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in

Erena M. (coord.), López-Francos A. (coord.), Montesinos S. (coord.), Berthoumieu J.-P. (coord.).
The use of remote sensing and geographic information systems for irrigation management in Southwest Europe

Zaragoza : CIHEAM / IMIDA / SUDOE Interreg IVB (EU-ERDF)
Options Méditerranéennes : Série B. Etudes et Recherches; n. 67

2012
pages 65-75

Assessment of vegetation indexes from remote sensing: Theoretical basis

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Abstract. Uncertainties in agricultural activities due to the scarcity of water and the increase in droughts could be ameliorated by considering early detection and spatio-temporal characterization of water stress conditions at a regional scale from remote sensing. Theoretical aspects of the spatio-temporal assessment of vegetation indexes related with soil moisture, based on remote sensing and meteorological data are presented.

Keywords. Remote sensing – Water stress indicators – Land surface temperature – Vegetation indexes – GIS.

Évaluation des indices de végétation par télédétection : Bases théoriques

Résumé. *Les incertitudes en la production agricole liées a la rareté de l'eau et l'augmentation des séche-resses peuvent être résolues par la détection précoce et la caractérisation spatio-temporelle du stress hydrique à échelle régionale. Les aspects théoriques de l'évaluation spatio-temporelle des indices de végé-tation liés à l'humidité du sol, basée sur la télédétection et les données météorologiques sont présentés.*

Mots-clés. *Télédétection – Indicateurs de stress hydrique – Température superficielle terrestre – Indices de végétation.*

I – Introduction

The potential of remote sensing in agriculture is high, because multispectral reflectance and temperatures of the crop canopies are related to photosynthesis and evapotranspiration (Basso *et al.*, 2004). Several studies present methodologies for the assessment of water stress indices from remote sensing (Moran *et al.*, 1994; Fensholt and Sandholt, 2003). The classical method for the monitoring and evaluation of vegetation water stress is the combined use of land surface temperature (LST) data and multispectral reflectance of the surface, from which the normalized difference vegetation index (NDVI) is derived. The information on wavelengths of the thermal region and visible / near-infrared (NIR), is relevant and useful for the purpose of monitoring the physiological state of vegetation and its level of stress, and especially the intensity of water stress.

In the assessment of the onset, severity, and duration of water stress and drought situations, indicators can be based on meteorological and crop data, or be indicators based only on remote sensing, or be process-based indicators.

Regarding the *indicators based on meteorological data*, the Crop Water Stress Index (CWSI) proposed by (Moran *et al.*, 1994), is widely applied. But the CWSI index, useful for surfaces completely covered with vegetation, requires a great deal of information in order to be applied.

As for *indicators based on remote sensing*, different methodologies of operational assessment of indices related with water deficit of soil and vegetation stress, soil moisture, could be applied. However, remote sensing-based products must be calibrated with ground data (ground truth). There will be a literature review of the main sensors currently used in relation to soil moisture estimation from remote sensing.

Soil moisture estimates can be obtained from various satellites, such as ERS SAR (European Remote Sensing Satellites, Synthetic Aperture Radar), Radarsat, ENVISAT ASAR, ADEOS II and EOS PM sensor AMSR (Advanced Microwave Scanning Radiometer). But most of them do not have temporal resolutions appropriate for monitoring highly dynamic processes. Among the latest tools that are available, the MIRAS (Microwave Imaging Radiometer using Aperture Synthesis) sensor of SMOS (Soil Moisture and Ocean Salinity) mission of the European Space Agency (ESA, 2009) should be highlighted. In all cases, the indicators (or variables) derived from remote sensing data must be validated *in situ* (ground truth).

