

Geo-Sciences

Assessment of spectral indexes for estimating soil water content in the Brazilian Pantanal

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ABSTRACT

The Pantanal is the largest floodplain of the globe occupying 138,183 km² in Brazil. The fundamental ecological factor of interaction between the Pantanal ecosystems is the flooding regime. Connected to properties of the soil-plant-atmosphere system, knowledge on the soil water content becomes increasingly necessary. The high temporal and spatial variability of water content in the soil caused by the vast heterogeneity of soil texture, vegetation, topography and climate makes it a difficult physical variable to be measured. However, its spatial and temporal variability can be determined by recent modern techniques of remote sensing based on data obtained by microwave or infrared sensors. Thus, the aim of this study was to evaluate the accuracy of vegetation and soil water indexes through satellite images from Landsat 5 in the northern Brazilian Pantanal. The study was conducted in a pasture, experimental site in the Northern Pantanal in Mato Grosso state. Soil moisture was measured using a TDR probe installed at 10 cm depth in the period from 2009 to 2011. For comparison, spectral indexes and the surface temperature provided by Geological Survey (USGS) were used, these indexes are derived from bands ratios of satellite reflectance products Landsat 5 TM. The data evaluation was performed using some indicators: accuracy - Willmott index, Root Mean Square Error and the Mean Absolute Error. This study demonstrated that the application of remote sensing in the management of water resources is very promising. The indexes correlated with soil moisture measurement. Among the soil water indexes the NBR-2 showed related to soil moisture measurement. For both types of soils EVI had the highest determination coefficient, lowest errors and highest Willmott's index of agreement.

Keywords: Pasture; Remote sensing; Landsat 5

1 INTRODUCTION

With approximately 250,000 km², the Pantanal is the largest floodplain of the globe (ANDRADE *et al.*, 2012). The fundamental ecological factor and main moderator of force interaction between the Pantanal ecosystems is the flooding regime (CATIAN *et al.*, 2017). Due to the expansion of the agricultural frontier and of agricultural activities increase the Pantanal has been considered a fragile ecosystem, as a result of such activities, the rivers and soils of this biome are affected by siltation of its banks (BAZZO *et al.*, 2012).

Much of the Pantanal (92%) is formed by hydromorphic soils, reflecting poor drainage and prone to prolonged and periodic flooding. The Pantanal soil geologically were developed from sandy unconsolidated sediments, clay and organic, deposited during the Quaternary period (CORINGA *et al.*, 2012). Constituting the formation of the Pantanal the much of its length is formed by sediments deposited in the Cenozoic detrital deposits of waste and surrounding highlands of Pleistocene, and the plain deposits of flooding of rivers, which occurred in the Holocene (FERNANDES *et al.*, 2007).

Closely linked to the properties of the soil-plant-atmosphere system, knowledge on the water content in soil becomes increasingly necessary (CREMON *et al.*, 2014). Due to the water system together with its geomorphology, the Pantanal has specific soil characteristics, soil formation with different characteristics that should be considered in its use (CORINGA *et al.*, 2012). The gleyzation and plintization are the most common pedogenic processes in these soils, which are responsible for the gray colors for the most part of your profile. Because of these processes, the formation of the Pantanal presents great diversity of soils, as Planosols, Plinthosols, Gleysols Cambisols Fluvic, Neossolos, Luvisols and Vertisols (COUTO & OLIVEIRA, 2010). Despite the simple physical concept of soil moisture, its determination presents difficulties in obtaining representative

values due to the spatial and temporal variability of soil physical properties (BAZZO *et al.*, 2012).

