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Using the dual-K_c approach to model evapotranspiration of Albariño vineyards (*Vitis vinifera* L. cv. Albariño) with consideration of active ground cover

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ABSTRACT

This research aims at testing the dual crop coefficient approach to model the evapotranspiration of the traditional Galician "semi-trellised" vineyard of *Vitis vinifera* cv. Albariño with active ground cover. A separate calculation of soil evaporation, transpiration of the vine crop and transpiration of the active ground cover was conducted. Three irrigation treatments – rain-fed, surface and subsurface drip irrigation – were conducted during three crop seasons (2008–2010). The SIMDualKc model, that performs the soil water balance with the dual K_c approach, was applied for estimating crop evapotranspiration (ET_c) by calculating a basal crop coefficient for the vine crop ($K_{cb\ full}$), another for the active ground cover ($K_{cb\ cover}$), which represent the transpiration component of ET_c, and a soil evaporation coefficient (K_e). The model was calibrated and validated by comparing model simulated with TDR observed soil water content data. A good fit was obtained showing that modeling was accurate when using the observed fraction of active ground cover, its density and its height, and calculating $K_{cb\ cover}$ with field measured data, thus allowing to assess the active ground cover transpiration. As for the vine crop, the best fit was obtained for $K_{cb\ full\ ini} = 0.30$, $K_{cb\ full\ mid} = 1.15$ and $K_{cb\ full\ end} = 0.90$.

1. Introduction

Active ground cover and cover crops are used in viticulture to control the vigor of the variety and manage the canopy (Smart and Robinson, 1991), to prevent erosion and increase infiltration rates during the rain period (Lopes et al., 2011), to improve and/or preserve the soil physical characteristics (Prichard, 1998) and, more recently, for sequestering carbon (Steenwerth and Belina, 2008). However, the ground cover crop competes with the vineyard for water and nutrients (Monteiro and Lopes, 2007; Celette et al., 2008; Centinari et al., 2012). Hence, in vineyards with active ground cover, crop evapotranspiration (ET_c) includes the vine plants transpiration (T_v), soil evaporation (E_s) and the transpiration of the active ground cover (T_g).

Modeling ET_c requires that the dynamics of vegetation growth be known for both the vineyard and the ground cover vegetation (Francone et al., 2010; Ripoche et al., 2011). The active ground cover changes following tillage operations or herbicide applications beneath the crop rows, so changing the evapotranspiration demand of the active ground cover during the crop season.

Research on ET_c and water use in vineyards has been performed using various methods and techniques including lysimeters (Johnson et al., 2005; Azevedo et al., 2008; Netzer et al., 2009), heat pulse (Yunusa et al., 1997; Intrigliolo et al., 2009), heat balance (Trambouze and Voltz, 2001; Zhang et al., 2010), Bowen ratio energy balance (Yunusa et al., 2004; Teixeira et al., 2007; Zhang et al., 2011), surface renewal energy balance (Castellví and Snyder, 2010; Moratiel and Martínez-Cob, 2012), eddy covariance (Ortega-Farias et al., 2010; Rodríguez et al., 2010), and soil water balance (Singleton and Maudsley, 1996; Fooladmand and Sepaskhah, 2009; Cancela et al., 2012). Current approaches adopt a crop coefficient (K_c) as the ratio between ET_c and the reference crop evapotranspiration (ET_o). Then, ET_c is operationally estimated as $ET_c = K_c \times ET_o$ (Allen et al., 1998).

Factors determining the K_c of vineyards include the crop growth stage, canopy height and architecture that relate to the trellis system; the fraction of soil covered by the crop, presence of mulches or active ground cover, as well as the soil fraction wetted and exposed to radiation that relates to the irrigation method and soil management; crop management and local climate. Two options exist for using K_c: the single crop coefficient approach, where K_c represents time averaged combined effects of crop transpiration and soil evaporation, and the dual K_c approach, where the K_c value is divided into a basal crop coefficient, K_{cb}, representing plant transpiration, and an evaporation coefficient, K_e, representing evaporation from the