In the case of *indicators estimated from remote sensing*, there indices that include ratios of two or more bands in the visible and NIR wavelengths (such as NDVI, etc.), and those obtained from the interpretation of LST-NDVI trapezoid *(Vegetation Index/Temperature Trapezoid*). These last include the Water Deficit Index (WDI) proposed by Moran *et al.* (1994) considering the Soil Adjusted Vegetation Index (SAVI) (Huete, 1988). The WDI index has been used to estimate evapotranspiration rates for mixed surfaces. WDI index reaches a value of 1 for conditions of extreme stress of the vegetation, and 0 for crop evaporation to its potential rate. The WDI index has been reformulated by Verstraeten *et al.* (2001), considering only terms of LST and air temperature.

Then Wang (2001) proposed the Vegetation Temperature Condition Index (VTCI), in which the LST-NDVI space behaved like a triangle. This methodology has been widely used in the U.S. Southern Plains (Wan *et al.,* 2004).

The Temperature-Vegetation Dryness Index (TVDI), proposed by Sandholt *et al.* (2002), is obtained from space LST-NDVI and can be used as an indicator of soil moisture and hence the vegetation water stress. Particularly in the rainy season, indices related to soil moisture obtained from wavelengths in the infrared short-wave and NIR can be a valuable supplement to the method based on LST-NDVI space interpretation. Since LST is very sensitive to atmospheric effects and clouds, the use of the SIWSI (Shortwave Infrared Water Stress Index) index, using near-infrared data (Fensholt and Sandholt, 2003) has been considered. According to these authors, working in areas of West Africa, the SIWSI is strongly related to soil moisture, and can be obtained even in the presence of clouds. Although from previous studies in Southeastern Spain (Garcia *et al*., 2006) it is not an appropriate index in semi-arid watersheds.

The STI Index (Standardized Thermal Index), obtained from data of air temperature and LST, may also constitute a relevant indicator of relative deficit of soil moisture (Park *et al*., 2004).

Finally, *indicators based on processes* are regarding with the modeling of actual evapotranspiration (ET_{act}). The methods considered simulate the mass and energy transfer between the atmosphere and surface.

II – Indices based on ratios of two or more bands in the visible and NIR wavelengths

1. NDVI (Normalized Difference Vegetation Index)

The Normalized Difference Vegetation Index (NDVI, Kriegler, 1969; Rouse *et al*., 1973), is based on the assumption that the vegetation subject to water stress presents a greater reflectivity in the visible region (0.4-0.7 μ) of the electromagnetic spectrum and a lower reflectance in the NIR region (0.7-1.1 μ). The NDVI is obtained by the following equation, where NIR is the near-infrared reflectivity and R corresponds to the red region of the electromagnet spectrum.

$$NDVI = \frac{NIR - R}{NIR + R} \qquad (1)$$

This index could be easily derived with the satellite information, using bands 1 and 2 in the case of AVHRR sensor (NOAA), or bands 3 and 4 in the case of ETM+ (Landsat). NDVI vary between -1 and 1.

2. RVI (Ratio Vegetation Index)

This RVI (Ratio Vegetation Index, Jordan, 1969), is estimated as,

$$RVI = \frac{NIR}{R} \quad (2)$$

3. GNDVI (Green Normalized Difference Vegetative Index) and DVI (Difference Vegetation Index)

The GNDVI (Green Normalized Difference Vegetative Index) is a modification of NDVI where the Red band is substituted by the reflectance in the Green band (Gitelson *et al*., 1996).

In the case of DVI (Difference Vegetation Index, Richardson and Everitt, 1992), is estimated as follows,

$$DVI = NIR - R \quad (3)$$

4. SAVI (Soil Adjusted Vegetation Index)

The SAVI (Soil Adjusted Vegetation Index) proposed by Huete (1988), takes into account the optical soil properties on the plant canopy reflectance. SAVI is involving a constant *L* to the NDVI equation, and with a range -1 to +1, is expressed as follows,

$$SAVI = \frac{NIR - R}{NIR + R + L}(1 + L) \quad (4)$$

Two or three optimal adjustment for *L* constant (*L*=1 for low vegetation densities; *L*=0.5 for intermediate vegetation densities; *L*= 0.35 for higher densities), are suggested by Huete (1988).