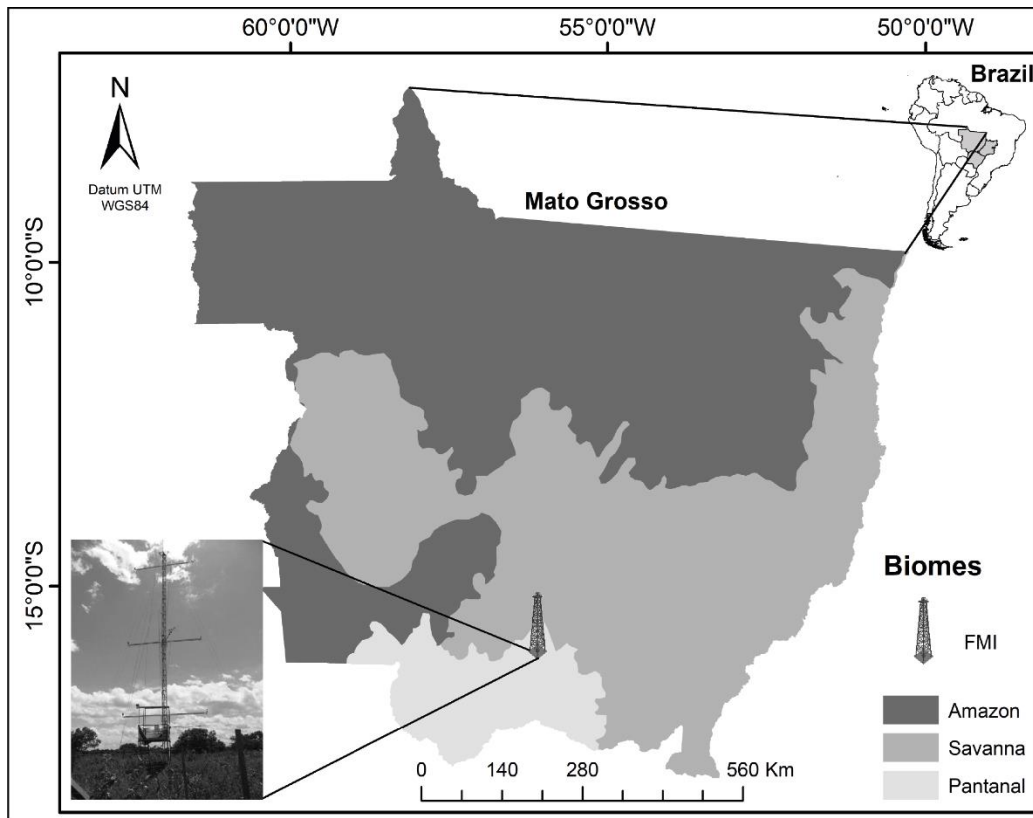
However, the spatial and temporal variability of soil moisture can be determined by recent modern techniques of remote sensing (PENG *et al.*, 2017). Thus, many indices have been proposed in the literature to estimate the water content in the soil (GAO, 1996; FORD *et al.*, 2019). McFeeters (1996) developed the normalized difference water index (NDWI). Gao (1996) proposed a different NDWI used to estimate the water content in the vegetation canopy. Although NDWI of McFeeters and Gao have the same terminology, the concepts of the two are different complements. Thus, the aim of this study was to evaluate the accuracy of vegetation and soil water indexes through satellite images from Landsat 5 - TM in the north of the Brazilian Pantanal.

2 MATERIAL AND METHODS

2.1 Site description

The study was conducted on one experimental site in the Northern Pantanal in Mato Grosso (Figure 1). This area has an average annual temperature of 26.2 °C, annual rainfall between 1300 and 1400 mm and a well-defined dry season, from May to September, and a rainy season from October to April (MACHADO *et al.* 2015). The experimental site was located at Fazenda Miranda (FMI) (15° 43' 53.65" S, 56° 4' 18.88" W and altitude of 157 m) in the city of Cuiabá, Mato Grosso State, Brazil. The vegetation of this experimental site was a non-native grassland (*Brachiaria humidicola*) and the soil was classified as Plinthosol (SEPLAN, 2001, BIUDES, 2013).

Figure 1 – Study area located on Miranda Farm (FMI)



2.2 Measurement of soil water content

The soil water content was measured from May 2009 to September 2011 at the FMI by a time-domain reflectometer (CS-616, Campbell Scientific, Inc., Logan, UT, USA) installed at 10 cm depth in two types of soil (lateritic and sandy), and connected to a datalogger (CR1000, Campbell Scientific, Inc., Logan, UT, USA), which has scan every 30 seconds and storage every 30 minutes, and then reorganized on a monthly scale.

2.3 Remote sensing data

For comparison with the soil water content measured, spectral indices and radiometric surface temperature with a spatial resolution of 30 m (Landsat 5 satellite), supplied by the Center Science Processing Architecture (ESPA) (<http://espa.cr.usgs.gov/>) of the US Geological Survey (USGS) were used (Table 1).

