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Determination of crop evapotranspiration of table grapes in a semi-arid region of Northwest Mexico using multi-spectral vegetation index

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ABSTRACT

The main goal of this research is to develop and to evaluate a relationship established between Normalized Difference Vegetation Index (NDVI) and crop coefficient (K_c) for estimating crop evapotranspiration (ET_c) of table grapes vineyards (*Vitis vinifera* L., cvs. Perlette and Superior) in the semi-arid region of Northwest Mexico. Two consecutive growing seasons (2005 and 2006) of continuous measurements of ET_c with the eddy covariance system were used to test the performance of the K_c–NDVI relationship. An exponential relation relating K_c to NDVI ($R^2 = 0.63$) is proposed and tested here as the basis for calculating ET_c. The obtained results indicate that the K_c–NDVI approach estimates ET_c reasonably well over two growing seasons. The root mean square error (RMSE) between measured and derived ET_c from NDVI during 2005 and 2006 were respectively about 0.45 and 0.76 mm day^{-1}. Some discrepancies between measured and simulated ET_c occurred when NDVI saturates at high values, causing the under-estimation of evapotranspiration.

1. Introduction

Grapevines are the major horticultural crops produced in the world (Mullins et al., 1992), and are used for different end products, e.g. wine production, table grapes and raisin grapes. In the North of Mexico, table grapes are becoming an important crop due to its potential to improve farmers' income and rural employment. Knowledge of crop water requirements or evapotranspiration is an important practical consideration for determining proper irrigation scheduling and for improving water use efficiency, based on soil water balance. The most practical and recommended method to determine crop evapotranspiration (ET_c) is to multiply a reference evapotranspiration (ET_0) by the crop coefficient (K_c) and adjusted to local conditions with stress coefficient (K_s) ($ET_{c_{adj}} = K_s K_c ET_0$, Allen et al., 1998, 2007). ET_0 can be estimated using the FAO-Penman–Monteith equation which is recommended by the FAO as the standard method (Allen et al., 1998).

The estimation of the second term (i.e. crop coefficient) has been investigated for different crops and under different climate conditions. Some studies focused on grapes (Williams et al., 2003; Williams and Ayars, 2005; Teixeira et al., 2007; Netzer et al., 2009), and more recently some studies using K_c dual approach (Fandiño et al., 2012; López-Urrea et al., 2012). However, these crop coefficients depend on several factors mainly pedological, biophysical, physiological and aerodynamic (Katerji et al., 1991; Katerji and Rana, 2006; Testi et al., 2004). Such factors can lead a big difference between the K_c values reported by Allen et al. (1998) for the specific conditions and the values obtained experimentally for different conditions. Values of K_c for table grapes in the semi-arid region of Northern Mexico are not currently available. In this region, the farmers used only the K_c values established in California by Williams and Ayars (2005) and modified by Osorio (2000). This leads to the overestimation of the applied irrigation as shown by Rodríguez et al. (2010). Consequently, specific adjustment of K_c in various climatic region, soil type and different agricultural practices is necessary. Determining local crop coefficient is possible by using the micro-meteorological measurements (e.g. Bowen ratio, eddy covariance system), or the eco-physiological techniques (e.g. sap flow) (Williams et al., 2004; Yepez et al., 2005; Scott et al., 2006). However, these methods are expensive and difficult to deploy and maintain in both time and space. In order to avoid the necessity

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to determine crop coefficient over each study area, which greatly limits its operational utilization, spectral data can be used as a good alternative method to derive such parameters.

It has been previously shown that spectral reflectance may provide an indirect estimate for K_c. In this context, several studies (e.g. Jackson et al., 1980; Bausch and Neale, 1987; Neale et al., 1989; Choudhury et al., 1994; Hunsaker et al., 2003, 2005; Duchemin et al., 2006; Er-Raki et al., 2006, 2007, 2010) have been specifically dedicated for estimating K_c from vegetation indices (VI), Normalized Difference Vegetation Index NDVI (Rouse et al., 1974) and Soil Adjusted Vegetation Index SAVI (Huete, 1988). All of these studies derived K_c or basal crop coefficient (K_{cb}) from VI for only annual crops as the wheat and corn and they have found linear relationships between K_c and NDVI over different study areas. Less attention has been paid on deriving K_c from spectral data for the table grapes. In this context, the present study was conducted to determine crop water requirements of table grapes from ground-based reflectance data through the use of the established relationship between NDVI and K_c. The performance of this relationship has been evaluated based on field data collected during two consecutive growing seasons (2005 and 2006).

2. Materials and methods

In this section, we firstly present the site description and crop management. After a detailed description of the different measurements (meteorological data, heat fluxes measured by eddy covariance and ground remotely sensed data) has been presented. Note that all the measurements described below have been taken over table grapes during two consecutive growing seasons: 2005 for cv. Perlette and 2006 for cv. Superior vineyards.

