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Landsat images and crop model for evaluating water stress of rainfed soybean

Silvina Sayago, Gustavo Ovando, Mónica Bocco *

Universidad Nacional de Córdoba, Córdoba, Argentina

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A B S T R A C T

Soil water content is a vital resource that plays a central role in agricultural areas. In Argentina the soybean (*Glycine* max (L.) Merrill) is the most important crop, considering the economic yield and the sown area. Actually, remote sensing allows continuous monitoring of crops and to evaluate the impact of water stress in their development. The combination of Land Surface Temperature (*LST*) and the Normalized Difference Vegetation Index (*NDVI*) is an indicator that provides information about the condition of the vegetation and surface soil moisture content. In this study we evaluate relationships between indicators of crop water stress and the Temperature Vegetation Dryness Index (*TVDI*) determined from Landsat, for sites with rainfed soybean in the agricultural central zone of Córdoba (Argentina).

Field data were acquired continuously throughout the whole growing season. For each sample date and plot, data of percent green vegetation cover, soil moisture content and phenology were registered. The use of a simulation crop model allowed obtaining indicators of crop water stress indices: (1) soil water deficit, (2) crop water use vs. reference crop evapotranspiration, and (3) fraction of the available water capacity that is readily available.

The *NDVI*/*LST* spaces presented a trapezoidal form, which indicated that *TVDI* will have similar sensitivity for the full range of *NDVI* and showed temporal changes of wet and dry edges.

When soybean cover exceeds 60%, the combination of *TVDI* with (2) and (3) can enhance the ability of detecting crop water stress conditions ($R^2 = 0.62$ and 0.82, respectively). However, the relationship between *TVDI* and (1) showed low correlation values ($R^2 = 0.21$).

1. Introduction

Soil water content is a vital resource that plays an important role in agricultural areas, that determines the partition of available energy between sensible and latent heat flux, the distribution of precipitation in surface runoff or infiltration, and becoming a crucial factor for crop growth (Álvarez-Mozos et al., 2005). In the last 20 years, soybean (*Glycine* max (L.) Merrill) is the most important crop in Argentina, considering the economic yield obtained by farmers and the sown surface (19.800.000 ha), in particularly, in Córdoba province thearea cultivated with soybean is equivalent to approximately 27% of this surface (Bocco et al., 2012 and Ministerio de Agroindustria, 2016).

Drought is a recurrent potential natural disaster characterized by an extended period of time in which less water is available than expected in an ecological system (Zhang et al., 2016). Agricultural drought occurs when there is not enough soil moisture to support average crop production on farms (Carrão et al., 2016) and increase risks in rainfed agricultural production. In particular, more than two-thirds of Argentine territory suffers frequent periods of erratic rainfall (variations in time and space); this behavior constitutes an obstacle for crop production (Scian and Donnari, 1997). To characterize quantitative drought levels drought indices are used, which incorporate data from one or several variables such as precipitation and evapotranspiration into a single numerical value (Zargar et al., 2011).

The crop water stress index (*CWSI*), is an agricultural drought index that has been employed to schedule irrigations using canopy temperature. *CWSI* can be calculated using the difference between canopy and air temperatures measured under three conditions: at field, crop canopy transpiration not limited by available soil moisture and nontranspiring crop; a CWSI of 0 indicates no water stress, and a value of 1 represents maximum water stress. Jackson et al. (1981) expressed this index in terms of latent heat flux as the ratio between instantaneous crop and potential evapotranspiration, of a full canopy. Colaizzi et al. (2003a, b) introduced the Soil Water Deficit Index (SWDI), assuming that, instantaneous and daily latent heat flux ratio are similar during the maximum diurnal atmospheric demand ratio.

* Corresponding author.
E-mail address: mbocco@gmail.com (M. Bocco).

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In order to evaluate state of soil moisture, different methodologies can be applied:

i) Point based methods which using instruments, such as gravimetric, tensiometers, time domain reflectometry and neutron probes, gypsum blocks, and capacitance sensors. These field measurements are often widely spaced. So, is difficult to select representative field when local scale variations in soil properties, terrain and vegetation cover are present. Furthermore, field methods are complex, labor-intensive and expensive.
ii) Remote sensing methods can monitor a larger region and obtain images at short time intervals (Narasimhan and Srinivasan, 2005 and Zhang et al., 2014). Moreover these methodologies allow continuous monitoring of agricultural crops and so to evaluate the impact of water stress, in all stages of their development. In general, for study of crop along the growing season, MODIS images offer the advantage of data with a daily revisit frequency, and therefore a major possibility of obtaining cloud free data. However, the relatively coarse spatial resolution may subsume significant heterogeneity in vegetation and, hence, introduce error. Landsat images offers high spatial resolution (30 m) that would be more suitable in areas where the plot sizes are small, even when the temporal frequency is16 days (Bocco et al., 2012).

Among the indicators to detect the onset of drought conditions the relationship between surface temperature and soil moisture regime can be used (Gao et al., 2011 and Sandholt et al., 2002). To evaluate drought from satellite data, Moran et al. (1994); Wang and Qu (2007); Fensholt and Sandholt (2003) and Chen et al. (2011b) have considered indicators that relate surface temperature (*LST*, Land Surface Temperature) and the Normalized Difference Vegetation Index (*NDVI*).