These indexes are derived from bands ratios of satellite reflectance products Landsat 5 TM, are generated from a specialized software called Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS). LEDAPS was originally developed by the National Aeronautics and Space Administration (NASA). The software applies the routines of atmospheric correction for level 1 Landsat TM or ETM + data (MASEK *et al.*, 2006). The satellite Landsat 5 was launched on 1 March 1984 and works in equatorial orbit at 705 km altitude. The sensor TM (Thematic Mapper) on board the satellite makes the imaging of the earth's surface producing images with 185 km wide on the ground spatial resolution of 30 meters and 7 spectral bands. The satellite revisit time to image the same portion of the land is 16 days. In this study 46 images of the Landsat 5 satellite reflectance were used.

In this work, we admit that the burning indexes (NBR and NBR-2) are referred to as water deficit indicators. In the same way, we admit the spectral index (NDWI to NDMI) proposed by Gao *et al.* (1996) as a reference acronym by the USGS (U.S. Geological Survey) for more current discussion in the scientific literature (Table 1). The monthly precipitation (V7 product 3B43) was obtained in Distributed Active Archive System (DAAC) (<http://disc.sci.gsfc.nasa.gov/precipitation/tovas/>) by satellite Tropical Rainfall Measuring Mission (TRMM).

Table 1 – Spectral indexes for vegetation estimation and soil water content (NDVI, EVI, SAVI, MSAVI, NDMI, NBR and NBR-2)

Spectral indexes	Authors
Normalized Difference Vegetation Index (NDVI)	Rouse <i>et al.</i> , 1973
Enhanced Vegetation Index (EVI)	Huete <i>et al.</i> , 1997
Soil Adjusted Vegetation Index (SAVI)	Huete, 1988
Modified Soil Adjusted Vegetation Index (MSAVI)	Qi <i>et al.</i> , 1994
Normalized Difference Moisture Index (NDMI)	Gao <i>et al.</i> , 1996
Normalized Burn Ratio (NBR)	Lopez Garcia & Caselles, 1991
Normalized Burn Ratio 2 (NBR2)	Miller & Thode, 2007

The performance of the indices in relation to the soil water content measured was analyzed by the Willmott's index of agreement (d), Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE) (WILLMOTT *et al.*, 2012).

The accuracy is related to the removal of the estimated values on the observed. Mathematically this approach is given by a designated concordance index can be widely applied to model comparison (WILLMOTT *et al.*, 1985). Their values range from zero, with no agreement, to 1, with perfect agreement.

$$d = 1 - \left[\frac{\sum (P_i - O_i)^2}{\sum (\|P_i - O\| + \|O_i - O\|)^2} \right] \quad (1)$$

where P_i is the estimated value, O_i the observed value and O the average of the observed values.

The RMSE indicates how the model fails to estimate the variability of measurements around the mean and measures the change in the estimated values around the measured values (WILLMOTT AND MATSUURA, 2005). The lower RMSE limit is 0, which means that there is full compliance between model estimates and measurements.

$$RMSE = \sqrt{\frac{\sum (P_i - O_i)^2}{n}} \quad (2)$$

The MAE indicates the distance (deviation) absolute average of the estimated values on the measured values. Ideally, the values of the MAE and the RMSE were close to zero (WILLMOTT AND MATSUURA, 2005).

$$MAE = \sum \frac{|P_i - O_i|}{n} \quad (3)$$

The decrease and increase in soil water content are related to the period of soil drying and wetting, respectively, depending on the local precipitation (Figure 2). Daily estimates of the TRMM satellite had relationship with soil moisture (Table 2).