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Nomenclature

AAE	average absolute error (mm)
b	regression coefficient
d_{IA}	index of agreement
EF	modeling efficiency
E_s	soil evaporation (mm)
ET	evapotranspiration (mm or mm d^{-1})
ET_a	actual evapotranspiration (mm d^{-1})
ET_c	crop evapotranspiration (mm d^{-1})
ET_o	reference crop evapotranspiration (mm d^{-1})
f_c	fraction of soil surface covered by vegetation
$f_{c\,eff}$	effective fraction of ground covered or shaded by vegetation
$f_{c\,eff\,g\,cover}$	effective fraction of ground covered or shaded by green active ground cover
$f_{r\,g\,cover}$	fraction of the green active ground cover
h	vegetation height (m)
h_{canopy}	crop height (m)
$h_{g\,cover}$	height of the green active ground cover (m)
HWR	height to width ratio
K_c	crop coefficient general
$K_{c\,adj}$	actual crop coefficient when plant density and/or leaf area are at or lower than full cover
$K_{cb\,cover}$	basal crop coefficient for active ground cover
$K_{c\,min}$	minimum value of K_c for bare soil
K_{cb}	basal crop coefficient
$K_{cb\,full}$	basal K_{cb} anticipated for vegetation under full cover conditions
$K_{cb\,mid}$	average K_{cb} during the midseason period
$K_{cb\,vine}$	basal crop coefficient for vine
$K_{cb(crop+gcover)}$	basal crop coefficient for vine and the active ground cover
K_d	vegetation density factor
K_e	soil evaporation coefficient
K_s	adjustment coefficient for water stress
M_L	multiplier on $f_{c\,eff}$ to impose an upper limit on relative transpiration per unit ground area
p	soil water depletion fraction for no-stress
r^2	coefficient of determination
REW	readily evaporable water from the surface soil layer (mm)
RMSE	root mean square error (mm)
TAW	total available water in the root zone (mm)
TEW	total evaporable water that can be evaporated from the surface soil layer (mm)
T_g	active ground cover transpiration (mm)
T_v	vine transpiration (mm)
Width	width of the crop row as viewed from an east–west direction (m)
Z_e	effective depth of the surface soil subject to drying by way of evaporation (m)
β	the mean angle of the sun above the horizon during the period of maximum ET (rad)
Γ	angle of the plant row from the east–west direction (rad)

soil surface, resulting $K_c = K_{cb} + K_e$. Thus, the actual crop evapotranspiration, which is smaller than ET_c when water stress occurs, is defined as:

$$ET_a = (K_s K_{cb} + K_e)ET_o \quad (1)$$

where ET_a is the actual crop evapotranspiration (mm d^{-1}), K_{cb} is the basal crop coefficient, K_s is the water stress coefficient, K_e is the soil evaporation coefficient and ET_o is the reference crop evapotranspiration (mm d^{-1}) (Allen et al., 1998, 2007).

Most previous studies on vineyards irrigation adopted single crop coefficients to compute ET_c and to determine the amount of irrigation water required at different crop growth stages (Esteban et al., 1999; Williams and Ayars, 2005) or the K_c related to the phenological stages of the vineyard (Lissarrague et al., 2007). A few authors adopted the Shuttleworth and Wallace model to estimate separate values for T_v and E_s in vineyards (e.g. Ortega-Farias et al., 2007; Poblete-Echevarría and Ortega-Farias, 2009; Zhang et al., 2009). Other authors achieved that separation using combined equipment and techniques such as a combination of energy balance, sap flow and microlysimetry techniques (Trambouze and Voltz, 2001; Yunusa et al., 2004; Zhang et al., 2011).

Few studies refer to vineyards ET_c in presence of an active ground cover or a cover crop. An approach to simulate a vineyard ET with active ground cover or an inter-row cover crop is the partitioning of the available soil water through a double reservoir model such as WaLIS, a simple model to simulate water partitioning in a crop association (Celette et al., 2010). Centinari et al. (2012) used mini lysimeters to obtain the evapotranspiration of the vineyard's cover crop; authors concluded that it mainly depended on the solar energy available at the cover crop for evapotranspiration. Water use by the cover crop was also assessed by soil water monitoring (e.g., Monteiro and Lopes, 2007; Costello, 2010).

The dual K_c approach with calibration of K_{cb} for local conditions, crop variety, trellis system, and cultural practices is not yet used. However, Fooladmand and Sepaskhah (2009) used the dual K_c approach to assess water use of vineyards in a water harvesting system. Differently, Yunusa et al. (2004) estimated the T_v and E_s components of ET_c from their separate measurements but not modeling. By using the dual K_c approach it is possible to take into account the active ground cover vegetation and its variation throughout the year as shown for several tree crops by Allen and Pereira (2009). Moreover, adopting a model that incorporates the dual-K_c approach allows to easily understand the processes of water use by the vine crop and the ground cover as well as through soil evaporation, to develop alternative scenarios for water management of the vineyard, and to simulate impacts on water use of alternative ground cover and soil management practices.