2.1. Site description and crop management

The study was conducted during 2005 and 2006 in two plots of table grapes (more than 10 ha each) vineyards (*Vitis vinifera* L., cvs. Perlette and Superior) located in the Costa de Hermosillo (111, 348 W; 28.929 N and 111, 343 W; 28.928 N for Perlette and Superior vineyards respectively). This region is the lower part of Sonora river watershed in northwest Mexico. This is mainly a flat agricultural area of 169,593 ha, where the annual and perennial crops occupy around 53,000 ha every year, irrigated using water from some 500 deep wells. The climate of the region is arid with an annual rainfall of around 200 mm. The rainy season is from July to September (with about 70% of the annual rainfall) and there is a very dry season with almost no rainfall from March to June. The mean daily temperature ranges from about 17 °C in January to 31 °C in summer (July–August), with sporadic frosts in the winter and temperatures that are frequently above 40 °C from the end of spring into summer. The vines were planted in rows, 1.0 m apart for the Perlette vineyard and 1.8 m apart for the Superior vineyard. The rows spacing was 3.8 m for both cases, the cross section size is 2.80 m and the total height is of 2.25 m. A "*Y*" trellis was utilized in both the Perlette and Superior vineyards. Fertilization, pest and weed control were performed (Rodríguez et al., 2010 for more details). The soils have high sand and low clay contents (64% of sand, 22% of clay, and 14% of silt). The soil field capacity (33 kPa) and permanent wilting point (1500 kPa) were determined using pressure method development by Richards (1965) and the value of soil moisture are 14 and 6% at 30 cm depth respectively. The crop was maintained in well watered conditions by drip irrigation, and the amount of water applied depends to climatic demand and rainfall conditions, in order to avoid water stress. The emitters in the vineyards were installed every 0.8 m, the maximum water flow rate was of 2.6 L h^{-1} and the wetted area around each emitter was about 1 m^2.

In order to determine the phenological stages of vines, the measurements of fraction of ground cover by vegetation (f_c) have been taken. It was determined based on shaded area beneath the vines by using 1 m^2 white plate, divided into 100 small squares of 100 cm^2 each. These measurements were performed at noon, generally between 12:07 and 12:38 a.m., every week on sunny days, following the methodology described by Williams and Ayars (2005). The measurements of vines canopy shadow have been taken from the centre of plant to the centre of the opposite plant in each site (Fig. 1). 52 and 54 sets of measurements were done on 40 sites between January and December of 2005 (cv. Perlette) and 2006 (cv. Superior) respectively. Those sampling site were selected close to Eddy Correlation system. The value of f_c in each date was obtained like simple average of all measurements taken in the same date.

2.2. Meteorological data

Meteorological measurements were made using an automated weather station consisting of, incoming solar radiation was measured with a, CM6 (Kipp and Zonen, Netherlands), air temperature and humidity were measured with Vaisala HMP45C probes, wind speed and direction were measured with anemometer model 034B (Met One, USA), net radiation (R_n) was measured with a net radiometer (Kipp and Zonen, Netherlands) placed over vines on the study sites. Rainfall was measured with a TE525 mm tipping bucket automatic rain gauge (Campbell Inc., USA). All meteorological measurements were measured at 2 m height, and were recorded in data logger (CR10, Campbell Scientific, Logan, UT), sampled at 10 s and averaged over 30 min. Daily averaged values of climatic data were calculated in order to compute the daily reference evapotranspiration ET_0 (mm day^{-1}), according to the FAO-56 Penman–Monteith equation (Allen et al., 1998).

The evolution of reference evapotranspiration (ET_0) which is the most important component in the determination of crop water requirement is presented in Fig. 2. The temporal pattern of ET_0 values is typically that of a semi-arid continental climate type. It is characterized by a high climatic demand, with an average accumulated annual ET_0 of 1800 mm. The lowest values of ET_0 occurred during the winter and autumn (2 mm day^{-1} for both seasons) and the highest values occurred in the summer (8.5 mm day^{-1} during 2005 and about 9.5 mm day^{-1} for the 2006). Comparing the annual average value of rainfall (≈350 mm) with $ET_c = K_c{}^*ET_0$ = 954 mm (K_c is the crop coefficients at initial, mid season and late season stages of table grapes given in the FAO-56 paper), indicates the necessity to irrigate the orchards to avoid water stress and hence to have a profitable yield.

2.3. Heat fluxes measurements

A complete eddy-covariance system was installed over table grapes during 2005 for CV. Perlette and 2006 for CV. Superior to provide continuous measurements of vertical fluxes of heat, water vapour at 6 m. The eddy covariance system used, consisted of commercially available instrumentation: a 3D sonic anemometer (CSAT3, Campbell Scientific Ltd.), which measured the fluctuations in the wind velocity components and temperature, and a KH20 (Campbell Scientific Ltd.) that measured concentration of water vapour. Raw data were sampled at a rate of 20 Hz and were recorded using CR5000 data loggers (Campbell Scientific Ltd.). The half-hourly values of fluxes were later calculated off-line after performing coordinate rotation, correcting the sonic temperature for the lateral velocity and the humidity effects, making frequency integration, and including the mean vertical velocity according to Webb et al. (1980), Schotanus et al. (1983) and Wilczak et al. (2001). Two heat flux plates (one between the rows and the other underneath the vines) were installed to measure the soil heat flux (*G*).

