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Remote sensing based water balance to estimate evapotranspiration and irrigation water requirements. Case study: Grape vineyards

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Abstract. In this paper the basis for the incorporation of remote sensing data into a soil water balance through the relationship between the basal crop coefficient (Kcb) and vegetation indices (VI) for grape vineyards is described. The remote sensing soil water balance has been applied in previous studies obtaining accurate estimates of actual evapotranspiration and crop coefficient in grape vineyard, and this methodology is evaluated in order to estimate irrigation necessities in an irrigated vineyard in Albacete, Spain. The model was also applied in vineyards under high deficit irrigation management. The model results: total irrigation necessities, crop evapotranspiration, and water stress coefficient (Ks) are analyzed. The evolution of Ks was compared with experimental measurements of stem water potential (ψs). Ks calculated present values between 0.2 and 0.4 during July and August, indicating severe stress levels. The ψs tendency coincides with the modelled Ks, showing a parallel evolution and values of about -1.4 MPa during the stress period. The evidences presented indicate that Kcb derived from VI overestimate the actual crop coefficient under water stress conditions. In these cases, it is therefore essential to properly estimate the stress coefficient in order to accurately estimate actual crop evapotranspiration and crop coefficient.

Keywords. Vineyard – Evapotranspiration – Vegetation indices – Basal crop coefficient – Soil water balance – Crop water necessities.

Bilan hydrique fondé sur la télédétection pour estimer l'évapotranspiration et les besoins en eau d'irrigation. Étude de cas sur des vignobles

Résumé. *Dans cet article sont décrits les fondements pour l'incorporation des données issues de la télédétection dans un bilan hydrique du sol à travers la relation entre le coefficient de base de la culture (Kcb) et les indices de végétation (VI) pour des vignobles. On a utilisé le bilan hydrique du sol par télédétection dans des études préalables, ce qui a permis d'obtenir des estimations exactes de l'évapotranspiration réelle et du coefficient des cultures pour des vignobles, et cette méthodologie est évaluée afin d'estimer les besoins en irrigation dans un vignoble à Albacete, Espagne. Le modèle a aussi été appliqué dans des vignobles conduits sous irrigation fortement déficitaire. Comme résultats du modèle, les besoins en irrigation totale, l'évapotranspiration des cultures, et le coefficient de stress hydrique (Ks) ont été analysés. L'évolution de Ks a été comparée aux mesures expérimentales de potentiel hydrique au niveau des tiges (ψs). Ks a pris des valeurs actuelles allant de 0,2 à 0,4 pendant juillet et août, indiquant des niveaux de stress sévères. La tendance ψs coïncide avec le Ks modélisé, montrant une évolution parallèle et des valeurs d'environ -1,4 MPa pendant la période de stress. Les résultats présentés indiquent que le Kcb dérivé de VI surestime le coefficient réel des cultures en conditions de stress hydrique. Dans ces cas, il est donc essentiel d'estimer de façon appropriée le coefficient de stress afin d'évaluer avec exactitude l'évapotranspiration réelle des cultures et le coefficient des cultures.*

Mots-clés. *Vignobles – Évapotranspiration – Indices de végétation – Coefficient de base de la culture – Bilan hydrique du sol – Besoins en eau des cultures.*

I – Introduction

Precise information about crop water necessities, adapted to the actual crop development and meteorological conditions, and its knowledge on near-real time is a paramount in agriculture. Remote sensing data, obtained from space, aerial or terrain platforms could provide significant advances for this purpose. During the last decades some research efforts have been conducted to develop and to evaluate specific algorithms, models, and indicators for agronomic applications based on remote sensing data, as well as to provide easy and near-real time access to this information.

One of the most accepted methodologies for the estimation of crop water requirements is the use of reference evapotranspiration and a crop coefficient (FAO-56 methodology) (Allen *et al.*, 1998). Estimation of the crop coefficient (Kc) is required to calculate crop evapotranspiration and maintaining a soil moisture balance as described by the FAO56 methodology. A large amount of research has been conducted to estimate the standard values and temporal evolution of Kc, but the adaptation to local crop varieties, management practices and climate is always recommended.