Table 2 – Pearson correlation matrix between soil moisture measurement (sandy soil and laterite), vegetation indexes (EVI, NDVI, SAVI and MSAVI), soil water indexes (NDMI, NBR and NBR-2), land surface temperature (LST), daily precipitation (TRMM daily) and monthly precipitation (TRMM monthly) of Miranda Farm (* $p < 0.05$, ** $p < 0.001$)

	Sand.	Lat.	EVI	MSAVI	NBR	NBR2	NDMI	NDVI	SAVI	LST	TRMM day	TRMM mon
Sand.	1											
Lat.	0.92**	1										
EVI	0.46**	0.58**	1									
MSAVI	-0.28	-0.17	0.26	1								
NBR	-0.24	-0.15	0.03	0.57**	1							
NBR2	0.38*	0.46**	0.78**	0.24	0.20	1						
NDMI	0.37*	0.45**	0.73**	0.35**	0.19	0.87**	1					
NDVI	0.45**	0.57**	0.72**	0.21	0.21	0.90**	0.74**	1				
SAVI	0.32*	0.47**	0.69**	0.51**	0.28*	0.65**	0.64**	0.68**	1			
LST	0.18	0.18	-0.07	-0.36**	-0.07	-0.07	-0.22	0.01	-0.13	1		
TRMM day	0.51	0.41	0.29	-0.20	0.48	0.45	0.41	0.56	-0.08	0.91**	1	
TRMM mon	-0.36	-0.23	-0.13	0.18	-0.03	-0.36	-0.03	-0.46*	0.22	-0.45*	-0.64	1

Featuring well-defined seasons, in the Midwest region where the experimental site is located, the summer is characterized by high soil moisture and drier winter. From April the frontal systems start to act more frequently in the winter period in the southern hemisphere, favoring the advance of cold fronts to the south of Brazil (Gevaerd & Freitas, 2006).

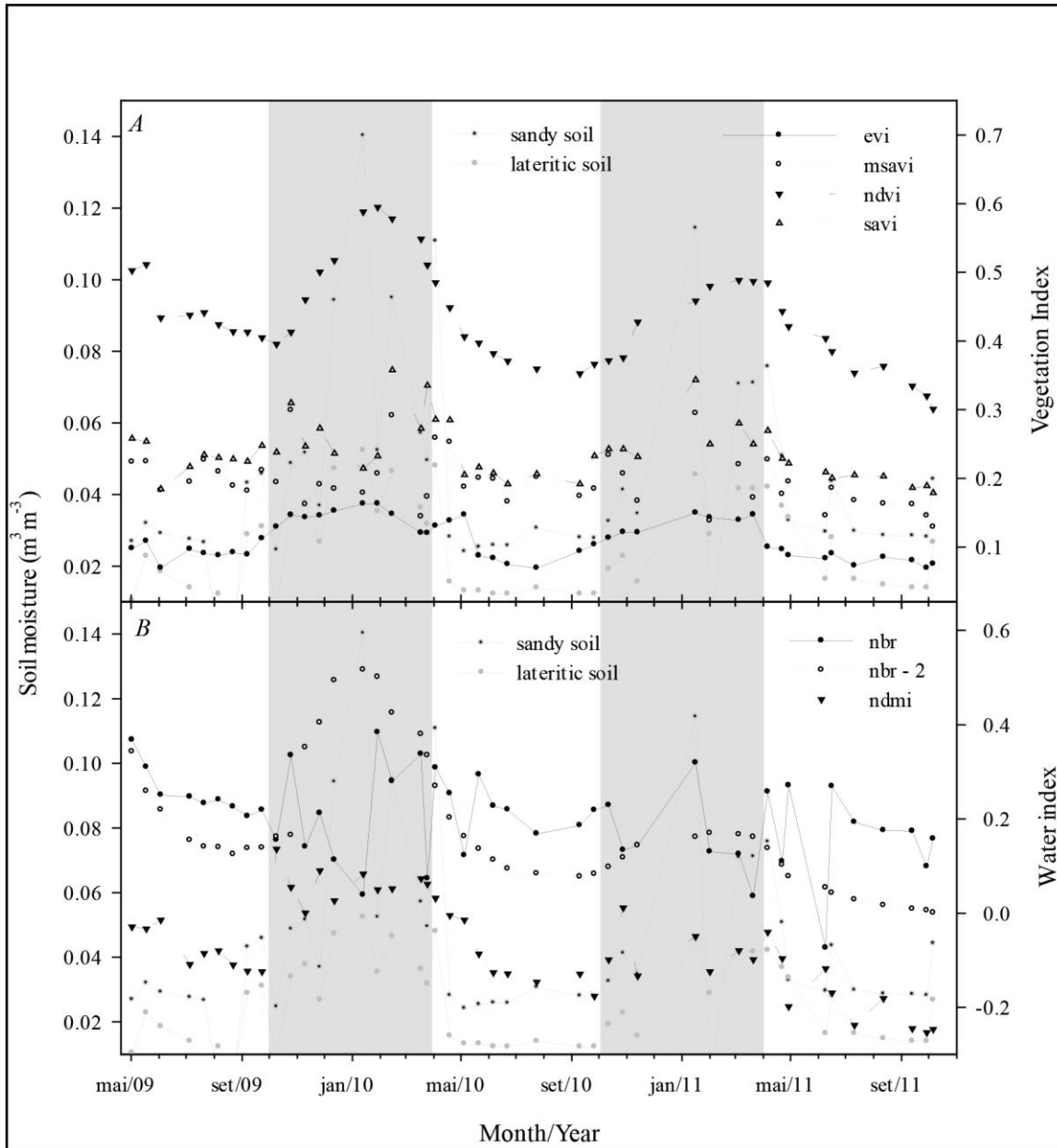
Soil moisture showed a strong correlation in different soils (sandy and laterite), in both dry and rainy seasons, along the entire study period (Table 2). In the pasture area the sandy soil showed a small difference in soil moisture, which was only 2% higher than in the lateritic soil. This difference is expected because the land cover change causes physical and chemical changes in the soil (Cremon *et al.*, 2014). In the pasture area, soil density tends to be higher in the soil surface layer, due to the influence of management factors such as effect of the pressure applied, soil texture and porosity (CREMON *et al.*, 2014).