Fig. 1. Overall view of the vineyard study field with f_c and NDVI measurements strategy.

The calculation of vines evapotranspiration ET_c (mm) at a daily time scale was obtained by summation of the half hourly values. ET_c measurements were taken from a central location of the field, determinated by the frequency of the wind direction analysis, to obtain the longest unobstructed wind fetch (Rodríguez et al., 2010). It has been stated that the size of both fields are large enough so that the required fetch conditions for eddy covariance are fulfilled. Missing data in some days was due to problems with the power supply. The measurements of ET_c are used to calculate the crop coefficient K_c as the ratio of ET_c and ET_0.

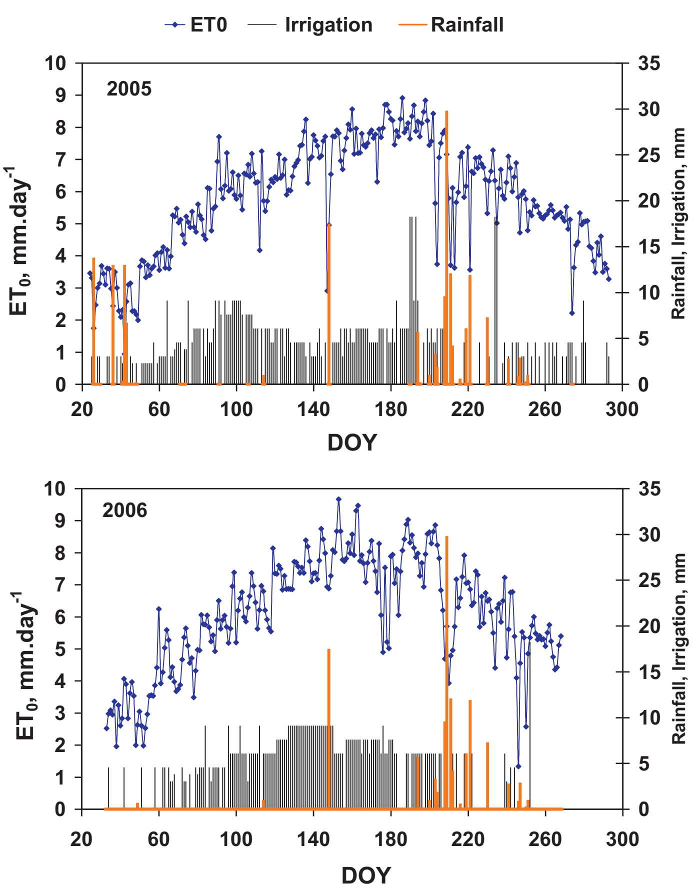

Fig. 2. Daily reference evapotranspiration (ET_0-FAO-Penman–Monteith) during 2005 and 2006 of table grapes in semi-arid region of Northwest Mexico. Rainfall and irrigation are also shown.

The performance of flux measurements was assessed by the energy balance closure. By neglecting the term of canopy heat storage and the radiative energy used in photosynthesis (Baldocchi et al., 2000; Testi et al., 2004), the energy balance equation is given by:

$$R_n - G = H + LE$$

Where R_n is the net radiation; G is the soil heat flux; H and LE are respectively the sensible heat flux and the latent heat flux measured by eddy covariance system. Fig. 3 shows how well the available energy ($R_n - G$) was balanced by (H + LE) at daily time scale over two sites of study. The slope of the regression forced through the origin was 1.04 and 1.21 during 2005 and 2006, respectively, indicating an underestimation of the flux (H + LE) was less than 20% of the available energy ($R_n - G$). These results indicate a satisfactory closure of the energy balance, which is in agreement with other studies (Baldocchi et al., 2000; Twine et al., 2000; Testi et al., 2004; Ezzahar et al., 2007).

2.4. Ground remotely sensed data

On a weekly basis, measurements of canopy reflectances were made using hand-held radiometer (MSR16 MultiSpectral Radiometer, Cropscan Inc., USA). Before the start of the measurements in each year, the radiometer has been calibrated with the panel calibration. Reflectance measurements were performed following a transect of 100 m (perpendicular to the rows and between two vines), taking data every 5 m, with five samples in each site. Bare soil measurements were included at each site to obtain the radiometric characteristics of the soil line. The field-of-view (FOV) was about 30° and the instrument sampled an elementary area of around 4 m^2 each time.

