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Contribution of remote sensing in analysis of crop water stress. Case study on durum wheat

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Abstract. Precision irrigation requires frequent information on crop conditions spatial and temporal variability. Image-based remote sensing is one promising techniques for precision irrigation management. In this study, we investigated the use of broad band multispectral (visible, near infrared and thermal infrared bands) and thermal airborne imagery for the characterization of water status of durum wheat crop through two indices: the Water Deficit Index (WDI) and the Simplified Surface Energy Balance Index (S-SEBI). Comparisons between these two indices and the ratio between actual and potential evapotranspiration (AET/PET) show that such techniques are promising for precision irrigation management.

Keywords. Irrigation – Water stress – Remote sensing – Thermal infrared – Airborne images – Surface temperature – WDI – S-SEBI – Evapotranspiration.

Contribution de la télédétection à l'analyse du stress hydrique des cultures. Etude de cas du blé dur

Résumé. *L'irrigation de précision requiert des informations fréquentes sur la variabilité spatiale et temporelle de l'état des cultures. L'imagerie acquise par télédétection constitue une technique prometteuse pour la gestion de l'irrigation de précision. Dans cette étude, nous avons étudié l'utilisation de l'imagerie multispectrale large bande (bandes visible, proche infrarouge et infrarouge thermique) acquise par voie aéroportée pour la caractérisation de l'état hydrique des cultures de blé dur à travers deux indices: le Water Deficit Index (WDI) et le Simplified Surface Energy Balance Index (S-SEBI). Les comparaisons entre ces deux indices et l'indice de satisfaction des besoins en eau de la plante (ETR / ETM) montrent que ces techniques sont prometteuses pour la gestion de l'irrigation de précision.*

Mots-clés. *Irrigation – Stress hydrique – Télédétection – Infrarouge thermique – Images aéroportées – Température de surface – WDI – S-SEBI – Évapotranspiration.*

I – Introduction

In the present context of global warming, crops are increasingly faced with non-optimal growing conditions. Thereby, researches on crop tolerance to water stress or a better use of irrigation are the major challenges of tomorrow's agriculture (Hamdy *et al*. 2003). Agriculture is the most important water-consuming activity in the world but would consume two times more water than necessary (Fernandez and Verdier, 2004). In the past few decades, new approaches for plant water status sensing have been proposed using infrared thermometry. Canopy temperature has been known for a long time to be linked to the water status of crops . Based on this statement, many crop water stress indices derived from thermal infrared (TIR) measurements were developed, and some of these have been suggested for use in irrigation management. The most successful index is the crop water stress index (CWSI) that has been empirically developed by Idso *et al*. (1981) and theoretically defined by Jackson *et al*. (1981). CWSI is restricted to full-canopy conditions, to avoid the influence of viewed soil on the canopy temperature measurements. However, when thermal infrared spectra are remotely sensed at the vertical mode using an aircraft platform, the difficulty in interpreting these data as an index of crop water stress is linked to the proportion of soil that can be viewed by the sensor over partial crop cover. To overcome these limitations, Moran *et al*. (1994) developed the Vegetation Index / Temperature (VIT) concept, which allows for the application of the Crop Water Stress Index (CWSI) to partially covered canopies. It is based on the relationship between surface minus air temperature and a spectral vegetation index, such as the Normalized Difference Vegetation Index (NDVI) (Rouse *et al*., 1973), representing the crop cover fraction. From this concept, Moran *et al*. (1994) developed the Water Deficit Index (WDI), which is related to the ratio of actual (AET) and potential (PET) evapotranspiration (WDI = 1 – AET / PET) and which is adapted to partially covered and fully vegetated canopies. Roerink *et al.* (1999) also proposed a Simplified Surface Energy Balance Index (S-SEBI), based on the use of the (temperature, albedo) space to estimate the evaporative fraction from visible, infrared and thermal remote sensing measurements.