Microporosity decreases in these soils with increasing depth (BEZERRA *et al.*, 2013). Collares *et al.* (2006) reported that with the increase of bulk density there is a redistribution of pore sizes, and this process tends to occur with reduced macroporosity and increased soil microporosity until the values of soil microporosity approach the values of total porosity.

All indexes were affected by local seasonality with maximum peaks in the rainy season and low values in the dry season (Figure 3). The vegetation and soil water indexes were affected by the water content measured in soil having correlations (p -value < 0.05) in different types of soil (Table 2). The EVI ($r_{\text{sandy}} = 0.46$ with sandy soil and $r_{\text{lateritic}} = 0.58$ with lateritic soil) was strongly related to soil moisture (p -value < 0.001).

The ratio of EVI and other vegetation indices with the surface water content is not strange nor new, given that the bands 1, 2, 3 and 4 of the Landsat 5, used for the calculation of these indexes, cover part of spectral signature of clean water (clear water) and cloudy water (turbid water). Sakamoto *et al.* (2007) used EVI, LSWI and the difference between them (DVEL) based on MODIS reflectances to map the Cambodian flood periods. These authors compared their results with RADARSAT radar products, results derived from Landsat 5 and hydrological data, and obtained coefficients of determination (R^2) greater than 0.89 with Landsat products and above 0.77 with RADARSAT data.

Figure 3 – Soil moisture measurement (sandy and lateritic soil – loco measurement) at Miranda Farm (FMI) in contrast to the vegetation indexes (EVI, MSAVI, NDVI and SAVI - A) and soil water indexes (NDMI, NBR-2 and NBR -B) for the entire study period. Light gray stripes correspond to the rainy season



In FMI the NDVI and SAVI vegetation indexes also showed correlated with soil moisture measured, for NDVI ($r_{\text{sandy}} = 0.45$ and $r_{\text{lateritic}} = 0.57$) and the SAVI ($r_{\text{sandy}} = 0.32$ and $r_{\text{lateritic}} = 0.47$) between the soil water indexes, the NBR-2 ($r_{\text{sandy}} = 0.38$ and

$r_{\text{lateritic}} = 0.46$) and NDMI ($r_{\text{sandy}} = 0.37$ and $r_{\text{lateritic}} = 0.45$) had the highest correlations (Table 2).

Interestingly, the NBR-2 index was correlated with soil moisture measured in two types of soil (Table 2). This index is the ratio of the sums of the bands 5 and 7 (approximately the range 1.5 to 2.5 μm). In Landsat 5 satellite, these bands, different from NDMI, which has the bands 4 and 5 in its computation, cover the two amplitudes of the spectral signature of grassy vegetation (GAO *et al.*, 1996).