As the fraction of ground cover by vegetation (f_c), 52 and 54 sets of measurements were also taken in the same sites from January to December of 2005 (cv. Perlette) and 2006 (cv. Superior) respectively. The reflectance was obtained like simple average of all measurements taken in each date. Reflectance values centred on red (ρ_{red}, 0.63–0.69 μm) and near infrared (ρ_{NIR}, 0.76–0.90 μm) bands are used to obtain NDVI values: (Rouse et al., 1974)

$$\mathrm{NDVI} = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}}$$

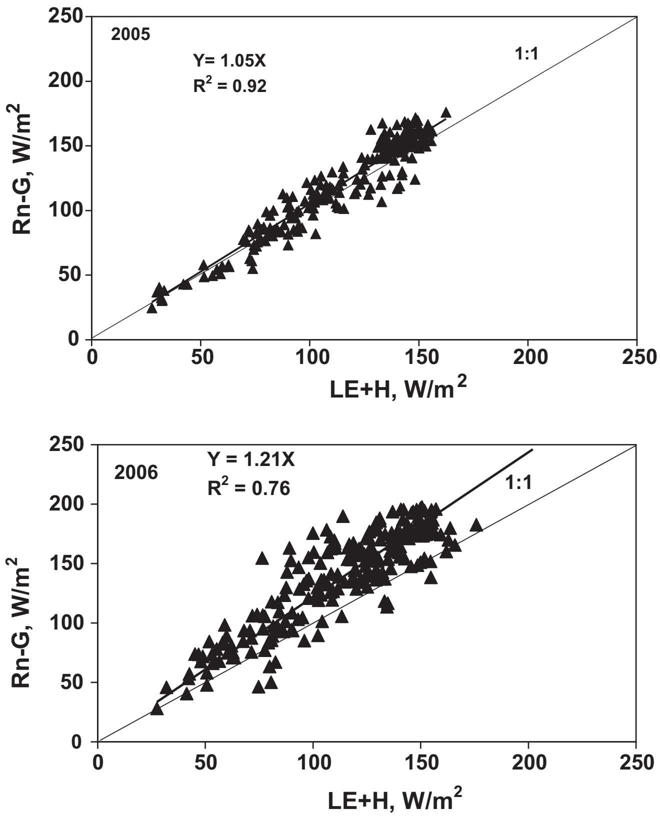

Fig. 3. Evaluation of energy balance closure. Daily average fluxes of net radiation (R_n) minus the soil heat flux (G) versus the sum of sensible (H) and latent heat (LE) measured by the eddy covariance system over table grapes during 2005 for Perlette (up) and 2006 for Superior (down).

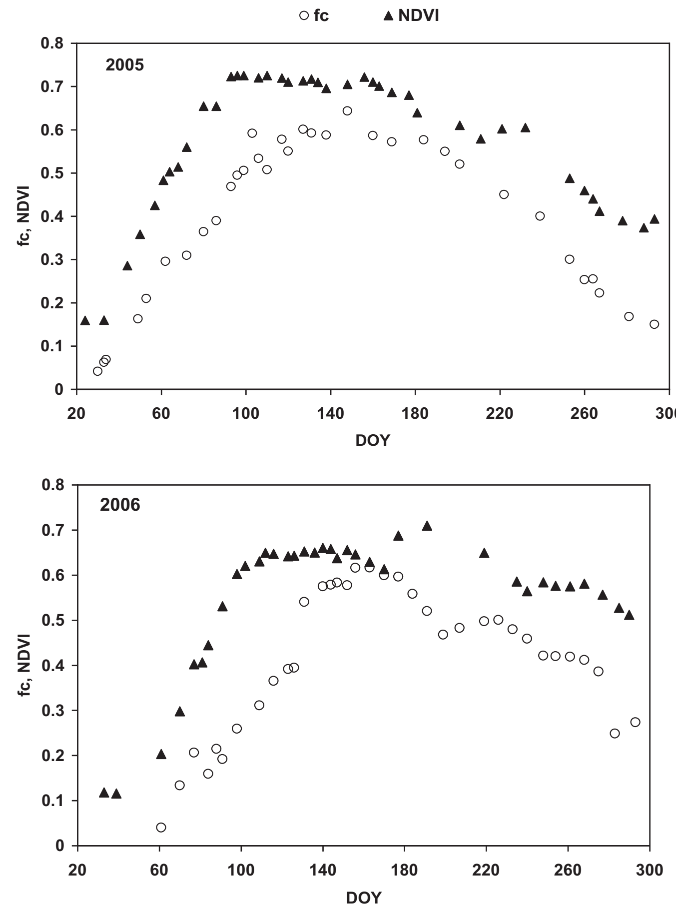

Fig. 4. Evolution of measured fraction of ground cover by vegetation (f_c) and measured Normalized Difference Vegetation Index (NDVI) of table grapes during 2005 for Perlette and 2006 for Superior.

