# Subsurface Soil Moisture Estimation by VI–LST Method

M. E. Holzman, R. Rivas, and M. Bayala

*Abstract*—**In this letter, the relationship between temperature vegetation dryness index (TVDI) from the Moderate Resolution Imaging Spectroradiometer and subsurface soil moisture (SM) over crop and native grassland of the Argentine Pampas is analyzed. High correlation ($R^2 > 0.69$) between TVDI and SM measurements was found at different soil depths. In addition, we found that the potential of this index to reflect subsurface soil wetness fluctuations depends on root system depth, root distribution in the soil, and physical soil characteristics. Results indicate that thermal and reflectance data combination could be used to monitor subsurface SM below vegetated areas.**

*Index Terms*—**Optical–thermal, soil moisture (SM), stress index.**

## I. Introduction

Soil moisture (SM) is one of the most important hydrological variables influencing the water availability for crops and the interaction between land surface and atmospheric processes [1]. However, reliable determination of this variable at regional scale through conventional point measurements is complex as they can only be conducted in large-scale field programs due to the high cost of these measurements. Remote sensing (RS) systems can provide diverse land surface parameters such as land surface temperature (LST) and vegetation indices (VIs), which can be used to estimate soil wetness conditions at regional scale. Thus, the development of RS methods for monitoring the spatial variability of SM is critical not only for agriculture but also for hydrological and climate applications.

For the last two decades, VI and LST data were widely combined to estimate soil wetness. Although several authors [2]–[4] have shown a strong relationship between VI–LST indices and surface SM, no comprehensive work has analyzed the sensitivity to subsurface SM below vegetated surfaces considering the influence of soil type and root system depth. In vegetated surfaces, water is removed from a soil principally by plant uptake as part of transpiration process. The major difference between transpiration and evaporation is that plants can exert some physiological control over the size of the stomatal openings and, hence, of vapor movement [5]. Moreover, one of the most important factors affecting the stomatal regulation is the water content of the leaf cells, which is directly related to soil water content in the root zone.

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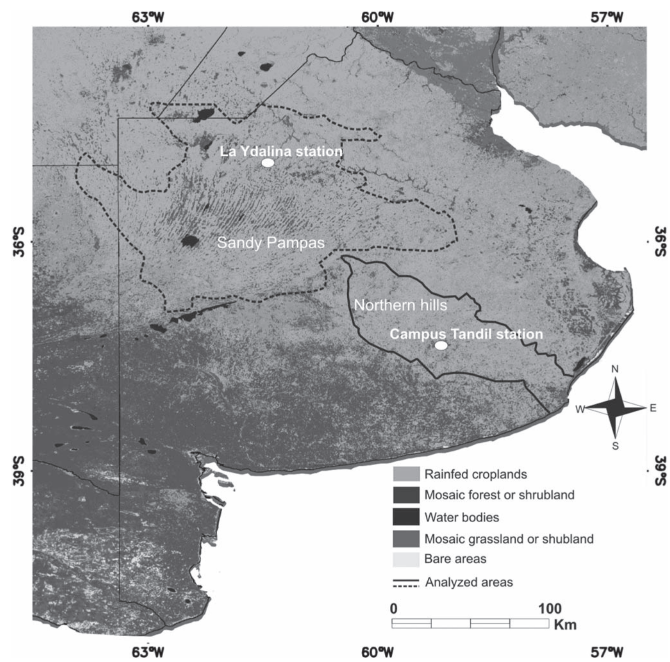


Fig. 1. Land cover map of the study area.

On the other hand, LST and VI largely depend on soil water availability. The former is closely related to stomatal regulation, increasing in early stages of water stress process [6]. In advanced stages of water stress, root zone SM is minimal, and the photosynthetic systems are affected, decreasing the VI. Therefore, short- and long-term variations of soil water content in root zone could be monitored through LST–VI stress indices. Within this context, the objective of this letter is to evaluate the ability of the temperature vegetation dryness index (TVDI) to estimate subsurface SM in two types of soil and land cover over Argentine Pampas. The TVDI is based on a parameterization of the relationship between LST and VI [7], being derived only from RS data.