For grapevines crops, such as many woody crops, local practices can largely vary many parameters related to crop evapotranspiration such as canopy cover, inter-rows vegetation and irrigation frequency. The review of vineyard Kc values obtained by field crop evapotranspiration measurements reveal Kc values ranging between 0.5 (Campos *et al.*, 2010; Montoro, 2008) to up to 0.9 (Teixeira *et al.*, 2007; Williams and Ayars, 2005) in irrigated row vineyards. This range is greater if we consider the mean values of 0.2 published by Oliver and Sene (1992) for rainfed bush vineyards.

Numerous studies rely on the capability of multispectral vegetation indices (VI) to assess vegetation development and so to estimate Kc. Several authors have reported relationships between Kc and VI and applications of this methodology (Bausch and Neale, 1987; Choudhury *et al.*, 1994; Duchemin *et al.*, 2006; Er-Raki *et al.*, 2007; González-Dugo and Mateos, 2008; González-Piqueras, 2006; Hunsaker *et al.*, 2003; Jayanthi *et al.*, 2007). These previous studies developed relationships between vegetation indices and basal crop coefficient for herbaceous crops, but the development and applications of this relationship for fruit trees was on the border of knowledge for this methodologies.

This paper aims to communicate an illustrative explanation about the practical application of remote sensing based soil water balance for grape vineyards and some of the most recent research applied to remote sensing soil water balance in grape vineyards are presented and analyzed.

II – Remote sensing soil water balance basis

1. Soil water balance in the root zone

The soil water balance (SWB) described in the FAO-56 methodology and reproduced in this work is a one layer soil water balance (performed in the plant root zone) with additions to simulate soil evaporation from the surface layer. SWB formulation for the root zone is presented in (Equation 1). $D_{r,i}$ and $D_{r,i-1}$ referring to the soil moisture depletion on the day and previous day time step. Runoff from the soil (RO) in the study field must be evaluated, further for great slopes and rain intensities and precipitation (P) can be measured by automatic weather stations. Capillary rise (CR) from groundwater table could be an important input in determined areas, but is semiarid regions this factor can be considered insignificant. Evenly, deep percolation (DP_i) is an important component in the soil water balance under high irrigation or precipitation regimes. For water necessities assessment Irrigation (I_i) is derived as residual in the formulation, but it requires the measurement or estimation of crop evapotranspiration (ET).

$$D_{r,i}=D_{r,i-1}-(P-RO)_i-I_i-CR_i+ET+DP_i \qquad \text{(Equation 1)}$$

For practical applications in operatives scenarios SWB is initialized for conditions of full watered soil profiles, which can occur after precipitation events. Thus, soil water balance is sometimes computed for periods longer than crop development seasons, even in the absence of vegetation cover, being ET mainly attributable to soil evaporation under these conditions. For practical considerations about soil evaporation estimation, the reader is referred to Torres and Calera (2010).

2. "Two steps" methodology for crop evapotranspiration estimation

A theoretical approach towards estimating crop evapotranspiration (ET) is given by the Penman-Monteith combination equation (Equation 2). The crop coefficient (Equation 3) (Allen *et al.*, 1998) is the ratio between crop evapotranspiration and reference crop evapotranspiration (ETo), which may be computed by means of the FAO56 Penman-Monteith equation (Equation 4) (Allen *et al.*, 1998). The variables utilized in the formulation of evapotranspiration are net radiation (R_n) heat flux into the soil (G), air density (ρ_a), specific heat of air (c_p), vapor pressure deficit (e_s-e_a), the thermodynamic psychrometric constant (γ), aerodynamic resistance (r_a), canopy resistance (r_c), wind speed adjusted to 2 m of height (u_2), air temperature (T) and saturation slope vapor pressure curve at air temperature (Δ). ETo formulation is the application of the generic Penman-Monteith combination equation to an ideal reference grass surface, the "reference surface". This adaptation includes the use of constant values and imposes the measurement or simulation of the parameter for this surface and the specific conditions described in the FAO-56 manual.