3. Results and discussions

3.1. Evolutions of f_c and NDVI

Fig. 4 presents the time evolutions of measured f_c and NDVI for both grape varieties (Perlette and Superior) during 2005 and 2006. The temporal evolution of f_c and NDVI is similar. It characterized by three main crop growth stages (initial, mid-season and maturity). Budbreak which is the point when water use by table grapes begins occurred on January 24, 2005 (DOY 24) and February 5, 2006 (DOY 36), for cvs Perlette and Superior, respectively. The maximum value of f_c reached during the season was about 62% in both vineyards. The length of different growing stages with the degree-days has been presented in Table 1. The period from budbreak to harvest is 120 days (1158 DD) for Perlette and 132 days (1197 DD) for Superior. The difference between two varieties is principally due to the accumulated growing degree-days (GDD). In California, it has been found that the period from budbreak to harvest for Thompson seedless grapes was about 175 days (Williams et al., 2003; Williams and Ayars, 2005) resulting in the difference of about 50 days due to the increase of GDD in California compared to the Mexican site.

Regarding the evolution of NDVI, it increased from the budbreak until a maximum value (the effective full cover) and it remains constant over a plateau characterizing the mid-season stage. The maximum value of NDVI was about 0.71 for both seasons. It was occurred about 70 days and 150 days after budbreak for the 2005 (CV. Perlette) and 2006 (CV. Superior) table growing seasons, respectively. The observed decrease in NDVI within the plateau (mid-season stage) for both seasons (2005 and 2006) on DOY 134 and DOY 170 respectively was probably due to the decrease in leaf area resulting from the mechanical pruning as found previously by Campos et al. (2010). Thereafter, NDVI decreased, showing the beginning of crop senescence and yielded smaller values at the end of the growing cycle. The NDVI values were slightly higher for CV. Perlette than the CV. Superior especially from budbreak to the full cover stage. This is due to the precocity of Perlette cultivar.

3.2. f_c–NDVI relationship

The Normalized Difference Vegetation Index (NDVI) is the most widely used vegetation index for retrieval of vegetation canopy biophysical properties such as the fraction of ground cover by vegetation (f_c). A lot of studies have explored the relationship between both parameters and they showed a strong linear relation between f_c and NDVI (e.g. Ormsby et al., 1987; Phulpin et al., 1990; Kustas et al., 1993; Huete and Liu, 1994; Leprieur et al., 2000; Er-Raki et al., 2007). All of these works have been focused only on annual crops (e.g. wheat, corn, etc.) with less attention for the perennial crops especially for table grapes. In this context, we investigated how remotely-sensed vegetation index data can be used to derive vegetation cover (f_c) for table grapes. Based on the finding above (Fig. 4), the seasonal pattern of NDVI and f_c of table grapes is similar. The two variables exhibit comparable seasonal patterns, primarily following the dynamics of the density and greenness of leaves. This allows us to develop the model relationship between NDVI and f_c. Fig. 5 above shows this relationship between NDVI and f_c during 2005. As expected, this relationship is linear with the coefficient of determination (R^2 = 0.90) and the slope (0.98) are close to one. The

Table 1
The length of different growing stages and the degree-days (DD) of table grapes in semi-arid region of Northwest Mexico.

Start	Finish	Start	Finish	Days	Degree-days
		*01/24/2005	02/08/2005	16	97
Budbreak	Veg. cover 10%	**02/05/2006	03/09/2006	30	248
		02/09/2005	04/27/2005	78	703
Veg. cover 10%	Effective full cover	03/10/2006	05/11/2006	63	667
		04/28/2005	07/03/2005	67	1098
Effective full cover	Start senescence	05/12/2006	07/19/2006	69	1303
		07/04/2005	10/20/2005	109	2142
Start senescence	Full senescence	07/20/2006	11/20/2006	124	2086
		01/24/2005	05/23/2005	120	1158
Budbreak	Harvest	02/08/2006	06/20/2006	132	1597

*, ** data for the first line corresponds to the CV. Perlette, and the second line corresponds to the CV. Superior.

minimum value of NDVI was equal to 0.15, which correspond to the bare soil. Plotting the values of f_c estimated from the established equation ($f_c = 0.98*(\mathrm{NDVI}-0.15)$) against the measured ones (Fig. 5 bottom) for other season (2006) gave a good agreement. The values of Root Mean Square Error (RMSE) and the Efficiency (E) were respectively 0.09 and 0.76. The equations used for calculating the statistical parameters are provided in Appendix. The obtained relation between NDVI and f_c is fundamental to the remote sensing of vegetation phenology and to retrieve the vegetation canopy biophysical properties as found in previous studies (Tucker and Sellers, 1986; Hall-Beyer, 2003; Pettorelli et al., 2005).