The combination of *NDVI* and *LST* provides information about the condition of the vegetation and surface soil moisture content and therefore successfully monitor the water stress of vegetation. The *NDVI* is a conservative indicator of water stress because the vegetation remains green even after the start of this stress (Garcìa Galiano, 2012). The *LST* takes into account the physical, chemical and soil biological processes (Becker and Li, 1990); its value increases rapidly with the presence of water stress (Sandholt et al., 2002). *LST* integrates the soil surface and vegetation temperatures, components that may not be linearly related (Friedl and Davis, 1994).This implies that the sensitivity of this index to soil moisture differs for the canopy and for the soil surface beneath the plants and tends to be much greater for bare soil than for canopies (Mallick et al., 2009).

Several authors showed that a scatter plot between *NDVI* and *LST* could have a triangular or trapezoidal form (Stisen et al., 2008, Wang et al., 2001 and Mallick et al., 2009). This relationship is often characterized by two lines that define the wet and dry edges. The dry edge represents the minimum rate of evapotranspiration, while the wet one gives its maximum value (areas without water restriction). Estimating the slopes of these lines is not always simple because diverse types of surfaces can have different slopes and intercept with the same atmospheric conditions and surface moisture (Garcìa Galiano, 2012 and Sandholt et al., 2002). Chen et al. (2011a, b) and Patel et al. (2009) showed relationships between the Temperature Vegetation Dryness Index (*TVDI*), derived from MODIS satellite data, and point-based soil moisture measurements data at different depths. Using Landsat, Gao et al. (2011) formulated *TVDI* for presenting a new drought assessment method at regional scale.

For Argentine Pampas, Holzman et al. (2014) estimated soil moisture availability and crop yield for soybean and wheat, using *TVDI* calculated with *LST* and Enhanced Vegetation Index (*EVI*) from MODIS.

In this study we evaluate relationships between indicators of crop water stress and Temperature Vegetation Dryness Index obtained from Landsat spectral data, in rainfed soybean plots located in the central zone of Córdoba (Argentina).

2. Materials and methods

2.1. Study area

The study area is located in the central plains of Córdoba province, Argentina (Fig. 1), in the sub–region known as “Pampa Alta” (32°S; 64°W), which presents a slightly undulating flat relief developed on loessic material, of silt loam texture with a small slope to the east. The soils in this area are classified as entic and typic Haplustol. The average annual rainfall is approximately 800 mm, concentrated in summer. The climate in the study area is classified as dry sub–humid (Mather, 1965).

In this area predominates summer crops, soybean and corn (*Zea mays* L.), due to climatic conditions and to rainfall seasonality. Soybean in this region is grown under no-till systems using transgenic varieties resistant to glyphosate, with maturity groups between 3 and 4, and 32cmrow spacing, without fertilizer application (Piatti and Ferreyra, 2009).

2.2. Ground data

Field data were acquired continuously throughout the whole growing season of soybean crops (from 10/05/2010 to 04/14/2011). For this survey, data of 14 plots were collected fortnightly, although on some dates and plots the acquisition of field data was not possible due to sowing, herbicide application or harvesting operations. The sowing dates were from 10/19/2010 to 01/05/2011.For each sample date and plot, data of proportion of green vegetation coverage (P_v), gravimetric soil moisture content and phenology were recorded.

In this region soybean plots show uniform plant stands, so only three vertical digital photographs from 3 m high in each plot were used to estimate P_v. These digital photographs were classified into two classes: green vegetation (soybean) and soil, using the maximum likelihood methodology. These P_v values were temporally interpolated by cubic splines to determinate green coverage for each day of growing season. Four repetitions of soil moisture content by gravimetric method were recorded at 0.05, 0.20, 0.40 and 0.80 m depth and for each layer, values of permanent wilting point (*PWP*, cm^3/cm^3) of 0.060, 0.091, 0.097 and 0.096 respectively, were considered. The soybean growth stages were determinated following the Fehr scale (Fehr et al., 1971).

Data of daily solar radiation, maximum, minimum and dew-point temperatures and wind speed from Pilar meteorological station (31.45°S, 64.12°W, 406 m.a.s.l.) were used for estimating reference crop evapotranspiration (*ETo*) with ETo Calculator v1.2 (FAO, 2009). Also values of daily precipitation, for the complete study period, were collected.

2.3. Satellite data

Nine images from Landsat satellites (path 229, row 82), obtained in clear days were used for this work, five of these belong to the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and the remaining to Landsat 5 TM (Table 1). Both sensors have the same spatial (30 m), temporal (16 days), radiometric and spectral resolution in visible and infrared bands. Thermal bands were resampled to 30 m for matching with the resolution of optical bands.

To determine the dry and wet edges, ensuring uniform atmospheric forcing and surface roughness, a rectangular subset (31°41′30″–31°47′30″S; 63°53′30″–63°59′00″W) of 107,086 pixels was chosen within the study area for each image.

For this work the bands of Landsat scenes in red (red, 630–690 nm, band 3) and near infrared (NIR, 760–900 nm, band 4) were used for *NDVI* determination and thermal infrared (TIR, 10,400–12,500 nm, band 6) for *LST* calculus. To avoid taking null value (due to SLC–Off, e.g. without the image effects caused by the scan line corrector failure aboard Landsat 7), data from all pixels with valid information were recorded in each of these same 14 plots.