$$ET=\frac{\Delta(R_n-G)+\rho_a c_p (e_s-e_a)/r_a}{\Delta+\gamma(1+r_c/r_a)} \qquad \text{(Equation 2)}$$

$$Kc=\frac{ET}{ETo} \qquad \text{(Equation 3)}$$

$$ETo=\frac{0.408\Delta(R_{no}-G_o)+\gamma(\frac{900}{T+273})u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \qquad \text{(Equation 4)}$$

The model proposed in FAO-56 for ET estimation and resumed in (Equation 3) is entitled the "Two step" methodology because it conceptually decouples ET in two components, mainly related to atmospheric demand, ETo, and mainly related to surface (canopy) properties, Kc. This approach was improved by calculating Kc as the sum of a basal crop coefficient (Kcb), related to plant transpiration, and an evaporation coefficient (Ke), linked to soil evaporation (Wright, 1982). In particular, we recommend the use of the dual crop coefficient approach and adjustments to Kcb to account for water stress in the root zone, modeled as Ks (Allen *et al.*, 1998), (Equation 5). Actual crop evapotranspiration resulting with this formulation taking into account the presence of water stress is named ETadj.

$$ETadj=(Ke+KcbKs)ETo \qquad \text{(Equation 5)}$$

In the FAO-56 methodology Ke is calculated using a parallel water budget in the top soil layer. The use of the stress coefficient confers additional capabilities to the SWB methodology because the model is able to simulate ET reduction under water stress conditions and the irrigation depth and frequency can be adapted to attach the desired water stress level.

A. FAO-56 Crop water stress sub-model

The coefficient K_s is estimated using the expression presented in (Equation 6) where TAW is the total available water in the root zone (mm). RAW is the proportion (p) of TAW that is used by a given crop without reduction of transpiration and $D_{r,i}$ is the water depletion for day i (mm) derived from the soil water balance (Equation 1).

$$K_s = 1 \qquad \text{if } D_{r,i} \leq RAW$$

$$K_s = \frac{TAW\text{-}D_{r,i}}{TAW\text{-}RAW} = \frac{TAW\text{-}D_{r,i}}{(1\text{-}p)\,TAW} \qquad \text{if } D_{r,i} > RAW$$

(Equation 6)

TAW value is estimated using the expression presented in (Equation 7) where Z_r is the depth of the root zone, θ_{FC} is the water content in the soil layer at field capacity (cm^3 cm^{-3}); θ_{WP} is the water content in the soil layer at wilting point (cm^3 cm^{-3}).

$$TAW = 1000\, Z_r\, (\theta_{FC} - \theta_{WP})$$

(Equation 7)

The formulation used to estimate Ks is strongly dependent on TAW, and consequently on root depth. In woody and perennial crops such as in vineyards the roots explore important volumes of soil extracting water up to 2 m depth (Pellegrino *et al.*, 2004). The water storage in the soil profile supposes an important source of resources and could suppose near to 50% of total water necessities in irrigated vineyards (Campos *et al.*, 2010). It is therefore essential to properly estimate roots depth and total available water in the root zone for an adequate estimation of irrigation necessities and plant water stress, being this factor one of the greatest uncertain sources for the model application.

3. Remote sensing inputs in the "Two steps" methodology

The assimilation of remote sensing inputs in the SWB model described in this work is based on the relationship between VI and the basal crop coefficient Kcb, which is defined as the ratio of the crop evapotranspiration over the reference evapotranspiration when the soil surface is dry but transpiration is occurring at potential rate (Allen *et al.*, 1998). Thus, the Kcb derived from VI relationships, Kcbrf in this paper, and experimental Kc will coincide only for the period with minimum soil evaporation and free of water stress in the root zone, see (Equation 5). And for a complete comparison during the entire growing season Ke and Ks must be added to the modeled Kc.