3.3. K_c–NDVI relationship

Here, we tried to establish a relation between crop coefficient (K_c) and NDVI. Time evolutions of both parameters during 2005 and 2006 are presented in Fig. 6. It is clearly that both parameters increased similarly from the budbreak until a maximum values (the effective full cover). As NDVI, K_c is lower at the beginning of season and increased continuously up to development stage and decreased during the maturity stage. The average K_c values for the table grapes at three crop growth stages (initial, mid-season and maturity) were about 0.22, 0.45, and 0.30. These results are lower than the values presented in FAO-56 (Allen et al., 1998) especially for the mid-season. The measured average value at this stage was 0.45 compared to 0.85 in FAO 56 paper. This difference is probably due to the difference between the climate and agricultural practices. The lower values of K_c could be ascribed to the practicing localized drip irrigation which reduces the soil evaporation. These results are considered reasonable since they support the reported conclusions of many studies regarding the significant reduction in crop coefficient when localized irrigation is practiced (Allen et al., 1998; Amayreh and Al-Abed, 2004; Er-Raki et al., 2009). Another

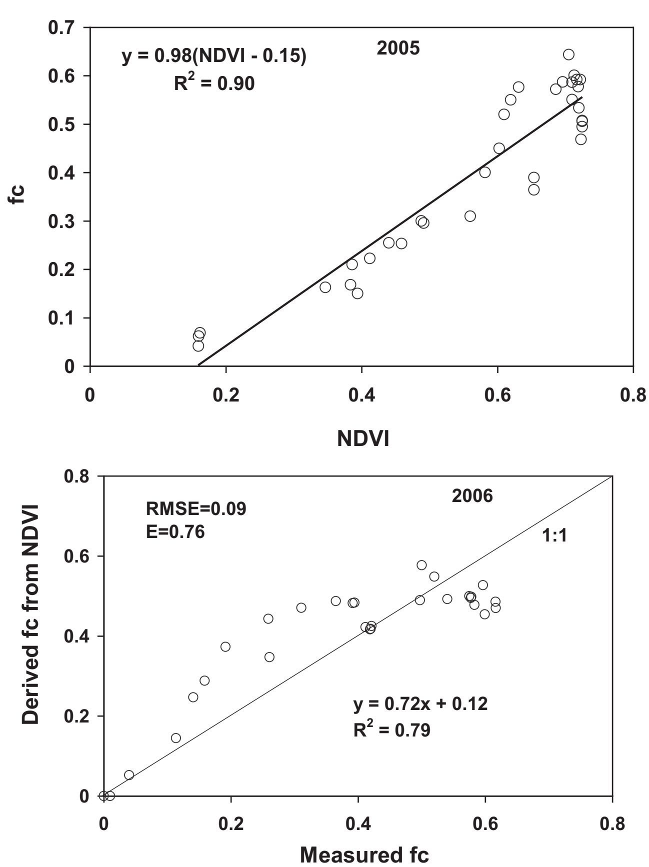

Fig. 5. Relationship between fraction of ground cover by vegetation (f_c) and NDVI of table grapes during 2005 (calibration) and 2006 (validation).

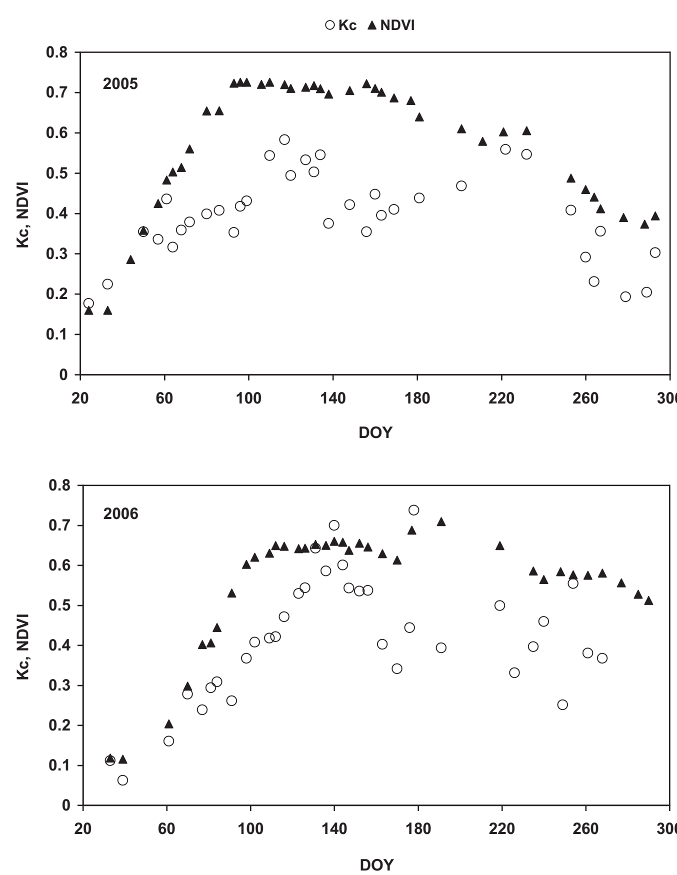

Fig. 6. Evolution of daily crop coefficient (K_c) and Normalized Difference Vegetation Index (NDVI) of table grapes during 2005 for Perlette (up) and 2006 for Superior (down). Note that the NDVI values are the same presented in Fig. 4.