## II. Study Area

Two different areas, spread over the Argentine Pampas, were selected for *in situ* soil water content measurements to evaluate the relationship between TVDI and subsurface SM: sandy Pampas (La Ydalina station) and northern hills (Campus Tandil station) (Fig. 1). In general, the climate is humid–subhumid temperate. In the sandy Pampas, the mean annual precipitation ($P$) is about 800 mm with an east–west gradient, and it is often

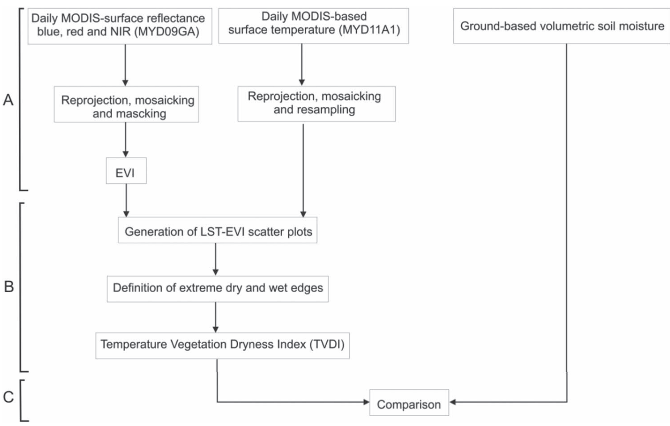


Fig. 2. Diagram of the methodology.

equal to potential evapotranspiration (PE). The mean annual temperature is 18 °C, increasing westward. In northern hills, the $P$ is about 1000 mm, the PE is 700 mm, with frequent water excess during March–August, and the mean annual temperature is 16 °C. Representative vegetation types over these areas were rain-fed maize crop (La Ydalina station) and native grassland, including *Dactylis glomerata*, *Festuca arundinacea*, and *Lolium multiflorum* (Campus Tandil station). The studied land cover represents two different vegetation types, differing largely in canopy architecture, root system, and physiological response to soil water conditions. Regarding the soil types, in the La Ydalina station, the soil is Entic Hapludoll, and the soil texture is sandy loam. In the Campus Tandil station, the soil is Typic Argiudoll, and the soil texture is silty loam and silty clay loam in deep soil horizons.

## III. Methodology

The schematic diagram of the methodology (Fig. 2) includes three main components: (A) RS data and preprocessing, (B) estimation of TVDI, and (C) TVDI and SM ground-based measurement comparison.

### *A. Satellite Data and Preprocessing*

Moderate Resolution Imaging Spectroradiometer (MODIS)-based products were acquired from the National Aeronautics and Space Administration's Earth Observing System Data and Information System (http://reverb.echo.nasa.gov/reverb). Those included the following: 1) MYD11A1 version 005: daily MODIS/Aqua LST at 1-km resolution (provides atmospherically corrected per-pixel temperature and emissivity values), level 3, and 2) MYD09GA version 005: daily MODIS/Aqua surface reflectance at 1-km and 500-m resolution (provides estimates of the surface spectral reflectance corrected of atmospheric scattering and absorption), level 2G. MODIS LST data were validated in the study area in [8], who found an error of $\pm 1$ K. Aqua data were used to consider periods of maximum atmospheric evaporative demand during the day. Thus, fluctuations in canopy LST are mainly explained by root zone SM variations. Daily images of summer 2012 (January–February) were included in the analysis to evaluate periods with high

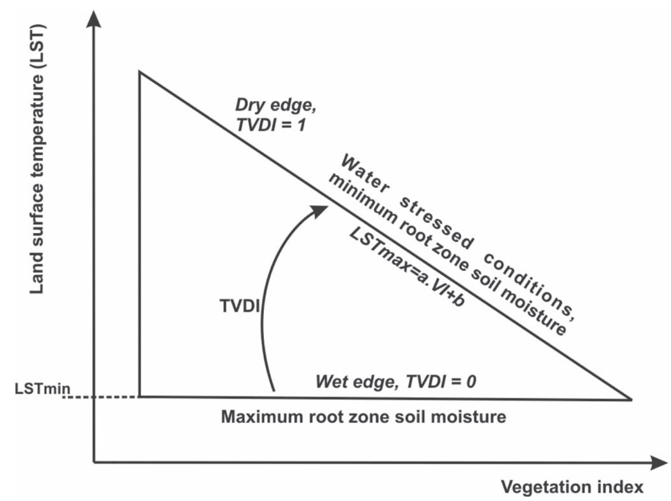


Fig. 3. Theoretical diagram of LST–VI scatter plot for defining TVDI (adapted from [7]).

evaporation rate, when LST and enhanced VI (EVI) are highly sensitive to soil wetness variability.