Tabled values for K_{cb} do not include wine grapes with active ground cover (Allen et al., 1998, 2007; Allen and Pereira, 2009). Tabling those K_{cb} values is difficult because ET demand of the active ground cover changes due to tillage operations and herbicide applications, hence instead of adopting a fixed combined K_{cb} value for the initial, mid-season and end-season stages it may be more appropriate to separate the K_{cb} of the crop from that of the active ground cover. The K_{cb} for the vine crop may be taken from standard tabled values adjusted to the actual ground cover conditions and then, after being combined with the K_{cb} of the active groundcover, it may be subject to additional adjustments while calibrating a model with observed soil water content. K_{cb} is not site dependent and only changes little with climate but varies with trellis system and crop architecture. Differently, the K_{cb} adjusted to actual soil water conditions ($K_{cb\,act}$) changes with crop management, irrigation management and environmental conditions. The soil evaporation coefficient changes with climate, mainly rainfall, and irrigation management.

To consider the influence of crop vegetation height and density on the basal K_{cb}, Allen and Pereira (2009) proposed the use of the effective fraction of ground covered or shaded by vegetation ($f_{c\,eff}$) and the vegetation height (h). A density factor K_d is considered, which allows adjusting K_{cb} to the vegetation and ground cover conditions (Allen et al., 2007; Allen and Pereira, 2009). K_d is estimated as:

$$K_d = \min(1, M_L f_{c\,eff}, f_{c\,eff}^{(1/(1+h))}) \quad (2)$$

where $f_{c\,eff}$ is the effective fraction of ground covered or shaded by vegetation near solar noon, h is crop height (m) and the M_L parameter is a multiplier of $f_{c\,eff}$, representing the ratio of ET per unit of horizontal vegetation surface to ET_o over the same surface. $f_{c\,eff}$ differs from the fraction of soil surface covered by vegetation as observed overhead (f_c) due to the combined effect of the canopy shape, plant height and solar angle above the horizon on the shaded area. For crops planted in rows, $f_{c\,eff}$ is computed from the height to width ratio (HWR) of the crop row:

$$f_{c\,eff} = f_c \left[1 + \frac{\mathrm{HWR}}{\tan(\beta)}\right] \quad (3)$$

with

$$\mathrm{HWR} = \frac{h_{canopy}(\cos(\Gamma))}{\mathrm{width}} \quad (4)$$

where Γ is the angle of the plant row from the east–west direction (rad), h_{canopy} is crop height (m), width is the width of the crop row as viewed from an east–west direction (m), and β is the mean angle (rad) of the sun above the horizon during the period of maximum ET, generally between 11.00 and 15.00 h (Allen et al., 1998).

In tree crops and vineyards, when the active ground cover competes with the crop for the available soil water and contributes to the total evapotranspiration of the canopy, the following approach (Allen et al., 2007; Allen and Pereira, 2009) is adopted for estimating the combined K_{cb}:

$$K_{cb} = K_{cb\,cover} + K_d \left(\max\left[K_{cb\,full} - K_{cb\,cover}, \frac{K_{cb\,full} - K_{cb\,Cover}}{2}\right]\right) \quad (5)$$

where $K_{cb\,cover}$ is the K_{cb} of the active ground cover in the absence of tree foliage, K_d is the density factor referring to the crop (Eq. (2)), and $K_{cb\,full}$ is the basal K_{cb} anticipated for the crop under full cover conditions and corrected for climate. The second term of the max function reduces the estimated K_{cb} by half the difference between $K_{cb\,full}$ and $K_{cb\,cover}$ when this difference is negative, i.e., it takes into account the effects of shading of the active ground cover by the taller plants when the vines may have K_{cb} that is lower than that of the ground cover due to differences in stomatal conductance.

The SIMDualKc model (Rosa et al., 2012a) provides for estimating a variable $K_{cb\,gcover}$ to consider changes in ET demand of the active ground cover due to its management (tillage operations, application of herbicides, etc.) using field observed data that are easily measurable, such as the fraction of the active ground cover, its density and its height, which is then daily included in Eq. (5). This approach was first tested for a peach orchard (Paço et al., 2012).

