens utilizadas no cálculo do índice, é possível obter dados confiáveis, tanto ao longo do ciclo de desenvolvimento, como entre as Regiões Ecoclimáticas. Estas características fazem com que o TDVI possa ser utilizado como indicador da condição hídrica compondo programas de monitoramento agrometeorológico no Estado do Rio Grande do Sul.

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