The MODIS LST and reflectance data are originally stored in integerized sinusoidal projection with a nominal spatial resolution of 1 km. The MODIS Conversion Toolkit was used to reproject the images into geographic latitude/longitude coordinates, Datum WGS-84. Two adjacent images were mosaicked to obtain the study area. LST images were processed to match up with the 500-m resolution of surface reflectance images using the resampling technique developed in [8]. This technique estimates LST at fine spatial resolution based on the difference between dry and wet edges of VI–LST relationship, with the former being modeled through a quadratic function. Thus, the TVDI was generated at 500-m resolution. The surface reflectance images (MYD09GA) were used to compute the EVI. EVI was used instead of the widely known NDVI, as the former has been developed to minimize the canopy background and atmospheric influences with improved sensitivity into high biomass regions [9]. Cloudy EVI observations were excluded from the analysis based on the cloud masks accompanying the MYD11A1 products.

### *B. Estimation of TVDI*

If a wide range of fractional vegetation cover and soil water conditions are represented in the data, the scatter plot of LST and VI frequently shows a triangular shape [7], [10]–[12] (Fig. 3). Such triangle is characterized by two physical limits, representing extreme conditions of SM and evapotranspiration. The dry edge ($\mathrm{LST_{max}}$) represents limiting SM in the root zone and evapotranspiration for different VI classes. The lower nearly horizontal wet edge ($\mathrm{LST_{min}}$) indicates maximum soil wetness and potential evapotranspiration. On the other hand, the left edge represents bare soil, ranging from dry to wet (maximum LST to minimum LST, respectively) [2].

In the triangular space, to obtain information of the surface soil wetness conditions, the TVDI was defined [7]

$$\mathrm{TVDI} = \frac{\mathrm{LST} - \mathrm{LST_{min}}}{\mathrm{LST_{max}} - \mathrm{LST_{min}}} \tag{1}$$

where LST is the observed surface temperature (in kelvins) at a given pixel, $LST_{\min}$ (the lower horizontal line of the triangle) is the minimum temperature in the triangle, defining the wet edge, $LST_{\max} = aVI + b$ (the upper straight line in the triangle) is the maximum temperature for a given value of VI, and "$a$" and "$b$" are the surface parameters of the image defining the dry edge, which is modeled as a linear fit to the data (Fig. 3). The TVDI values are close to one along the dry edge, indicating limited SM availability, and they are close to zero along the wet edge, indicating maximum evapotranspiration.

To estimate pixel-by-pixel TVDI by using (1), daily dry and wet edges were determined from LST–VI scatter plots. About the dry edge, the authors in [12] explained the difference between the theoretical and RS edges. The true dry edge represents zero SM and zero evapotranspiration, with LST reaching a physical maximum when no evaporative cooling and complete stomatal closure occur [13]. The RS dry edge is defined by lower LST than the theoretical dry edge, which is consistent with the physiological growth of the vegetation. In arid and semiarid areas, high LST is easily noticeable, and the RS dry edge frequently depicts the true dry edge. On the other hand, LST at observed wet edge commonly is higher than that at true wet edge, as pixels with minimum LST are limited. Therefore, in arid and semiarid areas, there is a high probability of SM overestimation using the observed wet edge. Consequently, daily dry and wet edges were obtained based on the LST–EVI scatter plots of semiarid and humid areas of Argentine Pampas, respectively. Dry edges were obtained using the least squares method, with a significance level of 5%. Wet edges were calculated by averaging a group of points with minimum LST for different EVI intervals in the LST/EVI scatter plots. Afterward, to obtain comparable TVDI values among different days and to avoid the temporal influence on the index, dry (maximum slope and intercept) and wet (minimum $LST_{\min}$) extreme edges were defined for the whole study period [14]. Finally, daily TVDI values were computed using these extreme edges.