The NDMI covering the two largest amplitudes for spectral signature of the dry grassy vegetation, 4 and 5 bands, correlated with the water content in the soil measured in pasture area (Table 2). The band 4 (0.76 to 0.90 μm) of the Landsat-5 corresponds to the NIR band and the band 5 (1.55 to 1.75 μm) to the SWIR. These wavelengths were selected to (1) maximize the typical reflectance of water bodies; (2) minimize the low reflectance NIR by water bodies and (3) take advantage of high-reflectance NIR by surface vegetation and soil characteristics. When computed by sensors that obtain NDMI, multispectral images have positive values for water bodies and negative values or zero for soils and terrestrial vegetation, which effectively eliminates the terrestrial vegetation and soil information withholding information from bodies of water for analysis (PEREIRA *et al.*, 2018).

Serrano *et al.* (2000), comparing the reflectance of 23 types of vegetation of chaparral plant communities in California (USA) at different stages of phenology and structural and canopy cover, found that NDMI responds not only to structure and coverage, but also to the vegetation water content, at landscape scale. Similarly, Chen *et al.* (2005) found a high correlation coefficient (R^2) for soybean and corn in Iowa (USA) comparing the NDMI with the water content at different stages of growth of vegetation.

Results of studies involving simulations of the boundary layer and energy balance of forests and pastures in regions of the Pantanal and the Amazon region indicate that the development of pasture changes the height of the nocturnal boundary layer, causing the decrease in latent heat flux and increase in sensible

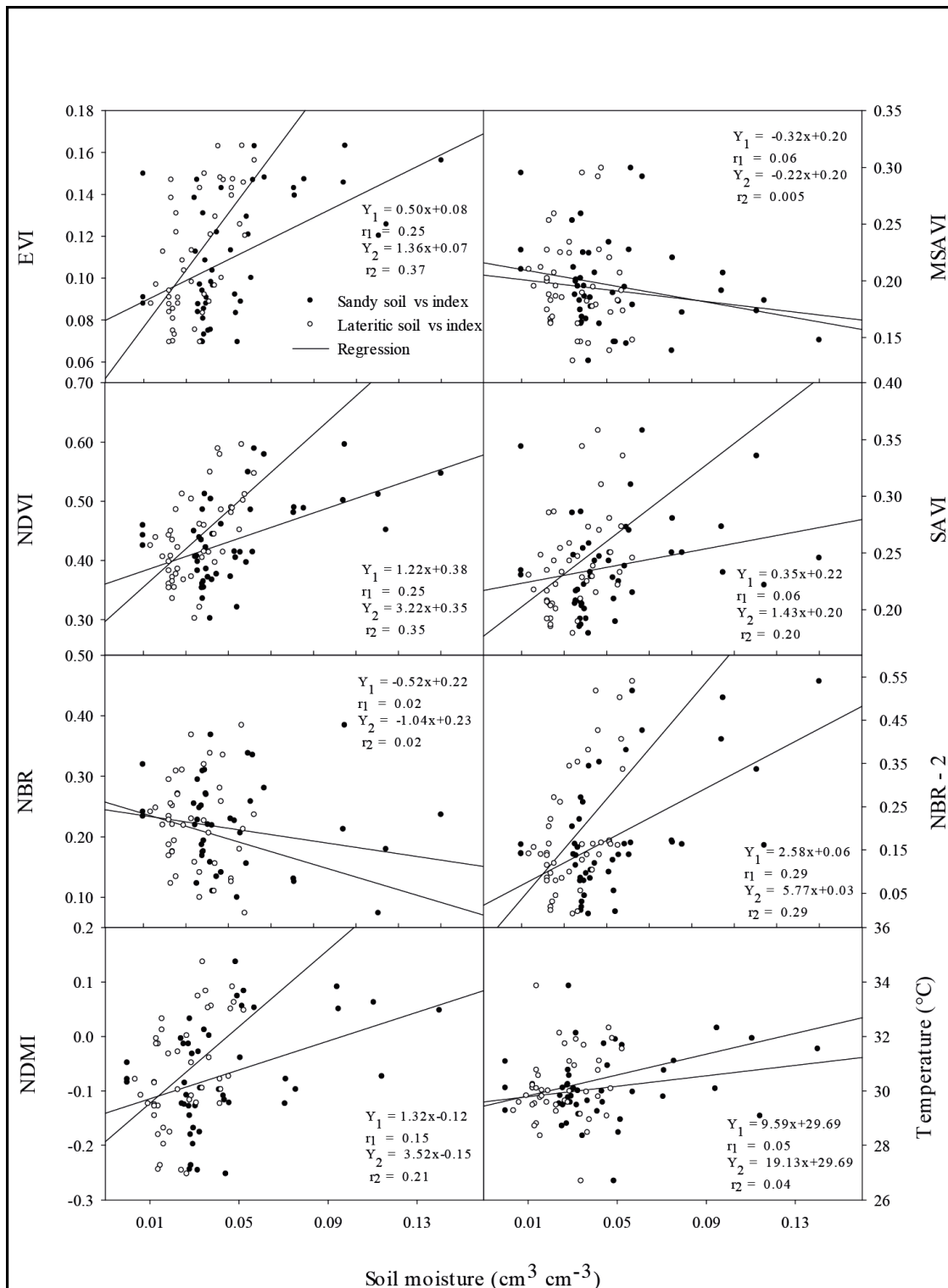
heat flux, which causes a complex change in local and regional patterns, reducing precipitation and evaporation (20 to 30%), increasing the air temperature (from 0.6 to 2.0 °C) and intensification of drought (NOBRE *et al.*, 1996). When comparing soil water content with spectral indexes, EVI presents higher correlations and lower errors (Table 3).