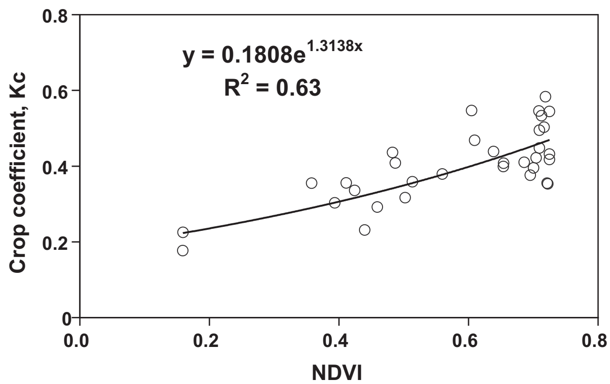

Fig. 7. Relationship between crop coefficient (K_c) and NDVI of table grapes (Perlette) during 2005.

factor that may partly explain the difference between the derived local K_c and that proposed by Allen et al. (1998) is the large areas of unshaded bare soil that reaches very high temperatures during the day (around 60 °C) and a significant amount of energy is lost as heat which is not available to the plants for transpiration. Cumulative crop evapotranspiration (ET_c) of table grapes calculated by using K_c proposed in FAO-56 was 1120 mm where as that calculated using the local calibrated K_c was 720 mm. Jairmain et al. (2007) reported similar seasonal values of ET_c for the table grapes in South Africa by using the water balance studies and they found that ET_c ranged from 519 to 827 mm depending to the length of growing season which varied between 6 and 8 months with only one harvest by year as in our study. According to the obtained results, the using of K_c-FAO-56 overestimates clearly the ET_c by about 46% (400 mm). This value represents about 36% of the amount of water supplied by irrigation (1100 mm). Therefore, a local calibration of K_c was needed to accurately estimate the crop water requirements of table grapes and thus to optimize the use of this scarce resource.

In order to avoid the time-consuming process of calibrating the K_c over each field, we investigated how remote sensing data can be used to derive some key parameters in the determination of crop evapotranspiration of table grapes (ET_c). As crop coefficient (K_c) is the key parameter for estimating ET_c, it is of interest to study the relationship between NDVI and K_c. Measurements of NDVI and K_c during 2005 were used to establish such relationship (Fig. 7). An exponential relation has been found with an acceptable coefficient of determination (R^2) of 0.63. It is clear that this relationship underestimates K_c for the higher values (after the effective full cover) due to the NDVI saturation. This is in agreement with the results obtained in previous studies (e.g. Asrar et al., 1984; Baret et al., 1989; Duchemin et al., 2006; Er-Raki et al., 2007) when they studied the relationship between NDVI and Leaf Area Index (LAI) of wheat and they reported that NDVI saturates for high values of LAI (LAI > 4) thus obtaining poor estimates of LAI for well-developed canopies using remotely sensed data. The extra-evaluation of K_c–NDVI relationship established here is undertaken through the comparison between the measured and estimated crop evapotranspiration (ET_c) for two growing seasons of table grapes (2005 and 2006) which is the main goal of the following section. The advantage of this relationship is the estimation of crop water requirements on an operational basis and at a regional scale by using satellite remote sensing data.

3.4. Crop evapotranspiration (ET_c)

By using the established relationship between K_c and NDVI (see above), we simulated ET_c over table grapes during two growing seasons (2005 and 2006). Fig. 8 shows the estimated ET_c versus

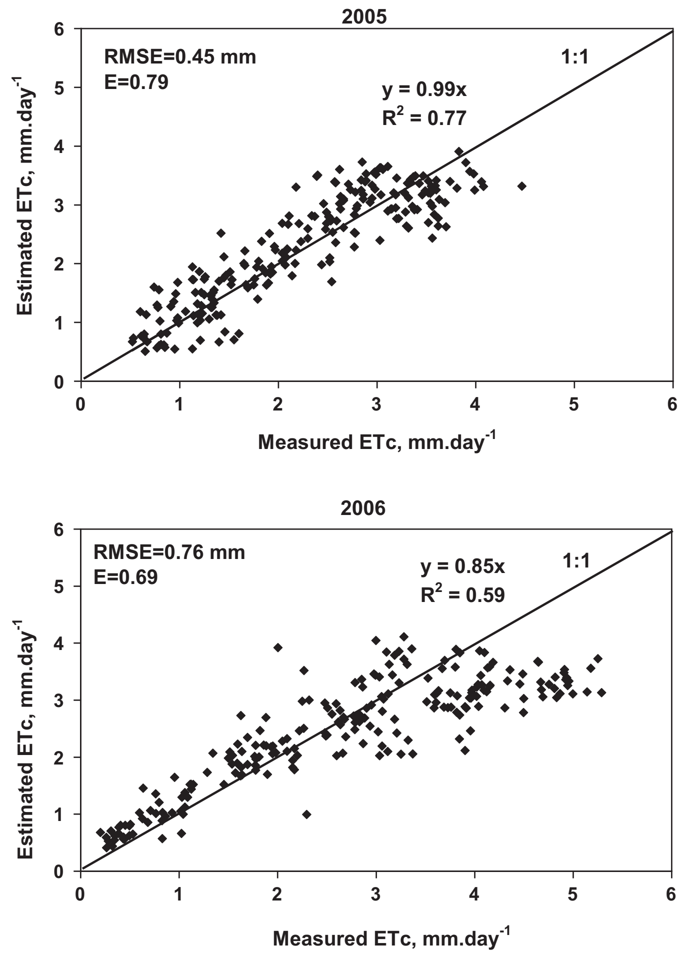

Fig. 8. Estimated ET_c from NDVI versus measured ET_c by eddy covariance during 2005 for Perlette and 2006 for Superior vineyards.