### C. TVDI and SM Ground-Based Measurement Comparison

To test the sensitivity of TVDI to different subsurface soil wetness conditions, ground-based SM measurements were continually conducted from January 1 to February 27, 2012, in La Ydalina station $(35^\circ 09' \text{ S}, 61^\circ 07' \text{ W})$ and Campus Tandil station $(37^\circ 19' \text{ S}, 59^\circ 05' \text{ W})$ (Fig. 1). This study period included low, normal, and high SM contents, allowing us to test the methodology over a wide range of soil wetness. After cloudy observation removal, 19 and 25 daily data for Campus Tandil and La Ydalina remained for the analysis, respectively.

On La Ydalina station, a tensiometer incorporated to a Davis Vantage Pro2 (Davis Instruments Corporation) station was used to measure SM at 60- and 120-cm depths. Shallow depth values were not considered, taking into account that sandy soils have limited water retention capacity and that plants extract deeper SM. Relative soil water content (in percent) was determined from tension measurements (in centibars) by the moisture-characteristic curve, previously defined in laboratory. On Campus Tandil, calibrated EC-10 H2O and EC-20 H2O (Decagon Devices, Inc.) single-panel SM probes were used to measure relative soil water content at 10-, 40-, and 60-cm depths. Such depths were selected to analyze the different soil horizons and different root system depths. Both probes measure the dielectric constant (in millivolts), which is directly related to the volumetric water content. The EC-10 H2O and EC-20 H2O measure the integrated SM at 10- and 20-cm depths with accuracy higher than 97%, respectively [15]. After that, daily TVDI values for pixels surrounding both stations were averaged using a $3 \times 3$ kernel size. Finally, TVDI values were compared with SM measurements.

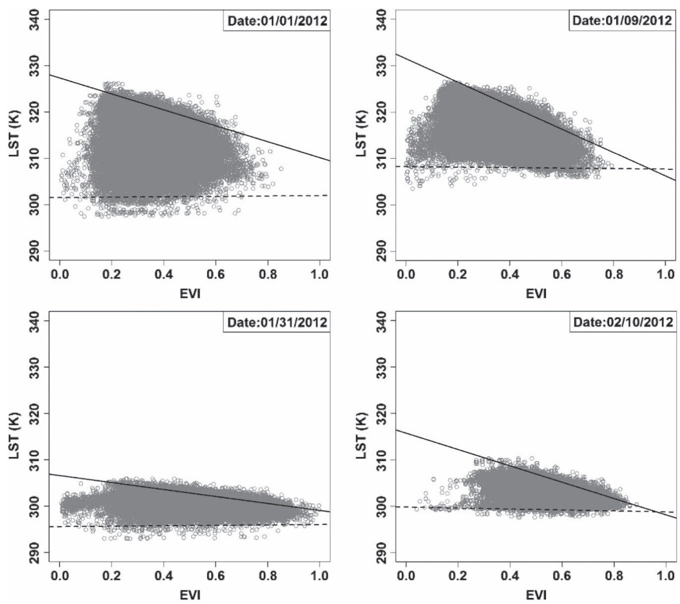


Fig. 4. Scatter plots of EVI and LST for four different images of the study period. The extreme dry edge corresponded to January 9, 2012, and wet edge corresponded to January 31, 2012.

## IV. Results and Discussion

### A. Extreme Edges in the LST–EVI Scatter Plots

In order to determine the parameters describing dry and wet edges, maximum and minimum temperatures observed for different intervals of EVI were extracted from daily LST–EVI triangular spaces, respectively. Based on the $LST_{\min}$, intercept, and slope of the edges, extreme dry and wet edges were determined to obtain daily TVDI values (Fig. 4). Observations were consistent with the concept proposed in [7] that LST decreases with an increase of VI. On the other hand, the large swath (2330 km) and moderate spatial resolution (1 km) of MODIS/Aqua sensor allow us to capture the variability in land surface conditions (dry and saturated bare soil, water stress, and well-watered vegetation) required by the TVDI method. Moreover, an adequate definition of dry and wet edges was achieved through scatter plots of semiarid and humid areas, respectively.