The present study adopted the dual crop coefficient approach to estimate ET_c in drip-irrigated vineyards with active ground cover under conditions of traditional "semi-trellised" vineyards of *Vitis vinifera* cv. Albariño in Galicia, in Northwest Spain. Adopting the dual K_c approach to "semi-trellised" vineyards with an active ground cover is innovative and of peculiar interest since Albariño vineyards are typical of agricultural landscapes of Galicia and Minho, in Northwest of Spain and Portugal, respectively. Thus, the objectives of this study consist of: (a) computing ET_c of Albariño vineyards in presence of active ground cover with the dual K_c approach, thus with its separation into crop transpiration and soil evaporation; (b) testing the SIMDualKc model (Rosa et al., 2012a) for the specific environmental conditions of Albariño vineyards; including when the active ground cover is modified by the application of herbicides and mowing at different stages of crop growth; and (c) calibrating and validating the K_{cb} values appropriate for this crop, including the determination of the $K_{cb\,cover}$ and $K_{cb\,full}$ using observed soil water data relative to various irrigation treatments and three years of observations (2008–2010). In addition, it was intended that the parameterization of the crop and the soil would provide for further use of the model in irrigation management. It must be noted that modeling applications in this study base upon 3 years of field observations and 3 water management treatments in each year.

Table 1
Vineyard crop growth stages.

Crop growth stages	2008	2009	2010
Planting/initiation	01 March	01 March	01 March
Start rapid growth	28 March	21 March	16 March
Start mid-season	28 May	15 May	15 May
Start senescence/maturity	13 August	05 August	13 August
End-season/harvesting	15 September	14 September	05 September

2. Materials and methods

2.1. Site, crop and irrigation treatments

The study was conducted during the period 2008–2010 (March–September) in a commercial Albariño vineyard located at Arantei, in the wine-producing region of Rías Baixas, Pontevedra, NW of Spain. The vine plants were spaced 1.5 m along the row with 3.0 m rows spacing. The predominant rows direction was north to south, but some vineyard plots were oriented northwest to southeast. Vines were trained on a semi-trellised system with four wires, and spur-pruned on Guyot system.

During the three years of study, the dates of each phenological stage were determined according to Baggiolini (1952). The crop coefficients curve was based on these dates (Allen et al., 1998): the day when the vine reaches the stage D (leaf emergence) corresponds to the last day of the initial crop stage and the mid season corresponds to the phases I (flowering) to M (veraison) as classified by Baggiolini (1952). The dates limiting each crop growth stage are given in Table 1 for the three years under analysis.

The average crop height was 2 m and the effective average root depth 0.6 m. Soils were sandy-loam Cambisols with total available water (TAW) down to 0.6 m equal to 112.8 mm. TAW was calculated as the difference between the average field capacity and the permanent wilting point (0.294 and 0.106 $cm^3\,cm^{-3}$, respectively). The total evaporable water (TEW), the readily evaporable water (REW) and the depth of the evaporable layer (Z_e) were first estimated from standard data proposed by Allen et al. (1998, 2005) and then adjusted when calibrating/validating the model, then resulting in TEW = 36.7 mm, REW = 9 mm and Z_e = 0.15 m.

Agrometeorological data were available from a nearby station explored by the Consellería de Medio Rural, Xunta de Galicia (Entenza – Salceda de Caselas, 42°7.1′ N, 8°56.1′ W and 50 m a.s.l.). They consisted of daily data of maximum and minimum temperature, wind speed, and rainfall for the period 2008–2010 (Fig. 1). The reference evapotranspiration (ET_o) was computed with the Penman–Monteith equation using the methodology proposed by Allen et al. (1998) for limited weather data, i.e., estimating the actual vapor pressure from the daily minimum temperature and solar radiation from daily maximum and minimum temperature. This method was positively tested by Popova et al. (2006) for a relatively similar climate, and by Paredes and Rodrigues (2010) for Northern Portugal.

The experimental study included three irrigation treatments:

