

Spatial crop yield estimation based on remotely sensed stress index

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Abstract. The improvement of methods to evaluate the real impact of soil moisture availability on crop systems is crucial because the importance for world economy and food production. The relationship between the remote sensed stress index TVDI, root-zone soil moisture and soybean yield was analyzed in a sandy region of Argentine Pampas. High correlation ($R^2=0.68$) between TVDI and soybean yield was observed. The obtained adjustment allows us to evaluate the spatial variability of yield during a humid and dry period 2-3 months before harvest. Since the method requires remote sensed data, it could be applied over areas with poor data coverage.

Keywords: stress index, soil moisture, remote sensing.

1 Introduction

The impact of climate variability on natural and productive systems motivates the development of tools and strategies for mitigation and adaptation of subsequent consequences for populations and the economy. Although global mean climate conditions could be projected with certain level of accuracy, the improvement of methods to evaluate the real impact on water-soil-vegetation systems is crucial because the importance for world economy and food production. In relation to agricultural systems, soil moisture is an essential variable governing the fluctuations of rainfed crop yield. Given the spatial changes of such variable and the difficulty of obtaining large-scale measurements of soil moisture using ground-based networks, several works have been dedicated to develop remote sensing techniques for soil wetness condition retrieving.

Basically, these techniques are based on the use of passive and active microwave [1,2] or optical and thermal information [3,4]. Retrievals based on microwave data directly estimate volumetric water content using the dielectric difference between soil and water, but they can sense the surface soil layer (0-10 cm). On the other hand, optical-thermal techniques can indirectly infer root-zone soil moisture based on the effects of soil water availability for plants on photosynthetic systems and that such water controls the partitioning of energy between latent (evapotranspiration) and sensible heat fluxes [5]. Thus, optical-thermal methods are more suitable to monitor hydrological process determining the crop yield, as vegetation can extract deep soil moisture.

Although several authors have analyzed the relationship between surface wetness condition and optical-thermal data [6,7,8,9], more attempts should aim at evaluating the relationship between estimates of water content in soil profile and crops yield. In this sense, recent works [4], [10] have shown the strong correlation between optical-thermal data combination, root-zone soil moisture and yield of different crops in Argentine Pampas. In [4], vegetation index (VI) and land surface temperature (LST) data were combined through the temperature vegetation dryness index (TVDI) [3] to analyze subsurface soil moisture over vegetated areas. They found strong correlation ($R^2>0.69$) between such index and soil moisture up to 120 cm depth. Also the authors showed that the potential of that stress index to sense subsurface soil moisture depends on root system depth and physical limitations of soil for root growth. In [10], the relationship between TVDI and crop yield was estimated for central-eastern areas of such region, with high coefficient of determination ($R^2>0.68$). Also, in that work a generalized model of yield-stress index was proposed.

Given the high correlation between subsurface soil moisture and TVDI, the aim of this work was to analyze the relationship between the TVDI and soybean in a sandy area of Argentine Pampas and evaluate its spatial variability during dry and wet periods.

2 Study area

The Argentine Pampas is the most productive rainfed region of Argentina, being one of the six most important producers of wheat, maize and soybean [11]. The climate is humid temperate, with an east-west rainfall gradient. The agro-climatic zone named Sandy Pampas was considered to evaluate TVDI-soybean yield relationship (Fig. 1). About climatic characteristics, the mean annual precipitation is more than 800 mm and the evapotranspiration is 800 mm, with eventual soil water deficits during summer. The dominant soil type is Udipsamment (predominant soil textures are sandy loam), whose main limitation for cropping is the low water retention capacity and organic matter of soils. The representative crop over this study area was soybean, covering approximately 30% of the area during the analyzed periods.

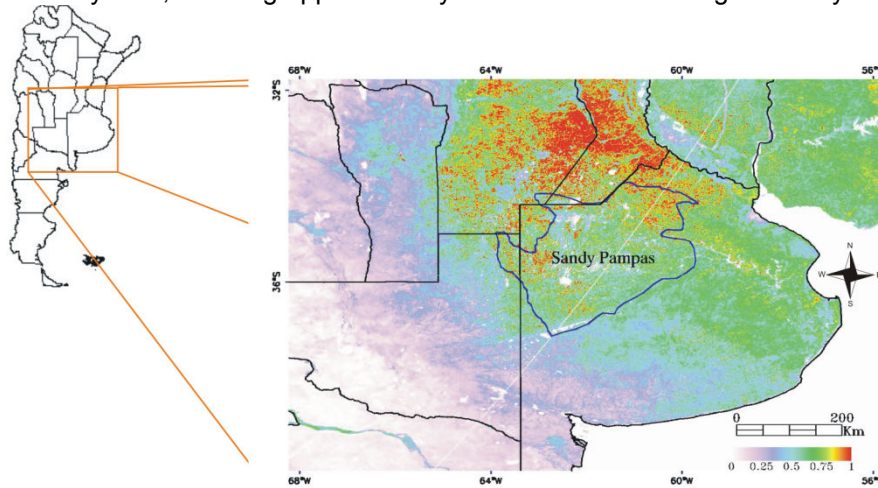


Fig. 1. Analyzed agro-climatic zone of Argentine Pampas over an EVI map of January 2003.