The general objective of this study is to test the ability of an ultra-light airborne system equipped with multispectral sensors (visible, near infrared and thermal) to characterize the water status of durum wheat crop through WDI and S-SEBI indices at field scale.

II – Material and methods

In order to validate the use of broad band multispectral (visible and infrared bands) and thermal airborne imagery for the characterization of water status of durum wheat crop, we compared WDI and S-SEBI derived from the aerial acquisition with AET/PET derived from a crop model («PILOT», Maihol *et al*., 1997 and Maihol *et al*., 2004) and in situ measurements.

The study was conducted in two farms (in Prades and Castries cities) located near Montpellier. In each farm, two durum wheat fields having the same characteristics and agricultural practices (cultivar, soil, nitrogen supply…) were chosen. In one field per farm, the irrigation was stopped during the experiment in order to obtain contrasted water statuses between the fields.

Two flights were performed above each field during summer 2011.

1. Data acquisition

A. Aerial acquisitions

a] Spectral image acquisition

The acquisition system used in this study consisted of an ultra-light aircraft or and helicopter equipped with sensors that measured the sunlight reflected in four different spectral bands, as well as the radiation emitted by the Earth's surface. To measure the radiometric signal in the visible RGB spectral bands (Red, Green and Blue), a commercial camera (Sony A850) was used. The same type of camera was adapted and equipped with a 715 nm band pass filter (XNiteBPG, LDP LLC) to measure the radiation in the Near Infrared (NIR) spectral band. The settings of the two cameras (aperture, shutter speed, and sensitivity) were kept unchanged throughout the duration of the experiment. Images were recorded in raw format, allowing us to work on unprocessed CMOS data files.

The radiation emitted by the canopy was also measured using a microbolometer thermal infrared (TIR) camera (B20 HSV, FLIR). The radiance detected over the 7.5-13 µm spectral band is equivalent to the temperature, assuming a target emissivity equal to unity. The system provided 240 x 320-pixel images with a radiometric resolution of 0.1°C and an absolute precision of 2°C.

b] Pre-processing

The signal measured by a numeric camera is not linearly proportional to the radiance of the target. Factors affecting the signal are related to features of the camera (colour processing algorithms, camera settings and vignetting) and environment (sun geometry, atmosphere and flight altitude). The correction steps that were applied to the images (decoding the digital photo format and vignetting correction) are described in Lebourgeois *et al*. (2008a).

When remotely sensed from airborne sensors, the thermal infrared signal emitted by crops must be corrected for atmospheric effects (Jiménez-Muñoz and Sobrino, 2006). To correct for these effects, we used linear regressions established between ground and airborne surface temperature measurements for each acquisition date [see details in (Lebourgeois *et al*., 2008b)].

Blue, green, near infrared and thermal infrared images were co-registered using the red band as a reference.

B. In situ *measurements*

In situ measurements of soil water status and crop parameters (leaf area index, leaf humidity, foliar potential) were performed weekly on one point in each field.

2. Evapotranspiration indices

A. WDI and S-SEBI indices

The Vegetation Index / Temperature concept is based on the trapezoidal shape formed by the relationship between (Ts – Ta; Ts: leaf surface temperature; Ta: air temperature) and vegetation cover (Fig. 1), which can be represented by a spectral vegetation index such as NDVI. Theoretical equations for computation of the trapezoid vertices are given in (Moran *et al*., 1994). WDI has been defined from this concept (Moran *et al*., 1994). It is related to the ratio between actual (AET) and potential evapotranspiration (PET) and can be calculated using the following equation:

$$WDI = 1 - (AET/PET) = CA / BA$$

On the below graph of Fig.1: for a given fractionnal vegetation cover, A represents the surface temperature for a PET situation, B the surface temperature for the maximum stressed situation, if C represents the measured surface temperature then CA / BA represents the difference between C and A divided by the difference between B and A).