Regarding the extreme dry edge, the $R^2$ was 0.92, indicating that it was adequately represented by a linear equation. These results are consistent with several previous studies [3], [7], [14] that reported linear equations with $R^2 > 0.80$. The slope and

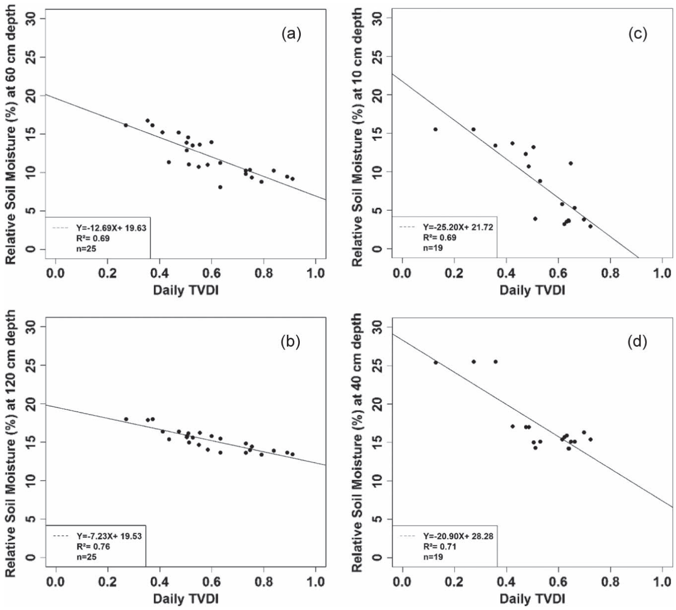


Fig. 5. Relationship between daily TVDI and relative SM at different soil depths in [(a) and (b)] La Ydalina Station and [(c) and (d)] Campus Tandil station.

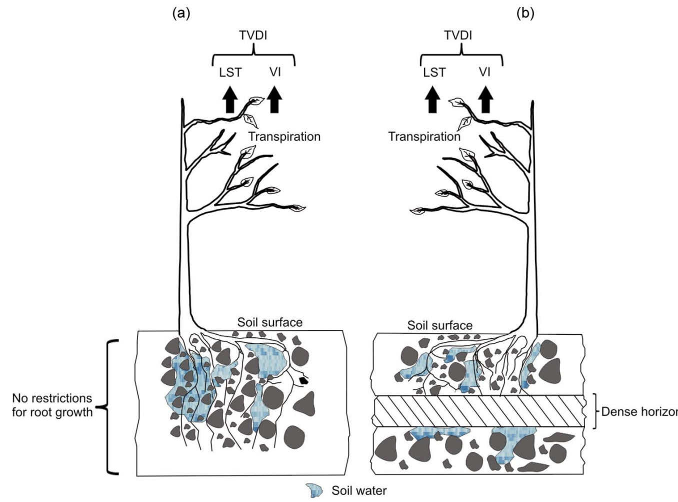


Fig. 6. Illustration of the relationship between transpiration process and TVDI in (a) deep root system and (b) shallow root system or soils with dense horizon. The TVDI would show subsurface soil water content depending on root system distribution in the soil profile.

intercept values ["$a$" and "$b$" in (1)] of $LST_{max}$ were $-20$ ($\pm 2$) and 331 K ($\pm 3$), respectively. The value of $LST_{min}$ was 296 K ($\pm 2$). These estimates were established as baselines for determining TVDI values across the whole data series. In addition, these edges were consistent with a previous multitemporal analysis (2002–2011) carried out in the study area [14].

### *B. Comparison to SM Measurements*

Earlier studies at regional scale [2]–[4], [7], [16], [17] have shown a strong relationship between spatial and temporal patterns of surface SM and TVDI. However, few works have analyzed the TVDI–subsurface-SM relationship.