5. TSAVI (Transformed Adjusted Vegetation Index)

The TSAVI (Transformed Adjusted Vegetation Index) original method was modified by Baret and Guyot (1991), as follows,

$$TSAVI = a\frac{NIR - aR - b}{aNIR + R - ab + \chi(1 + a^2)} \quad (5)$$

where *a* and *b* are soil line parameters, and *X* is 0.08. TSAVI varies from 0 for bare soil to 0.7 for very dense canopies (Baret and Guyot, 1991).

III – Interpretation of LST – NDVI space

The combination of LST and NDVI can provide information about the condition of vegetation and moisture on the surface. The combined information on the wavelengths of the thermal region and the visible/NIR region has proved satisfactory for monitoring vegetation conditions and stress, especially water stress. Numerous studies have provided different interpretations of space LST-NDVI, based on a wide range of vegetation types and crops, climate, and different scales.

The NDVI is a rather conservative indicator of water stress, because the vegetation remains green after the start of this stress. By contrast, the LST increases rapidly with the water stress

(Sandholt *et al*., 2002). For a given dry zone, the relationship between LST and the NDVI is characterized by a cloud of dispersion in the LST-NDVI space, the highest values of LST correspond to the lowest values of NDVI (Nemani and Running, 1989). This relationship is often expressed by the slope of a line fitted to the dry edge of the space LST-NDVI.

Numerous studies have focused on the relationship between LST and the NDVI, to provide indirect information about the vegetation stress and the soil moisture conditions. Nemani and Running (1989) related the slope LST-NDVI to stomatal resistance and evapotranspiration of a deciduous forest. Boegh *et al*. (1998) and Jiang and Islam (1999), related the slope LST-NDVI to surface evapotranspiration. The analysis of LST-NDVI space was also used to derive information on conditions of regional soil moisture (Carlson and Gillies, 1993; Goetz, 1997, Goward *et al*., 2002 and Sandholt *et al*., 2002).

Often the estimate of the slope LST-NDVI is not direct (Troufleau and Soegaard, 1998), typically due to the significant variability caused by surface heterogeneity (Czajkowski, 2000). The scattering cloud formed by the LST and NDVI (or vegetation index) both derived from remote sensing, often results in a triangular (Price, 1990, Carlson *et al*., 1994) or trapezoidal (Moran *et al*., 1994) shape, if the data represent a full range of vegetation covers and soil moisture content. Different types of surfaces can have different slopes LST-NDVI and intercept the atmospheric conditions and surface moisture equally; the choice of scale can influence the shape of the relationship between these variables (Sandholt *et al*., 2002).

The vegetation index is linearly related to vegetation cover, and the gradient LST-air temperature is as a function of vegetation index. Assuming these premises, Moran *et al.* (1994) derived the shape of LST-NDVI space from modeling and proposed a theoretical justification for the concept.

The interpretation of the LST for bare soil is not straightforward, because the measured temperature integrates both the temperature of the soil surface temperature and vegetation temperature, and the components cannot be linearly related. Other studies have shown that, at least for well irrigated areas, the relationship between LST and the NDVI is more directly related to the moisture of the soil surface (Friedl and Davis, 1994).

Moran *et al.* (1994) combined the method of LST-NDVI space with standard meteorological data, as well as remote sensing data, to estimate the Water Deficit Index (WDI). They used the temperature difference between LST and air temperature ($\Delta T_s = LST - T_a$) and its relationship to vegetation index.

Sandholt *et al.* (2002) presented a simplification of the WDI index, which considers the variations in air temperature, water balance and atmospheric conditions to estimate the LST-NDVI space. The method is conceptually and computationally straightforward, and only uses information from satellites to define the Temperature-Vegetation Dryness Index (TVDI).

Other authors, such as Prihodko and Goward (1997), proposed the Temperature-Vegetation Index (TVX), estimated as a slope in the LST-NDVI space for a homogeneous area with little or no variation in surface moisture conditions. This method, like that proposed by Sandholt *et al.* (2002), does not requires auxiliary data. This is an advantage over other methods for defining the limits of LST-NDVI space, with high requirements of detailed information about weather conditions, including vapor pressure deficit, wind speed and surface resistance.