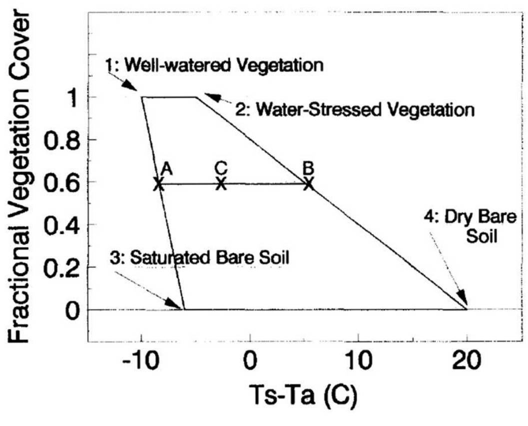

Fig. 1. Illustration of Moran's VIT concept and WDI calculation.

The analytical calculation of WDI requires many meteorological on-site measurements. When these inputs are missing, WDI can be defined empirically (Clarke, 1997) by calculation of the trapezoid based on the image data. However, defining empirical WDI boundaries is not easy when the scenes viewed by the airborne optical and thermal infrared sensors do not contain the dry and wet bare soil and vegetated states corresponding to the vertices of the trapezoid. Therefore, we chose to define the WDI boundaries using a statistical method by calculating the 1% and 99% quantiles of NDVI for the upper and lower limits. Lines (1-3) and (2-4) (Fig. 1) were defined by calculating the 1% and 99% quantile regressions of (Ts – Ta) as a function of NDVI. The calculations were carried out using the R software, according to Koenker (2008).

The Simplified Surface Energy Balance Index (S-SEBI) has been developed by Roerink *et al.*(1999) to solve the surface energy balance with remote sensing techniques on a pixel-by-pixel basis. S-SEBI requires scanned spectral radiances under cloudfree conditions in the visible, near-infrared and thermal infrared range to determine its constitutive parameters: surface reflectance or albedo, surface temperature. With this input the energy budget at the surface can be determined. The upper and lower limits of the (albedo, surface temperature) scatter plot represent dry (Hmax) and well-watered conditions (λEmax). S-SEBI is then computed as follow (see also Fig. 2):

$$S\text{-}SEBI = T_H - T_S / T_H - T_{\lambda E}$$

Where T_s is the surface temperature, and T_H and $T_{\lambda E}$ are the maximal and minimal temperatures for a given range of albedo.

For more information concerning the upper and lower limits calculation, see Roerink *et al*. (1999).

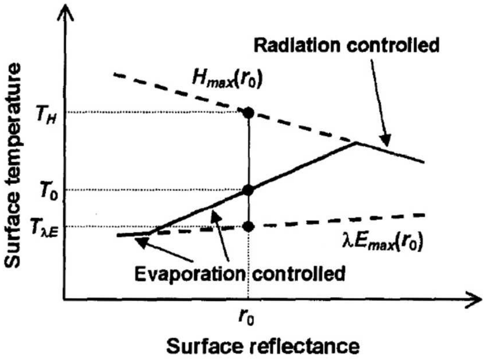

Fig. 2. Illustration of Roerink's S-SEBI concept.

WDI and S-SEBI ranges from 0 to 1:

– for WDI: 0 is a well-watered crop transpiring at the maximum rate and 1 is stressed;

– in contrast for the S-SEBI 1 is a well-watered crop and 0 is stressed.

These two indices were calculated for each acquisition date.

B. AET / PET

AET/PET was simulated using «PILOT» crop model (Maihol *et al*., 1997 and Maihol *et al*., 2004) and from *in situ* measurements. This model allows the simulation of water balance from an actual conduct or a defined irrigation strategy (dates and amount of water). The model outputs are validated through the comparison between observed and simulated water stock. It provides a daily estimation of crop water stress. For a best simulation, PET is corrected by a crop coefficient (Kc) to obtain the maximal evapotranspiration (MET).