- rainfed (R), with four replications,

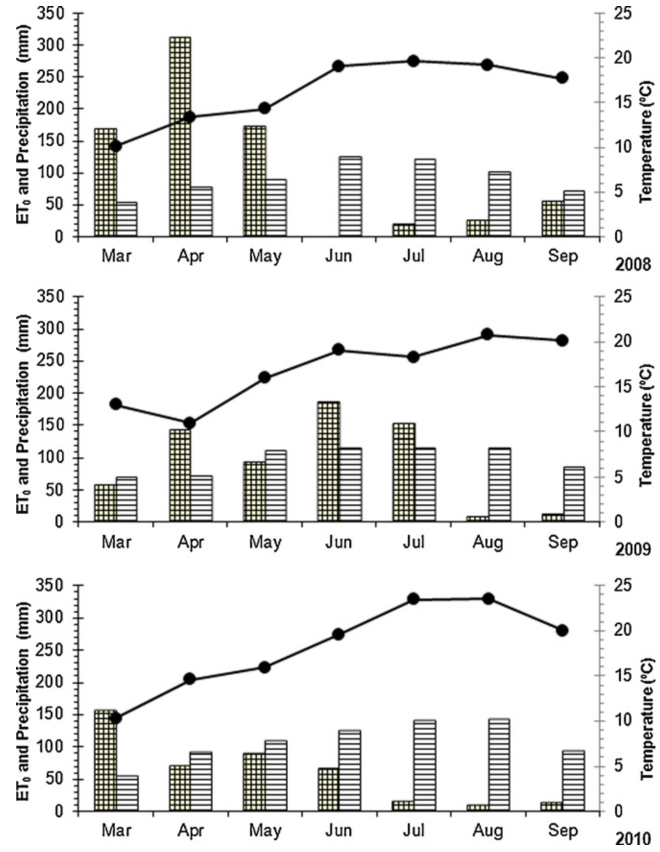

Fig. 1. Mean daily temperature (-●-), total monthly precipitation (▦) and reference evapotranspiration (▤) in the 2008, 2009 and 2010 seasons, at Arantei, Galicia (Spain).

- surface drip irrigation (DI), with three replications, using drippers of 2 l h^{-1} per plant located 30 cm above the ground, and
- subsurface drip irrigation (SDI), with five replications, using pressure compensating drippers (2 l h^{-1}) buried at 30 cm depth.

Both DI and SDI systems were used for application of nutrients (N, P, K and Mg) adopting an application of 0.44–0.66 mm d^{-1}, which was scheduled as 1.5 h daily for five days a week from April 15 to September 5, in 2008 and 2009, and May 4 to August 31 in 2010.

The soil water content was monitored with a TDR100 (Campbell Scientific – Logan, UT, USA), which operates in the field using the software PCTDR for PCs. The equation of Topp et al. (1980) relating the volumetric water content (θ) with the measured bulk dielectric constant (ε_{eff}) was used since it has proven successful in soils that do not contain substantial amounts of bound water, e.g., most sandy and loamy soils (Robinson et al., 2003). This equipment was used for 6, 13 and 11 measurements per year in 2008, 2009 and 2010 respectively, i.e., about one measurement per three weeks in average. The number of measurements per treatment corresponded to the number of replications of each treatment (R – 4, DI – 3 and SDI – 5). Sensors were placed at 40 cm from the row and at the mid distance between two vine plants, thus to observe the soil water content in the root zone as influenced by the vine plants and the active ground cover vegetation since both root systems of the vine crop and active groundcover surely intermingle in the soil and compete for water (Morlat and Jacquet, 2003; Celette et al., 2008, 2010; Guerra and Steenwerth, 2012). Observations were performed at four depths, which allowed estimating θ at depth intervals of 15 cm (Fandiño et al., 2009).

Table 2
Observed average fraction of ground shaded by the vine plants.

	Fraction of ground cover (f_c)			
	Initial value	End of crop development period	During the mid season	Final value
2008	0.01	0.50	0.50	0.45
2009	0.01	0.60	0.60	0.55
2010	0.01	0.50	0.50	0.45

2.2. Fraction of ground cover and active ground cover data

The vegetative growth of the vineyards was low in the initial stage, during March, but was fast during the crop development period. The maximum fraction of ground cover (f_c) was attained at the mid season; f_c decreased later during the end season period. The variation of f_c during all crop growth stages was observed because it plays a main role for the estimation of K_e for computing soil evaporation (Allen et al., 2005), as well as to compute K_d (Eq. (2)). Table 2 summarizes the observed values of f_c relative to the three years of experimentation. No noticeable differences among treatments were observed.

An active ground cover was maintained in the inter-row area consisting of natural herbaceous vegetation. For its characterization, observations were performed during the crop season, from March to September, including its density, height (h_{gcover}) and fraction of green active ground cover ($f_{\text{rg cover}}$). The characteristics of the active ground cover changed throughout the season due to various cultivation practices, mainly mowing and application of herbicides along the vine row. These practices are common in Rías Baixas wine-producing region. Results from observations are presented in Table 3. It can be noticed that density and $f_{\text{r g cover}}$ reduced little after mowing; contrarily, $h_{\text{g cover}}$ were substantially decreased after those operations.