Adapting the method proposed by Sandholt *et al.* (2002), described above, the location of a pixel in the LST-NDVI space is determined by several factors:

(i) *Vegetation cover*. The vegetation cover does not necessarily have to be related to spectral vegetation indices through a simple linear transformation. Furthermore, the fraction of vegetation cover affects the amount of bare soil and vegetation, visible by the sensor. Thus the LST can be affected by differences in temperature radiated by the bare soil and by sparse vegetation

(ii) *Evapotranspiration (ET).* The evapotranspiration can control the LST by the surface energy balance. To lower evapotranspiration, more energy will be available for heating the surface. The stomatal resistance, which characterizes the control of the plants to water vapor transfer by transpiration, is a key parameter in the estimation of ET. With greater stress of plants, there is therefore more resistance of the plants to water transfer. This resistance can be expressed in terms of soil factors (soil moisture or soil water potential) and of climate factors (radiation, relative humidity and air temperature).

(iii) *Thermal properties of the surface*. In the case of partially vegetated surfaces, LST is influenced by the heat capacity and thermal conductivity of the soil. These properties are a function of soil type, and change with the soil moisture.

(iv) *Net radiation*. The available energy, incident on the surface, affects the LST. The radiation control of LST implies that areas with high albedo values present low temperatures. The albedo is controlled by the type of soil, surface soil moisture and vegetation cover.

(v) *Weather conditions and surface roughness*. The ability to transfer energy from the surface to the atmosphere is an important factor in controlling the LST. The concept of *surface resistance* is used to quantify this ability to transfer sensible and latent heat (evaporation). This resistance depends on the surface roughness, wind speed and atmospheric stability conditions. Under similar conditions of leaf area index and water availability, the vegetation cover with high roughness (forests) and low surface resistance will have lower LST than surfaces with low roughness (low vegetation) and higher surface resistance. This influences the shape of LST-NDVI space.

The above-mentioned factors have been summarized in Fig. 1. It is clear that the relationship between LST and surface soil moisture is not straightforward. For bare soil with constant irradiance, the LST is defined primarily by the soil moisture content, via control of evaporation and thermal properties of the surface (Sandholt *et al*., 2002).

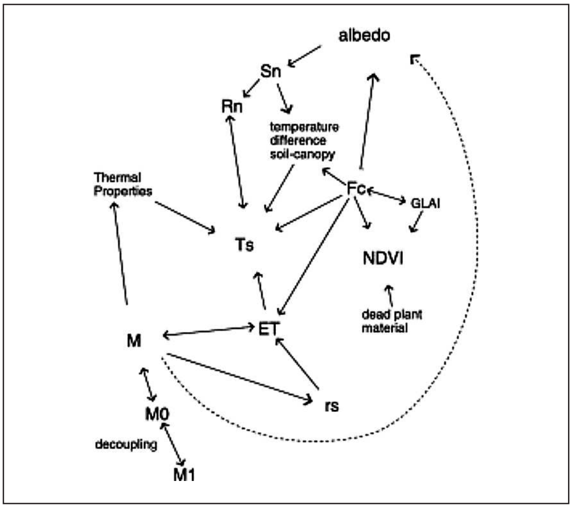

Fig. 1. Factors for the definition of LST of the illuminated surface (adapted from Sandholt *et al*., 2002).

From Fig. 1 above, variables enclosed by the circle can be estimated using satellite data. S_n = shortwave net radiation; R_n = net radiation; *GLAI* = leaf area index; F_c = fraction of soil covered by vegetation; *ET* = evapotranspiration; *rs* = stomatal resistence; *M1* = soil moisture content (root zone); *M0* = moisture content of top soil.

Figure 2 depicts the concept of LST-NDVI space. The left edge represents bare soil from dry to wet (top-down) range. As the amount of green vegetation increases, the NDVI value also increases along the X axis and therefore the maximum LST decreases. For dry conditions, the negative relationship between LST and NDVI is defined by the upper edge, which is the upper limit of LST for a given type of surface and climatic conditions (Sandholt *et al*., 2002).