3 Methods

In bare soil and vegetated surfaces, soil moisture determines LST through evaporative control, thermal inertia and the amount of energy involved in the evapotranspiration process [8], with differences in radiative temperature between soil and canopy. Basically, decreases in soil moisture produce increases of LST, with decreasing VI in advanced stages of stress process. Thus, combination of LST and fractional vegetation viewed for the sensor through VI allows the estimation of short and long-term fluctuations in soil water availability from bare soil to full vegetated surfaces.

To obtain information of the soil moisture condition, VI and LST were combined through the TVDI equation [3]:

$$TVDI = \frac{LST - LST_{\min}}{LST_{\max} - LST_{\min}} \quad (1)$$

where LST is the observed surface temperature (in kelvin) at a given pixel, LST_{\min} is the minimum temperature of the image, $LST_{\max} = aVI + b$ is the maximum temperature for a given value of VI, a and b are surface parameters of the image, being LST_{\max} modelled as a linear fit to the data. The value of TVDI is 1 in pixels closed to LST_{\max} , indicating limited soil moisture availability and its value is 0 in pixels closed to along the wet edge, showing unlimited water access and maximum evapotranspiration.

MODIS AQUA 8-day composite surface temperature, level-3, version-5, 1 km (MYD11A25) and 16-day composite enhanced vegetation index (EVI) level-3, version-5, 1 km (MYD13A25) were processed to calculate the TVDI. The satellite data were acquired from NASA's Earth Observing System Data and Information System (<http://reverb.echo.nasa.gov/reverb>) in Sinusoidal projection and were processed with ENVI software and reprojected using MODIS conversion toolkit to Geographic Lat/Lon coordinates, Datum WGS-84.

LST and EVI images were averaged to obtain monthly data and thereafter monthly TVDI images. LST_{\max} and LST_{\min} were defined over semi-arid and humid zones of Argentine Pampas,

respectively, to obtain a correct definition of Eq. (1) parameters. The former edges were obtained using the least square method considering pixels with maximum LST for different EVI intervals, significance level of 5%. The latter ones were calculated averaging the pixels with minimum LST for different EVI intervals. Then, minimum LST_{min} and maximum LST_{max} were defined over the whole study period to obtain comparable TVDI values for the multitemporal analysis. Monthly TVDI images were obtained using these extremes parameters.

To test the methodology over a wide range of wetness conditions, images of summer 2002-2003 and 2007-2008 were analyzed as wet and dry study periods, respectively. Critical growth stage (flowering and grain filling) was considered to analyze TVDI/crop yield relationship, as it is the most decisive for most crops yield. Water stress and/or excess during this stage would result in reduced grain yield. For soybean this stage includes January and February in Sandy Pampas (ORA-MAGyP, <http://www.ora.gov.ar>). Inside this zone, crop cover areas of interest that included only cultivated surfaces were defined for each county. In this manner the effect of uncultivated areas on the TVDI signal was eliminated.

Prior to the TVDI/crop yield analysis, the TVDI/soil moisture relationship was tested daily in the study area. Ground-based soil moisture measurements were carried out daily in La Ydalina station (35°09' S, 61°07' W) from January 1st to February 27th, 2012. After cloudy observations removal, 25 daily data remained for the analysis. A tensiometer incorporated to a Davis Vantage Pro2 (Davis Instruments Corp.) station was used to measure SM at 60 cm and 120 cm depth. Thus, the soil water content in root zone was evaluated. The relative soil water content (%) was determined from tension measurements (centibars) by the moisture-characteristic curve, previously obtained. Finally, daily TVDI values of a crop patch of 3 km x 3 km were compared with soil moisture measurements.

Regarding crop yield data, official statistics of soybean ($kg\ ha^{-1}$) during the study period were obtained at county level from Statistics Argentina (Statistics Argentina, 2012). Yield data (dependent variable) were correlated with averaged TVDI (independent variable) of the cultivated areas in the following counties: Carlos Casares, Carlos Tejedor, Pellegrini. The robustness of the obtained adjustments to forecast crops grain yield was tested comparing estimated and observed yield on counties previously not considered: Gral. Viamonte, Tres Lomas, Bolivar. The validation was evaluated through the RMSE, bias and the index of agreement d [12].