2.3. SIMDualKc model and the active ground cover extension

The SIMDualKc model (Rosa et al., 2012a,b) uses the dual crop coefficient approach to calculate crop evapotranspiration (ET$_c$), with separate consideration of the soil evaporation and crop transpiration components, which allows for more precise analysis on how water from precipitation and irrigation is used by the crop. A schematic representation of the model is shown in Fig. 2 and it summarizes typical model input data, computational routines and output results. The accuracy of SIMDualKc model depends upon the quality of data relative to the crop (e.g., phenological dates, crop height and density), the soil (soil hydraulic and evaporative properties) and climate. However, in vineyards, in addition to those aspects, crop architecture and trellis system affect results; hence a proper calibration/validation may be required when the model is to be used under different trellis system, crop management and environmental conditions.

SIMDualKc includes the adjustment of K_{cb} for full cover fruit trees, vines and shrubs ($K_{\text{cb full}}$) to actual crop density, as well as a procedure for estimating K_{cb} for the active (green) ground cover ($K_{\text{cb cover}}$) as a function of its development and management, to be further combined with the K_{cb} of the crop (Rosa et al., 2012a). To use the active ground cover extension, the user must enter the initial values of the fraction of the active ground cover, its density and height, and then update these values throughout the crop cycle, mainly before and after any cultivation operation.

The procedure consists of using the concept of K_{cb} for full cover natural vegetation (Allen et al., 1998, 2007; Allen and Pereira, 2009), dependent of vegetation height and local climatic conditions (minimum relative humidity and wind speed), which is then adjusted to daily changes in actual density conditions, by using a

Table 3
Fraction and height of the green active ground cover before and after each ground cover management operation for the 3 experimental seasons (2008–2010).

Date	Operation	$f_{\text{g cover}}$ Before	$f_{\text{g cover}}$ After	Density Before	Density After	$h_{\text{g cover}}$ Before	$h_{\text{g cover}}$ After
2008							
01-Mar	Initial conditions	0.75	0.75	0.15			
02-Mar	Mowing	0.75	0.65	0.75	0.65	0.15	0.05
18-Mar	Herbicide[a]	0.70	0.65	0.70	0.70	0.08	0.08
25-Apr	Mowing	0.80	0.65	0.85	0.65	0.08	0.05
26-May	Mowing	0.90	0.85	0.95	0.85	0.15	0.05
02-Jun	Herbicide[a]	0.85	0.75	0.85	0.85	0.07	0.07
26-Jun	Mowing	0.80	0.65	0.85	0.70	0.15	0.07
6-Aug	Mowing	0.75	0.60	0.75	0.50	0.15	0.05
20-Sep	End of season	0.85	0.85	0.13			
2009							
01-Mar	Initial conditions	0.85	0.60	0.07			
14-Apr	Mowing	0.83	0.83	0.75	0.75	0.14	0.05
22-Apr	Herbicide[a]	0.85	0.65	0.75	0.75	0.08	0.08
19-May	Mowing	0.65	0.65	0.75	0.58	0.16	0.05
17-Jun	Mowing + Herbicide[a]	0.95	0.50	0.90	0.55	0.24	0.05
13-Jul	Mowing	0.70	0.65	0.75	0.70	0.18	0.05
28-Aug	Mowing	0.90	0.65	0.95	0.65	0.25	0.05
20-Sep	End of season	0.75	0.78	0.09			
2010							
01-Mar	Initial conditions	0.80	0.80	0.09			
09-Apr	Mowing + Herbicide[a]	0.90	0.90	0.90	0.80	0.12	0.05
28-Apr	Mowing	0.60	0.60	0.75	0.70	0.12	0.05
25-May	Mowing	0.75	0.70	0.70	0.65	0.10	0.05
15-Jun	Mowing + Herbicide[a]	0.75	0.60	0.75	0.60	0.08	0.05
16-Sep	End of season	0.80	0.80	0.25			

$f_{\text{g cover}}$: fraction of the green active ground cover; $h_{\text{g cover}}$: height of the green active ground cover.

[a] The herbicide was applied along the plant row.