Table 3 – The performance of the indices in relation to the soil water content measured (lateritic soil and sandy soil). The Willmott's index of agreement (d), Correlation (r), Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE)

	Lateritic soil				Sandy soil			
	MAE	RMSE	d	r	MAE	RMSE	d	r
EVI	0.09	0.09	0.58	0.61	0.07	0.08	0.77	0.51
MSAVI	0.17	0.18	0.38	-0.07	0.15	0.16	0.55	-0.24
NBR	0.18	0.20	0.32	-0.16	0.16	0.19	0.48	-0.17
NBR2	0.16	0.21	0.32	0.54	0.15	0.20	0.50	0.54
NDMI	0.09	0.13	0.12	0.46	0.11	0.14	0.17	0.39
NDVI	0.41	0.42	0.20	0.59	0.40	0.40	0.32	0.50
SAVI	0.21	0.22	0.34	0.45	0.20	0.20	0.50	0.25

In FMI the EVI, NDVI and NBR-2 indexes showed higher coefficients of determination for the two soil types (sandy and laterite). Among the indexes, EVI showed higher performance, overestimating soil moisture in the lateritic soil by 36% (Figure 4). These results are consistent with studies conducted by Ahmad & Bastiaanssen (2003) and Bezerra *et al.* (2013), who used the SEBAL to estimate the evaporative fraction with bases on Landsat 5 satellite reflectances relating to soil moisture obtained in cotton crops in Brazil, wheat and rice in Pakistan. The authors found an RMSE greater than $0.05 \text{ m}^3 \text{ m}^{-3}$. Ahmad & Bastiaanssen (2003) found that these errors tend to increase systematically with the absolute values, such as evaporative fraction, which showed similar values to those found by Scott *et al.* (2003) in irrigated soils in the Lerma-Chapala basin in Mexico.

Figure 4 – Regression of soil moisture measured at FMI in contrast to the vegetation indexes, soil water indexes and surface temperature. Equations with index 1 indicate relationship with variables in contrast to moisture in the sandy soil, while equations with index 2 indicate list of variables with moisture in the laterite soil



4 CONCLUSIONS

1. This study demonstrated that the application of the use of remote sensing products in the management of water resources is very promising. However, only proper use, awareness of limitations and correct interpretation of remote sensing data can facilitate water management and planning operations.

2. The decrease and increase in soil water indexes were related to the periods of soil drying and moistening, depending on local precipitation. The EVI and NDVI correlated with soil moisture measurement. Among the soil water indexes the NBR-2 showed related to soil moisture.

3. For both types of soils, the EVI had the highest coefficient of determination, lowest errors and highest Willmott's index of agreement.

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Contribution: Supervision, Visualization

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