4 Results and discussion

To test the TVDI/root zone soil moisture relationship, TVDI was compared with daily measurements in La Ydalina station (Fig. 2). The data show that the TVDI was sensitive to root zone soil water fluctuations, increasing with decrease in water availability. Linear relationship was found with R^2 values ranging from 0.69 to 0.76. These results are consistent with previous works using thermal and reflectance data in Argentine Pampas [10], which reported high correlation at 10 cm ($R^2=0.83$) and 20 cm ($R^2=0.61$) depth. In addition, the results show the aptitude of TVDI to sense wetness condition in the soil profile especially in areas where roots can explore deep soil horizons, like in sandy soils. That is, the reflective and thermal information sensed by TVDI is associated with transpiration of water in the root zone.

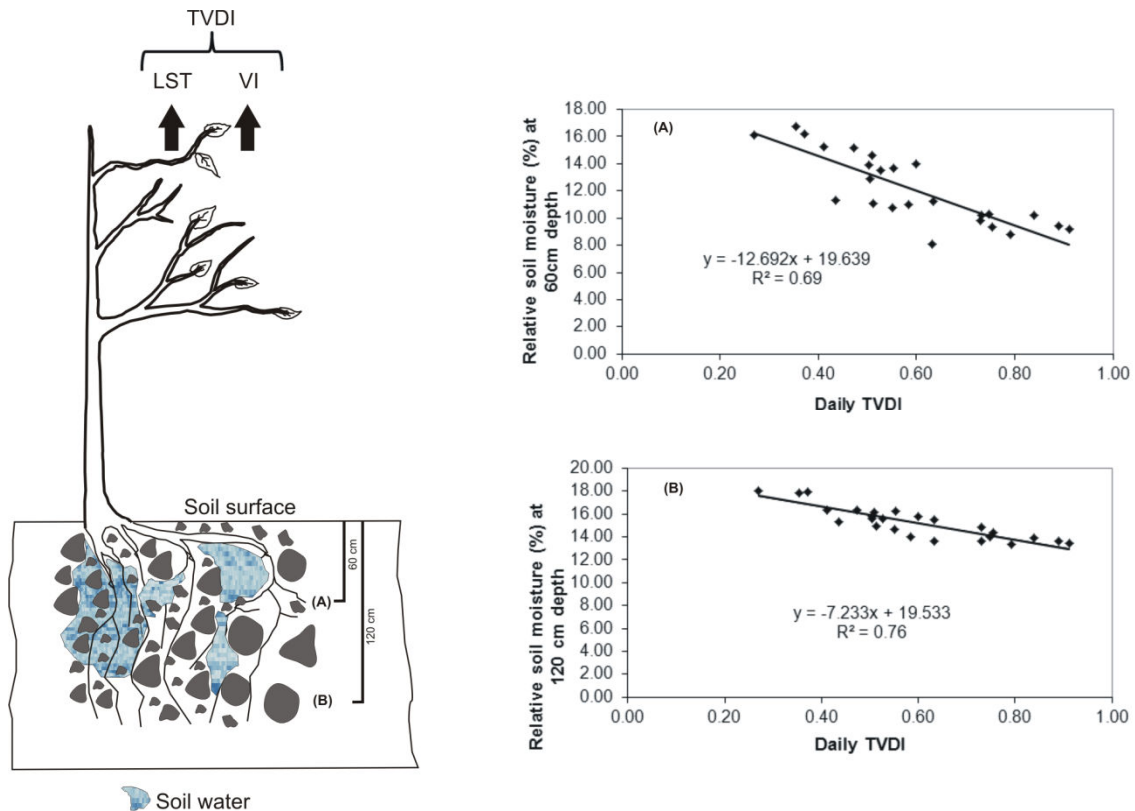


Fig. 2. Diagram of soil moisture measurements depths (left) and TVDI/root zone soil moisture relationship (right) in La Ydalina station (adapted from [10]).