Neale *et al.* (1989) proposed the development of this relationship by means of linear scaling relating the average VI of dry tilled bare soil for the site (VImin) with the Kcb value for dry bare soil (Kcb,min) and the average maximum VI value for the site at effective cover (VImax) with the Kcb value at effective cover (Kcb,max) (Equation 8).

$$Kcb = Kcb{,}max \cdot \left[1 - \frac{\left(1 - Kcb{,}min\right)\cdot\left(IVmax - IV\right)}{IVmax - IVmin} \right]$$

(Equation 8)

This relationship has been considered non-linear for the NDVI such as other VI (Choudhury *et al.*, 1994) and the formulation is rewritten accounting for this effect including an exponent η (Equation 9) (González-Dugo *et al.*, 2010).

$$Kcb = Kcb{,}max \cdot \left[1 - \left(\frac{IVmax - IVmin}{IVmax - IVmin} \right)^{\eta} \right]$$

(Equation 9)

Other approaches relay on the use of empirical relationships correlating experimental Kc values obtained with minimum soil evaporation and free of water stress in the root zone (analogous to experimental Kcb) with the VI obtained in the plot. This is the method used to derive the relationship between VI and Kcb in a row vineyard (Campos *et al.*, 2010) presented in (Equation 10).

$$K_{cb} = 1.44NDVI - 0.10 \qquad \text{(Equation 10)}$$

III – Remote sensing SWB approaches in grape vineyards

1. Case study I. Crop coefficient and irrigation necessities estimation in irrigated vineyard in Albacete, Spain

In this case study we will analyze the crop evapotranspiration data obtained in a drip irrigated vineyard located in Albacete, Spain, using Eddy Covariance flux measurements. For additional information about the measurements methodologies, flux corrections and postprocessing, crop management and climatic conditions the reader is referred to Balbontín *et al.* (2011) and Campos *et al.* (2010). Measured crop evapotranspiration in the studied vineyard has been modeled by using the approach described in this paper and the results are published in Campos *et al.* (2010). In this work, we reanalyze these data improving the methodology proposed before by including the modifications to the FAO-56 soil evaporation sub-model proposed by Torres and Calera (2010).

The Kc modeled using the proposed methodology, including the modifications remarked before, following the measured Kc values increasing its value from the beginning of June to early July (Fig. 1) when the vegetation growth was stopped due to mechanical pruning. The variability in measured Kc after that date was affected by the irrigation events (22 mm every 12 days). After each irrigation event, a sudden increase in the Kc can be observed due to the presence of increased soil evaporation with a subsequent dry down period and decrease in the Kc lasting typically 3-4 days, these tendencies was reproduced by the model, Fig. 1, and the similarity between both modeled and measured coefficients was evident during the whole campaign, being RMSE=0.07. Both tendencies are even more similar outside of these drying periods, for which soil evaporation can be neglected and measured Kc is essentially equal to Kcb, and thus this similarity reinforces the capability of a VI based model to estimate Kcb in vineyards.

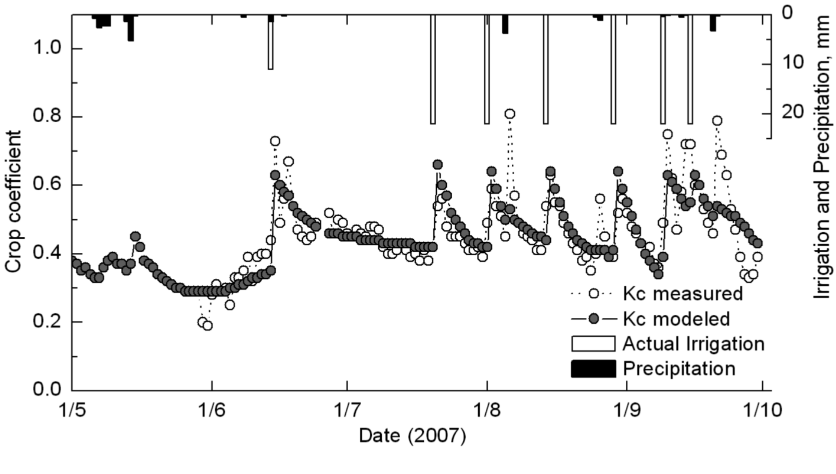

Fig. 1. Comparison of measured Kc and modeled Kc values in a drip irrigated vineyard in Albacete, Spain.