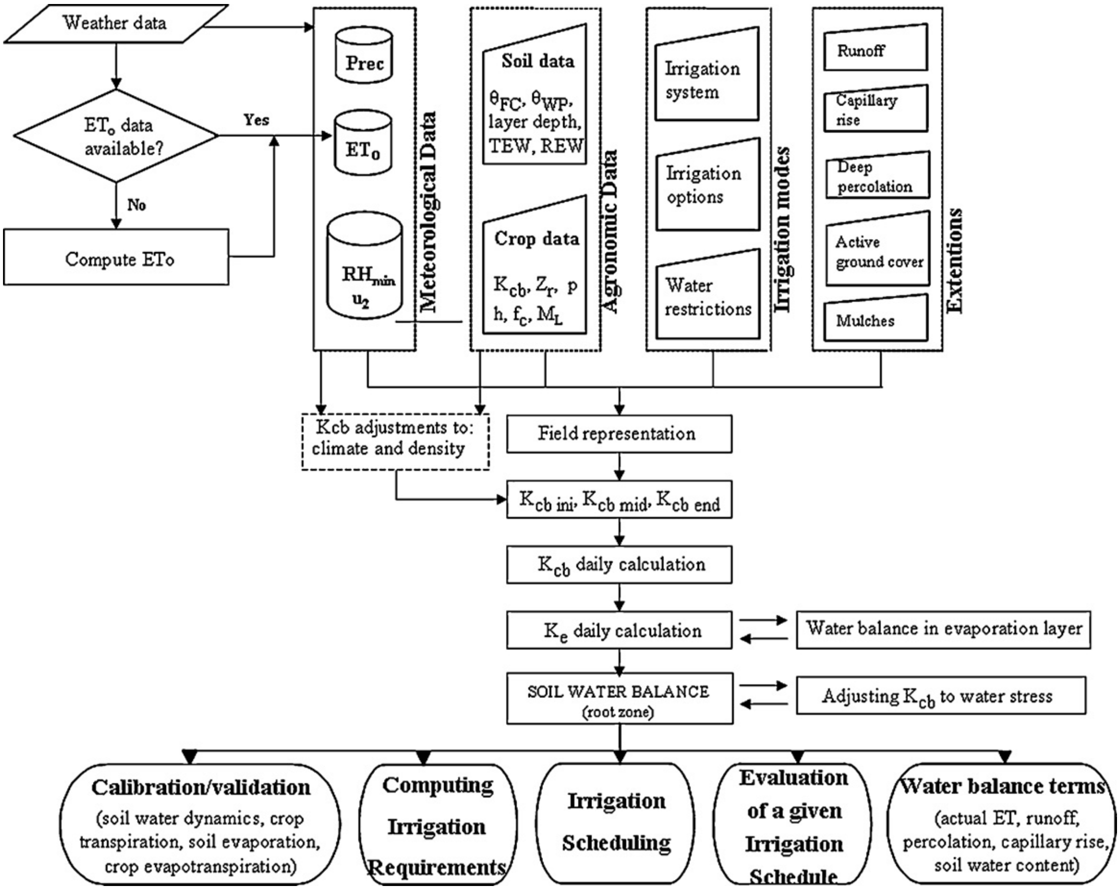

Fig. 2. Schematic representation of SIMDualKc model (from Rosa et al., 2012a).

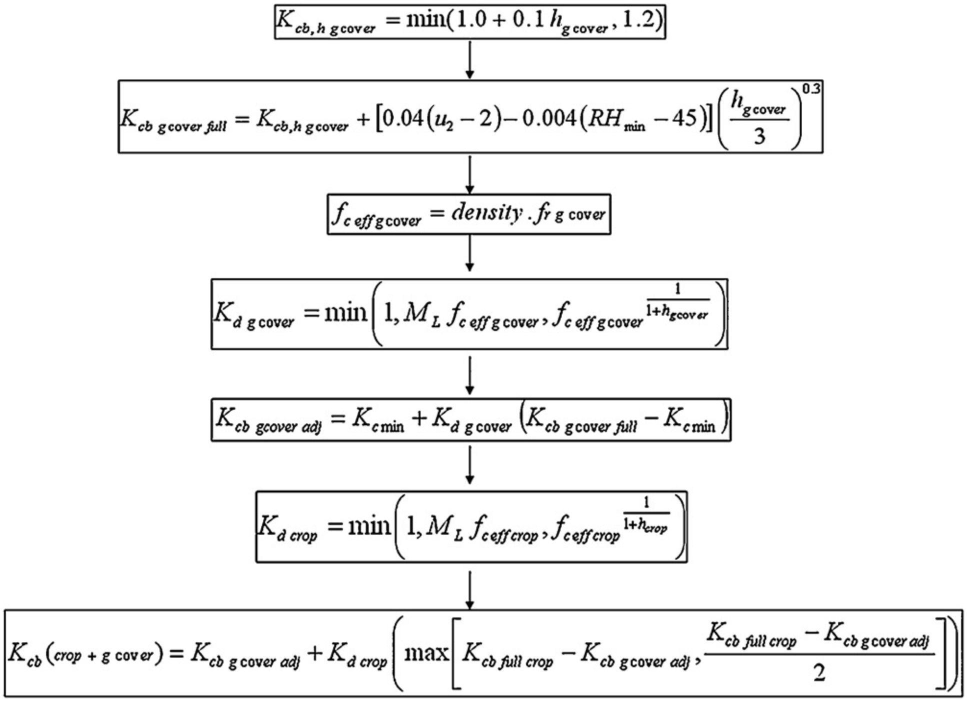

Fig. 3. Flowchart for the estimation of the K_{cb} of the active ground cover from its density, fraction of ground covered and height, and the computation of the combined K_{cb} for the crop and active ground cover.