measured one by the eddy covariance system during 2005 (top) and 2006 (bottom) growing seasons. This comparison revealed practically perfect agreement between observed and estimated ET_c values over 2005. The Root Mean Square Error (RMSE) and the Efficiency (E) between measured and simulated ET_c values were respectively about 0.45 mm per day and 0.79. A linear regression analysis forced through the origin was presented also in Fig. 8, which shows a slope (0.99) close to 1 and an acceptable coefficient of determination (R^2 = 0.77). In contrast to the 2005 season, the results provide less accurate estimates of ET_c during 2006 season. The RMSE, the efficiency and the slope were 0.76 mm per day, 0.69 and 0.85, respectively. This is expected because the daily ET_c during 2006 (cv. Superior) is generally greater than that for cv. Perlette (2005). Then, a clear underestimation of ET_c was observed during 2006 at higher values of ET_c (ET_c > 4 mm day^{-1}) when the estimated ET_c remains constant (see Fig. 8 bottom). This is certainly due to the effect of NDVI saturation (discussed above) which underestimates K_c and so ET_c. In practice, when NDVI saturates, LAI and vegetation transpiration still increasing as measured by eddy covariance system.

Globally, the obtained results showed a good reliability of K_c–NDVI relationship for estimating ET_c for table grapes under semi-arid region as far as before the effective full cover reached.

4. Summary and conclusions

The main results of this study showed that by using standard crop coefficients suggested by FAO-56 paper overestimates clearly crop evapotranspiration (ET_c) of table grapes by about 46% (400 mm) which represents about 36% of the amount of water supplied by irrigation (1100 mm). Therefore, the determination of the appropriate K_c values is needed to accurately estimate the crop water requirement and consumption for table grapes in semi-arid region of Northwest Mexico. In order to avoid the time-consuming process of determining crop coefficient over each field, we investigated how ground-based remotely sensed data can be used to derive K_c as the key parameter for estimating ET_c. The similarity between seasonal patterns of NDVI and K_c of table grapes showed potential for establishing relationship between both parameters. An exponential relation has been found with an acceptable coefficient of determination (R^2) of 0.63. This K_c–NDVI relationship provides accurate estimates of ET_c over two growing seasons (2005 and 2006). The Root Mean Square Error (RMSE) between measured and derived ET_c from NDVI during 2005 and 2006 were respectively about 0.45 and 0.76 mm day^{-1}. Some discrepancies between measured and simulated ET_c are occurred when NDVI suffer from saturation at high values and causing the under-estimation of evapotranspiration.

For improvement of ET_c estimates from NDVI, it should be developed a new and more accurate vegetation index that not saturates at high values such as MSAVI2 and MTVI2 developed and tested by Haboudane et al. (2004) and Qi et al. (1994) for different crops. Another way to overcome problems related to NDVI saturation consists of using two regression relations between K_c and NDVI as reported by Hunsaker et al. (2003) when they found a linear function of K_c versus NDVI for cotton from early vegetative growth to effective full cover and other one after effective full cover is attained.

Finally, it should be noted that the K_c–NDVI approach developed here have been solely tested over two irrigated fields of table grapes through using only ground remotely sensed data. Testing this approach with satellite remote sensing data is of interest for better management of irrigation water at an operational basis and at a regional scale.

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Appendix: statistical analysis

Three statistical parameters were used in this study for analysing the performance of the results: (1) the Root Mean Square Error (RMSE), which measures the variation of predicted values around observed values; (2) the efficiency (E), which characterizes the performances of the model simulation, the perfect model should have the efficiency close to 1, 3) the correlation coefficient (R^2), which shows the degree to which two variables are linearly related.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_{i\,\mathrm{mod}} - y_{i\,\mathrm{obs}})^2};\; E = 1 - \frac{\sum_{i=1}^{n}(y_{i\,\mathrm{mod}} - y_{i\,\mathrm{obs}})^2}{\sum_{i=1}^{n}(y_{i\,\mathrm{obs}} - \bar{y}_{\mathrm{obs}})^2} \tag{A.1}$$

where $\bar{y}_{\mathrm{mod}}$ and $\bar{y}_{\mathrm{obs}}$ are the averages of model and observations respectively, n is the number of available observations, $y_{i_{\mathrm{mod}}}$ and $y_{i_{\mathrm{obs}}}$ are daily values of modelled and observed variables respectively.

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