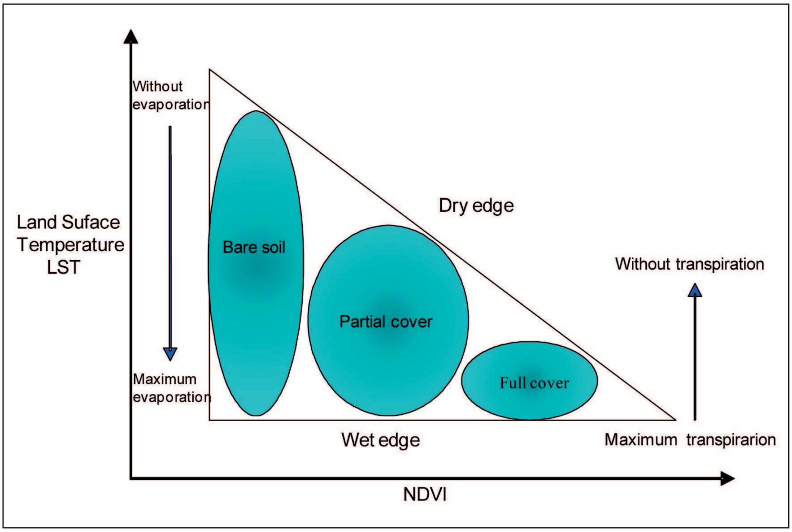

Fig. 2. Simplified LST/NDVI space (adapted from Lambin and Ehrlich, 1996 in Sandholt *et al*., 2002).

1. TVDI index

For deriving information regarding with content of surface soil moisture, Sandholt *et al.* (2002) proposed an index of aridity (TVDI), that takes values of 1 for the dry edge (limited water availability) and 0 for the wet edge (maximum evapotranspiration and thereby unlimited water availability).

The TVDI is inversely related to soil moisture, where high values indicate dry conditions and low values wet conditions. This is based on the fact that the LST is mainly controlled by the energy balance and thermal inertia, factors influencing moisture conditions at the surface and in the root zone (Andersen *et al*., 2002).

Following the concept in Fig. 3, the value of TVDI for a given pixel in the LST-NDVI space, is calculated as the ratio of lines A and B, and therefore calculated using the following equation (Sandholt *et al.* 2002),

$$TVDI = \frac{A}{B} = \frac{LST - LST_{\min}}{a + bNDVI - LST_{\min}} \quad (6)$$

where LST_{min} is the minimum LST in the triangle, defining the wet edge, and LST corresponds to the pixel. Then, *a* and *b* are the coefficients of the regression line that define the dry edge, as follows,

$$LST_{max} = a + bNDVI \quad (7)$$

where LST_{max} is the maximum LST for a certain NDVI.

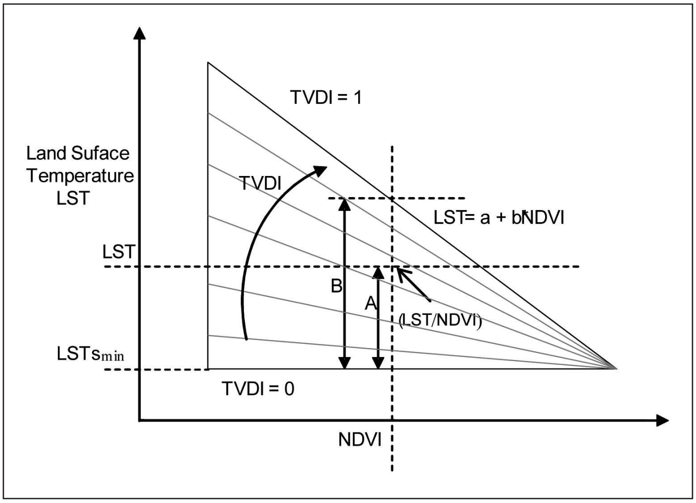

Fig. 3. Definition of TVDI index (adapted from Sandholt *et al.*, 2002).