III – Results and discussion

1. Water stress indices

A. Indices derived from airborne acquisitions

Maps of water stress indices derived from airborne images correctly reflect the situation observed in the field as seen on Fig. 3 example: high WDI on non-irrigated plot, very low WDI on parts of the field where irrigation is in progress.

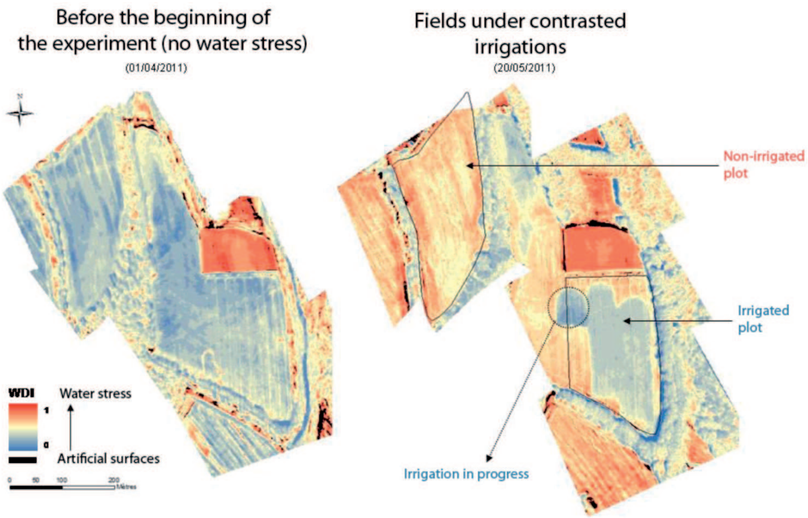

Fig. 3. Maps of WDI (Castries fields).

The dispersion of WDI values (data from the second flight) shows a good discrimination between irrigated plots and non-irrigated plots (Fig. 4).

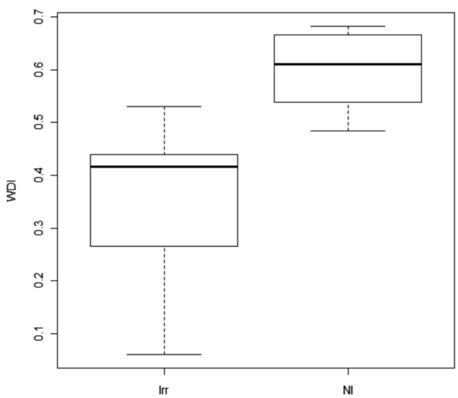

Fig. 4. Dispersion of WDI of irrigated (irr) and non-irrigated (NI) plots (flight no. 2).

B. AET / MET

The temporal evolution of AET / MET obtained from «PILOT» simulations seems consistent with water supply (Fig. 5). However, some parameters (drainage, runoff, root depth) could not be measured during the study. Consequently, they have been estimated and adjusted until the simulated data better approximate the measured data.