After verifying the TVDI response to soil moisture variability, TVDI/soybean yield relationship was evaluated. Taking into account soybean yield data of Carlos Casares, Carlos Tejedor, Pellegrini counties, a linear correlation ($R^2=0.68$) was obtained:

$$\text{soybean yield}(\text{kg. ha}^{-1}) = -2036 \times \text{TVDI} + 4240 \quad (2)$$

where TVDI is the cumulative TVDI for soybean critical growth stage (January and February in the study area). These results indicate that TVDI is highly correlated with grain yield and that the adjustment can explain up to 68% of soybean crop yield variability. The linear correlation shows that soybean yield decreased with increased water stress. Decreases in crop productivity by water excess were not observed, probably because of the low water retention capacity of the soil. Little works have analyzed the relationship between LST, VI and soybean yield [13,14]. [13] found R^2 values ranged from 0.44 to 0.80 between soybean yield and NDVI in Canada. On the other hand, [14] reported linear adjustment ($r=0.78-0.92$) between LST, NDVI from MODIS, precipitation estimates and soybean yield in arid and humid areas of USA. These results reflect that LST and VI combination could provide more precise information about short and long term hydrological processes that affects crop grain yield that the traditional use of VI. For validation of the obtained adjustment, a comparison between satellite-derived and official statistics of soybean yield was performed. The obtained values were: $\text{RMSE}=376 \text{ kg. ha}^{-1}$ (13% of average yield), $\text{Bias}=216 \text{ kg. ha}^{-1}$ and $d=0.88$. The parameters of validation show that the developed model predicts well the yield, with a slight trend to underestimation. In addition, our results demonstrate that TVDI from MODIS was a suitable tool for early prediction of soybean crop yield with 2–3 months before harvest.

After crop yield model validation, maps of soybean yield for 2002-2003 and 2007-2008 were evaluated using the obtained adjustment (Fig. 3). A large spatial variability of yield was observed, depending on fluctuations of soil wetness. In general, low soybean yields are located in the western area, associated with low water availability and the east-west rainfall gradient. During the humid period a generalized increase of yield was observed, showing the 48.7% of the area yield values lower than 2000 kg ha^{-1} . In addition, during the dry period 60.5% of the area showed low yield values ($<2000 \text{ kg. ha}^{-1}$). In this period high yield are mainly located over depression in the landscape corresponding to moist conditions and shallow water table.

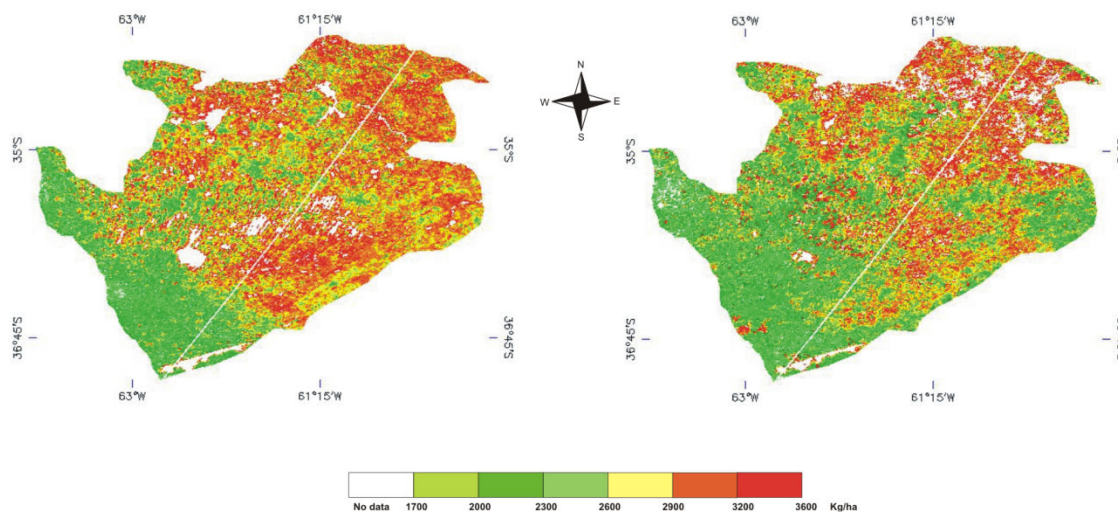


Fig. 3. Maps of soybean yield for a humid period (2002-2003) and dry period (2007-2008).

5 Conclusions

In this work the relationship between the remote sensed stress index TVDI and soybean yield was analyzed in a sandy area of Argentine Pampas. The observed high correlation TVDI/yield showed that this index can be used effectively to derive soil moisture conditions and predict crop yield 2–3 months before harvest. The errors of estimates were found to be comparable with results reported over different regions using satellite data. Moreover, the results showed that LST-VI methods can reflect more accurately short and long hydrological process that affect crop yield than the single use of VI. Finally, it should be noted that this method requires only remote sensed data. Therefore it could be applied in other regions where yield measurements are not available or with poor data coverage.

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