The same model formulation used to estimate ET and the showed vineyard crop coefficient were inverted to estimate vineyard irrigation necessities during the vines growing season. In this simulation the maximum irrigation depth (maximum irrigated volume per irrigation event) were limited to 22 mm according to farming practices. Total irrigation necessities during the vines growing season was estimated in 132 mm, resulting in a low difference with respect to the actual irrigation measured in the field, 143 mm. Interesting discrepancies between the actual irrigation manage and the models results were the start date of the irrigation campaign and the irrigation frequency during that. The farming practices include one irrigation event during mid June besides to soil depletion simulated by the model indicating significant levels of water available for the plants until early August, Fig. 2. Irrigation frequency is limited in the studied plot to one event every 12-14 days. This frequency seems to not be enough for the vineyard requirements during the campaign. Nevertheless, the vines water status was evaluated during the campaign using a pressure chamber and only low levels of water stress in certain dates (August 30th) was detected, in accordance with the stress coefficient predicted by the model, being Ks greater than 0.9 during the whole analyzed period.

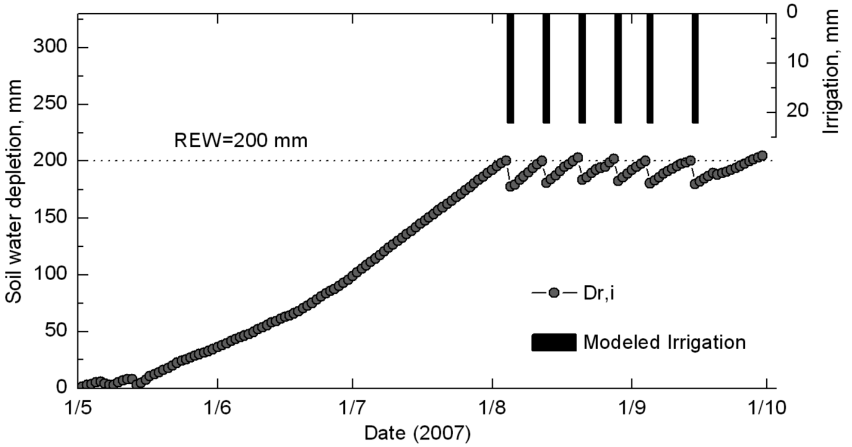

Fig. 2. Date and depth of irrigation necessities simulated by the model and measured in the field plotted along with soil water depletion (Dr,i) during the vines growing season modelled using the irrigation necessities predicted by the model. In the graphic is also shown the value of readily available water (REW).

The results presented before were obtained in conditions of no water limitations for the plants. Under water stress conditions, Kc measurements are expected to be lower than Kcb derived from its relationships with VI. In line with this theory, Silvestre *et al.* (2009) found an overestimation of measured ET, in water stressed vineyards when the expression Kcbrf*ETo is applied and proposed the inclusion of a stress coefficient derived from sap-flow measurements to correct that. O'Connell *et al.* (2010) found a strong relationship between NDVI and the ET/ETo ratio (experimental Kc) calculated using the model METRIC (Allen *et al.*, 2007) in vineyards. In this experiment, the Kc-NDVI observations that fall below the mean Kc-NDVI line are subjected to increasing levels of water stress.

NDVI such as other multispectral vegetation indices are not sensitive to water stress, at least not prior to structural changes, such as plant defoliation induced by water stress. Thus, dual crop coefficient methodology improved with remote sensing data provides, through the expression

Kcbrf*Eto, that maximum or "potential" rate of transpiration of the actual canopy. This potential transpiration will only coincide with real transpiration in absence of stress, being real transpiration lower than potential under water stress conditions. The model is able to estimate that effect by including in the formulation the stress coefficient presented before.

2. Case study II. SWB in vineyards under high deficit irrigation in the Alentejo, Portugal, preliminary results

In this case study, we will analyze the remote sensing SWB model results in two commercial vineyards under high deficit irrigation management during two consecutive years in the Alentejo, Portugal. The study plots are named P1 and P2 in this project. The model results analyzed here are crop evapotranspiration, soil moisture and water stress coefficient (Ks). The evolution of Ks was compared with experimental measurements of midday stem water potential (ψs).