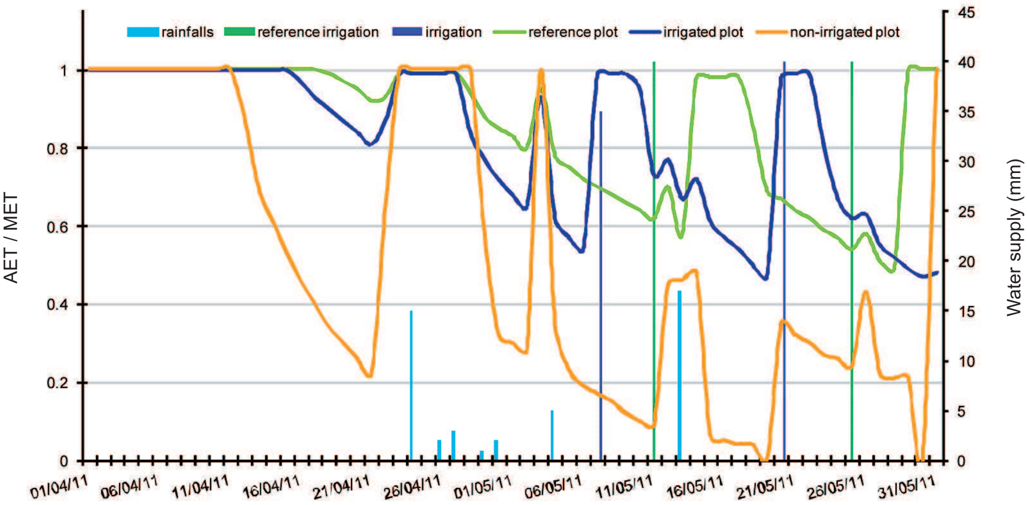

Fig. 5. Evolution of simulated AET / MET and water supply (irrigations and rainfalls) on Prades fields.

2. Relationships between AET / MET and indices derived from airborne acquisitions

A. Evapotranspiration: AET / MET

Linear regressions show a good correlation between indices derived from airborne acquisitions and AET / MET ($R^2 = 0.64$ and $R^2 = 0.61$ for WDI and S-SEBI respectively). An example of linear regression between WDI and AET MET is given on Fig. 6 (left). In this graph, we can see that the correlation between WDI and AET / MET is weaker for the points corresponding to the non irrigated plots. This is due to "PILOT" model that is not initially designed to simulate AET / MET in conditions of strongly limited water supply. Therefore, the points corresponding to non irrigated plots were removed, improving the relationships between AET / MET and the water stress indices derived from airborne acquisitions ($R^2 = 0.8$ and $R^2 = 0.75$ for WDI and S-SEBI respectively) (see Fig. 6, right).

B. Plant humidity

Relationships between the water stress indices derived from airborne acquisitions and the other measurements of plant water status (like leaf humidity or leaf potential) are weak as seen in Table 1.

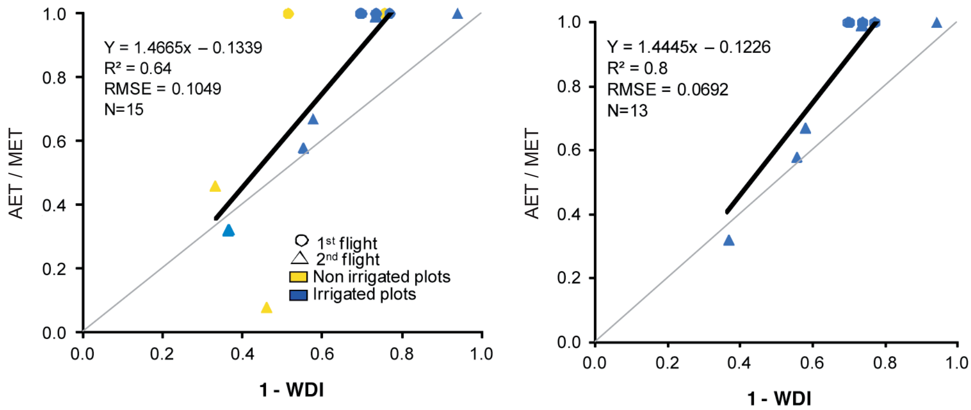

Fig. 6. Linear regressions between WDI and AET / MET (left: all values, right: without values of non irrigated plots).

Table 1. Relationships between the water stress indices derived from airborne acquisitions (WDI, S-SEBI) and the other measurements of plant water status

R^2	WDI	S-SEB	INb points
AET/MET (all points)	0.64	0.61	15A
ET/MET (without non-irrigated fields)	0.8	0.75	11
Leaf humidity	0.06	0.01	8
Leaf potential	0.06	0.23	4
Available soil water	0.32	0.5	13

IV – Conclusion

In this study, we show that the calculation of WDI and S-SEBI using multispectral airborne imagery in visible, near infrared and thermal infrared bands allowed the estimation of the water status of durum wheat through a good estimation of AET / MET. These first results are promising regarding the use of remote sensing techniques for precision irrigation management.

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