The parameters *a* and *b* are estimated based on pixels from an large enough area to represent the full range of surface soil moisture content, from wet to dry, and from bare soil to fully vegetated surfaces.

Uncertainty about TVDI is greater in the high range of NDVI, where the TVDI isolines are grouped. The simplification of representing LST-NDVI with a triangle instead of a trapezoid (eg Moran *et al*., 1994) may add uncertainty to TVDI estimation for high values of NDVI. The wet edge is also modeled as a horizontal line as opposed to an inclined one, as in the trapezoidal method, which can lead to an overestimation of TVDI for low NDVI.

The TVDI isolines correspond to the TVX index, proposed by Prihodko and Goward (1997), thus being able to estimate such TVDI isolines as multiple superimposed TVX lines. For drier conditions, several studies of LST-NDVI spaces present steep slopes (eg, Goetz, 1997 and Nemani *et al*., 1993), which is consistent with TVDI. Since TVDI can be estimated for each pixel, the spatial resolution of the data is fully maintained. TVX requires an area wide enough for determination of the slope in the LST-NDVI space.

The main advantages of TVDI are: (i) its simplicity of calculation; and (ii) its derivation from satellite data alone regardless of factors such as weather, vapor pressure deficit, wind speed and surface resistance. However, this approach requires a large number of remote sensing observations to accurately define the limits of that space (Sandholt *et al*., 2002).

2. Water Deficit index

The Water Deficit Index (WDI, Moran *et al*. 1994), to estimate evapotranspiration in both areas completely covered by vegetation or partially covered, is based on the interpretation of the trapezoid formed by the relationship between the difference in LST and air temperature versus vegetation cover fraction (or vegetation index). The WDI quantifies the relative rate of latent heat flux, so it shows a value of 0 for fully wet surface (evapotranspiration only limited by the atmospheric demand), and 1 for dry surfaces where there is no latent heat flux.

The WDI index could be expressed as follows,

$$WDI = 1 - \frac{ET_{act}}{ET_{pot}} = 1 - \left[\frac{(LST_{\max} - T_a) - (LST - T_a)}{LST_{\max} - T_a) - (LST_{\min} - T_a)} \right] \quad (8)$$

where LST_{max} and LST_{min} are maximum and minimum LST respectively; ET_{act} and ET_{pot} represent actual and potential evapotranspiration respectively, found for a given vegetation cover (or vegetation index) in the left and right edges of the trapezoid VITT (Vegetation index versus difference of temperature). Then, T_a represents air temperature. Verstraeten *et al.* (2001) reformulated the WDI index equation, based on the trapezoid, considering the difference of temperature on the ordinate axis and the vegetation index on the abscissa axis.

IV – Other indexes

1. STI index

The Standardized Thermal Index (STI) describes the deviation experienced LST with respect to the air temperature, as the drought conditions are accentuated (Park *et al*., 2004). The STI index is based on the hypothesis that water-stressed areas present low values of NDVI and temperature gradients between the surface and the air, higher than in non-drought conditions. Therefore, the variation of this gradient will be inversely related to soil moisture and evapotranspiration of the area, and directly related to water stress.

The indicator ranges between 0 and 1, and it is defined by the following equation (Park *et al*., 2004):

$$STI = \frac{(LST - T_{air_{mean}})_{acum}}{(LST + T_{air_{mean}})_{acum}} \quad (9)$$

where $T_{air\ mean}$ is the mean air temperature. The STI index values show a significant correlation with the deviation of the NDVI. This demonstrates that higher values of STI correspond with more severe droughts.

Several studies have shown that the cumulative deviations of LST present significant negative relationships with soil moisture content and the ratio ET_{act}/ET_{pot}, while they have positive relationships with the ration moisture deficit/ET_{pot}. Then, it was found that STI values of 0.2 correspond to a decline of 15% in NDVI, making this the threshold for thermal detection of drought conditions.