The comparison of total irrigation requirements with respect to the actual irrigation volumes, Table 1, shows a water deficit in all plots and all periods analyzed, being applied volumes less than 50% of the total requirements estimated in P1 and less than 60% in P2. This result is consistent with the strategy of deficit irrigation imposed by farmers. The inclusion of real irrigation data in the model leads to reduced crop evapotranspiration as a result of water stress. ETadj cumulated during the growing season, April 15 to September 15, is less than 60% of the estimated maximum evapotranspiration, simulated under conditions of no water stress, and less than 80% in plot P2, Table 1.

Table 1. Seasonal cumulated values of total irrigation necessities, actual irrigation measured in the plot, maximum evapotranspiration and adjusted evapotranspiration accounting for water stress

	Total irrigation necessities, mm		Actual irrigation, mm		Maximum ET, mm		ETadj, mm	
	Year 2008	Year 2009	Year 2008	Year 2009	Year 2008	Year 2009	Year 2008	Year 2009
P1	300	360	102	177	505	540	320	366
P2	240	300	115	193	433	470	317	369

The model results indicate that soil moisture content is clearly below the RAW limit for much of the campaign. This causes a reduction in crop evapotranspiration, ETadj, Fig. 3, reaching values lower than 2 mm. ETadj increases after irrigation events due to the evaporation from the soil. During the 2009 campaign, irrigation events are more frequent in both plots resulting in higher ETadj values, Fig. 3.

The main strength of the remote sensing based SWB is the ability to analyze the relationship between the maximum irrigation needed and real irrigation applied, allowing to estimate the amount of water required to return the plants to a status of water "comfort" (free of water stress). For irrigation management and recommendations purposes, it is interesting to estimate the coefficient of stress and its simulation under different irrigation management scenarios, but its estimation and interpretation must be evaluated against crop evapotranspiration measurements and field estimators of plant water status, such as midday stem water potential, ψs.

The evolution of ψs measured in the study plots during the campaigns show a clear downward trend, Fig. 4. At the end of the season, in the period from DOY 190 to DOY 230, ψs values in all plots become stable around -1.3 or -1.4 MPa. ψs values in P2 plot during the 2008 campaign did not reach the stability around this minimum value in the indicated period and ψs values continued declining as low as values of -1.5 MPa. The low values obtained in the field indicate severe water stress conditions in the cases studies presented.

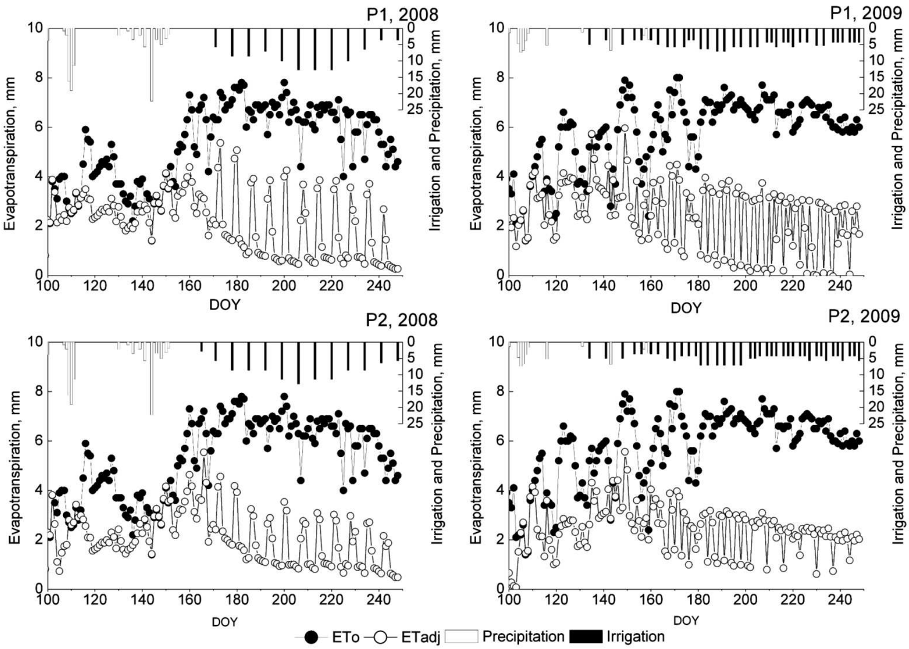

Fig. 3. Reference crop evapotranspiration (ETo), modeled adjusted evapotranspiration (ETadj), precipitation (P) y and actual irrigation in P1 and P2 during both analyzed periods.