To evaluate the ability of TVDI for subsurface soil water estimation, stress index values were compared with daily *in situ* relative SM measurements obtained from the aforementioned two stations placed in the study area (Fig. 5). The results show that the TVDI was sensitive to subsurface soil water fluctuations, decreasing with increase in SM. In La Ydalina station, SMs at different depths varied between 8% and 18%. In Campus Tandil station, they varied between 3% and 25%. This wide range of the data allowed us to test the methodology over different wetness conditions. Lower TVDI values and variation in Campus Tandil (0.13–0.72) than in La Ydalina (0.27–0.91) were observed. Although the water content was measured at different depths in each station, probably there are two reasons for those differences. One of them is the lower available water content for plant use in sandy loam and poorly structured soil of La Ydalina. Thus, high vegetation stress would be expected in soils with limited water availability. The other reason could be the higher sensitivity of maize (La Ydalina) to SM fluctuations than native grassland. Also, these processes could explain the higher slope of the obtained adjustments in Campus Tandil. A strong relationship between subsurface SM and TVDI was found in both stations, showing linear correlations with $R^2$ values of 0.69 (at 60-cm depth) and 0.76 (at 120-cm depth) in La Ydalina and 0.69 (at 10-cm depth) and 0.71 (at 40-cm depth) in Campus Tandil. The results are consistent with previous studies using thermal and reflectance data. In Thailand, the authors in [18], using an apparent-thermal-inertia approach with MODIS imagery, reported Pearson correlation coefficients between retrieved SM and measurements of 0.80–0.84, 0.54–0.57, and 0.49 for 10-, 100-, and 200-cm depths, respectively. Over agriculture cover type of western Canada, the authors in [19] found an agreement between the temperature vegetation wetness index and SM at different depths of the soil.

It should be noted that the aptitude of the TVDI to sense subsurface soil wetness fluctuations over vegetated areas depends on root system depth and root distribution in the soil (Fig. 6). The root biomass of native temperate grassland is mainly developed in shallow horizons of the soil [20]–[22]. On the other hand, crop root can explore deeper layers of soil, which would explain the high correlation between TVDI and SM at 120-cm depth in the sandy loam soil of La Ydalina station [Fig. 6(a)]. However, frequently, the root growth is inhibited by excessively dense soils for different reasons, including the soil resistance to penetration, poor aeration, and slow movement of water [23]–[25]. In this sense, different studies [26], [27] have reported that dense horizons (e.g., Bt horizon and fragipan) restrict the soil exploration by roots [Fig. 6(b)]. In the Campus Tandil station, no correlation was found between TVDI and soil water content at 60-cm depth, because of the presence of a Bt horizon at 40-cm depth and the shallow root system of grassland. In this manner, SM at 60-cm depth would not affect the water condition of vegetation in Campus Tandil because of the soil physical limitations and shallow soil exploration by roots. Therefore, although root distribution in the soil can vary between different species [28], deeper soil water content was inferred from TVDI images on cultivated surfaces (sandy loam soil) than on native grassland associated with a dense horizon.

## V. Conclusion

In this letter, we have demonstrated preliminarily the ability of the TVDI, which is based on LST and VI remotely sensed data, to estimate subsurface SM over crop and native grassland of Argentine Pampas. The traditional method of TVDI was improved using the EVI instead of the NDVI. The stress index showed a strong correlation ($R^2 = 0.69{-}0.76$) with daily subsurface soil water content measurements in Entic Hapludoll and Typic Argiudoll soils, increasing the index with a decrease of SM. In addition, we found that the potential of this index to reflect subsurface soil wetness fluctuations depends on root system depth, root distribution in the soil, and physical soil characteristics. In areas where deep root systems exist, high correlation between TVDI and soil water content was found up to 120-cm depth, showing the robustness of the index for spatial estimation of SM in the soil profile over large vegetated areas. A whole validation of the TVDI over several areas was not possible in the current context, but the results from the comparison with subsurface SM measurements were promising.

Given the limited works estimating subsurface SM using thermal and reflectance data, these results are valuable in areas where ground data are not available. As only remotely sensed data are needed to compute the TVDI, this method could be used to obtain maps of subsurface SM for hydrological and agricultural applications after estimating the TVDI–SM relationship for a study area. Future studies should analyze the TVDI/subsurface-SM relationship over several soils and vegetation types. Finally, microwave and dryness index data combination should be analyzed to study comprehensively hydrological processes in the soil–vegetation system.

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