2. SIWSI index

Physical models based on radiative transfer have shown that changes in water content of plant tissues present a large effect on leaf reflectance in several regions of the spectrum between the wavelengths of 0.4 to 2.5 mm. A major absorption value is presented in these wavelengths by foliar surfaces in well-hydrated tissues.

The reflectance is inversely related to water content (Ceccato *et al*., 2001), therefore an increase in the value of reflectance at these wavelengths implies in most cases a plant response to some type of stress, including water stress (Carter, 1994). In this case, it is possible to obtain a direct measurement of water content in plants. The region of the spectrum in which these changes occur is the short-wave infrared range 1.3-2.5 mm (SIR, Short Infrared), where the amount of water available in the internal structure of the leaf controls the spectral reflectance (Tucker, 1980). To illustrate this fact, Fig. 4 represents the location of the bands 5 and 6 of MODIS sensor (TERRA satellite of NASA), and the reflectance of a vegetated surface with different soil moisture content (CW).

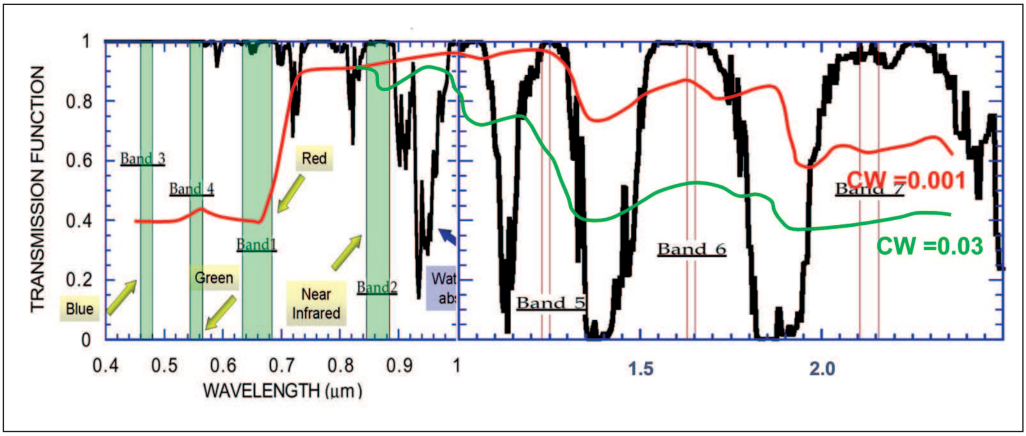

Fig. 4. Representation of MODIS sensor bands (source: Fensholt and Sandholt, 2003).

The reflectance of bare soil, leaf biochemical parameters, internal structure, leaf area index and the influence of the atmosphere affect the value of reflectance measured by satellite. Therefore, the influence of water in the tissues of the plant is needed for it to be independent of other factors. The SIWSI index with its formulation seeks to achieve this objective, and can be expressed considering the 6 band (eq. 10) or 5 band (eq. 11) of MODIS, which, as was seen from Fig. 4, can discern these differences,

$$SIWSI(6,2)= (r_6 - r_2)/((r_6+r_2) \quad (10)$$

$$SIWSI(5,2)= (r_5 - r_2)/((r_5+r_2) \quad (11)$$

where ρ is the reflectance in the spectral range of MODIS 841 a 876 nm in the band 2, 1230 a 1250 nm in the band 5 and 1628 to 1652 nm in the band 6. The SIWSI values from both equations are normalized, varying from -1 to 1. A positive value represents water stress on vegetation.

V – Conclusions

Some of the most widely used indicators, based on remote sensing, to assess water stress of vegetation, have been presented. It is important that the results of these methodologies are contrasted with the ground truth.

Acknowledgments

The funding from EU Project TELERIEG SUDOE INTERREG IV B, as well as the support from Project CGL2008-02530/BTE financed by the State Secretary of Research of Spanish Ministry of Science and Innovation (MICINN), are acknowledged.

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