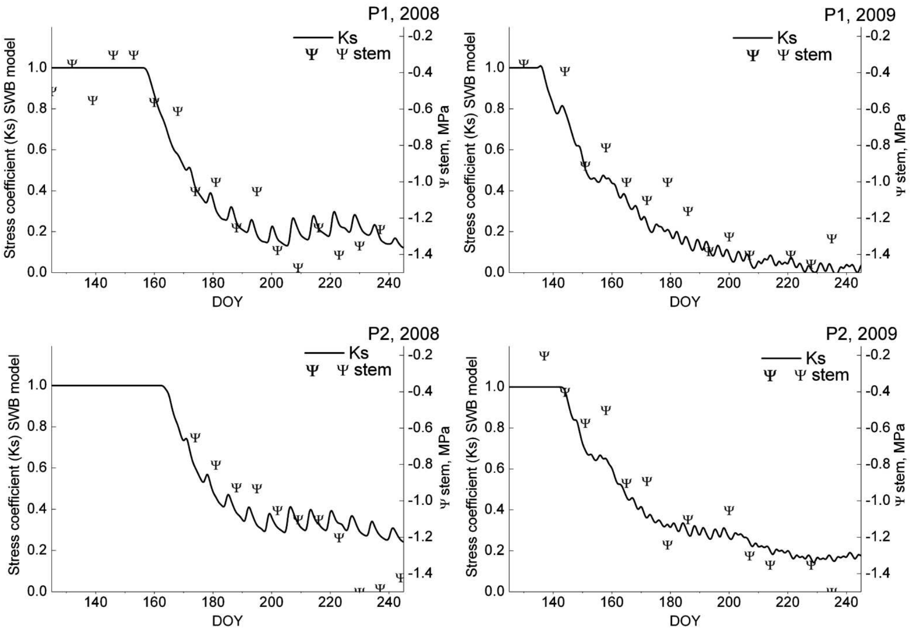

Fig. 4. Crop water stress estimated following the SWB approach plotted along with midday stem water potential measured in the field.

The temporal evolution of Ks estimated using the SWB model and ψs values show a parallel evolution in both plots during the two years analyzed,. The results indicate that the simulated stress coefficient has low sensitivity to ψs values lower than -1.4 MPa. For the periods in which the model does not detect water stress (beginning of the campaign) ψs values ranged between -0.3 and -0.5 MPa. It should be noted that ψs measurements have been obtained under different meteorological conditions (air temperature, vapour pressure deficit and illumination) and phenological stages, and the effect of these variables in ψs has not been evaluated in this work.

IV – Conclusions and remarks

Grape vineyards basal crop coefficient can be derived from its relationships with multispectral vegetation indices, measured using satellite images. This "spectral" or "remote sensing based" basal crop coefficient is adapted to the actual crop development and presents a fast, effective and precise method to estimate this parameter in great areas.

For an accurate estimation of experimental crop coefficient in vineyards, evaporation and stress coefficient must be added, using the formulation described in the text. The soil water balance in the root zone is needed for the estimation of the stress coefficient and this balance allows to estimate crop irrigation requirements with adequate precision for irrigated vineyards, such as it is presented in the text.

The methodology described in this paper has been tested in previous studies for grape vineyards, under different irrigation regimens and vegetation management (bush and row trellis system), but more experiments are necessary especially those centered in the study crop evapotranspiration under water stress conditions, evaluating the capacity of the soil water balance and water stress models. Additionally, a synergistic combination of this approach with those models estimate crop water stress using physiological measurements or are based on surface energy balance models (SEB), that provide real evapotranspiration, could be a future research line. The knowledge of the maximum transpiration rate from Kcb-VI procedure, combined with water stress or real evapotranspiration estimates, could provide an operational method for the assessment of irrigation recommendation on grape vineyards.

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