Adapted from Rosa et al. (2012a).

density coefficient ($K_{d\ gcover}$) (Fig. 3). $K_{d\ gcover}$ is computed using Eq. (2) on a daily basis, in a way similar to that for K_d relative to the vine crop (assuming $M_L = 1.5$), but calculating $f_{c\ eff}$ and vegetation height not for the vine crop but for the active ground cover ($f_{c\ eff\ g\ cover}$ and $h_{g\ cover}$, respectively) (Fig. 3). $f_{c\ eff\ g\ cover}$ is obtained by multiplying $f_{r\ g\ cover}$ by the density of the active ground cover. Then, the model computes the daily $K_{cb\ cover}$ values using a variant of Eq. (5), that is applicable when active ground cover does not exist (Allen et al., 2007; Allen and Pereira, 2009), i.e., $K_{cb\ cover} = K_{c\ min} \approx 0.15$. $K_{cb\ full}$ in this variant of Eq. (5) also refers not to the crop but to the active ground cover ($K_{cb\ g\ cover\ full}$) (Fig. 3). Finally, the daily combined K_{cb}, representing the effects of both the crop and the active ground cover ($K_{cb(crop+gcover)}$), is computed using Eq. (5) on a daily basis, now with K_d and $K_{cb\ full}$ calculated for the crop and not for the active ground cover ($K_{d\ crop}$ and $K_{cb\ full\ crop}$, respectively) as indicated in Fig. 3 (Rosa et al., 2012a). Adjustments of $K_{cb(crop+gcover)}$ to water stress are performed via the K_s coefficient (Eq. (1)). This simplified approach adopted in SIMDualKc, contrarily to the WaLIS model (Celette et al., 2010) that adopts two soil compartments for simulating a vine-cover crop association, considers only one common soil compartment where vine roots and cover crop roots intermingle and compete for water. Several studies evidence the existence of this mixed rooting systems in a vine-cover crop association (Morlat and Jacquet, 2003; Celette et al., 2008; Guerra and Steenwerth, 2012) including Celette et al. (2010), i.e., vine roots and cover crop roots intermingle mainly in the upper soil compartment, where the majority of cover crops roots are located, both depleting water from the common soil reservoir. While the WaLIS model approach is quite complex, the simpler one adopted in SIMDualKc has shown to be enough accurate for irrigation management purposes.

2.4. Model calibration and validation

The model was calibrated and validated by comparing simulated and field observed data of soil water content relative to the 2008–2010 seasons. The simulations were performed using soil, crop, active ground cover, irrigation, and weather data collected during the full crop seasons. One possible limitation of the dual-K_c approach is that it needs a model to be fully explored and such a model requires calibration/validation as referred before. Other information needed for running the model was initially estimated or taken from standard values and later upgraded through model calibration. This was the case for the basal crop coefficients for full cover vineyards ($K_{cb\ full}$), the soil water depletion fraction for no-stress (p) and the M_L adjustment parameter (Allen et al., 1998, 2007). The total evaporable water (TEW), readily evaporable water (REW) and thickness of the evaporation soil layer (Z_e), were also determined during the calibration process as referred before.

The calibration procedure consisted of adjusting the non-observed parameters ($K_{cb\ full}$, p, TEW, REW, and M_L) to minimize differences between observed and simulated available soil water values relative to the entire root depth profile as described by Popova and Pereira (2011). A trial and error procedure was developed as described by Rosa et al. (2012b) until differences between simulated and observed soil water values were minimized and stabilized. The $K_{cb\ cover}$ values were not adjusted during calibration but computed by the model from observed field data such as ground cover density, $f_{r\ g\ cover}$, and $h_{g\ cover}$, using the procedure summarized in Fig. 3. The values of every parameter used were verified to be in the respective acceptable range, e.g., by checking that K_{cb} values were not far from those tabled in literature (Allen et al., 1998, 2007; Allen and Pereira, 2009). To assure confidence on results obtained, these were compared with several other when discussing results later in this paper.

To assess the accuracy and goodness of fit of model predictions, several approaches were used. A first one consisted in analyzing the graphical time dependent representations of model-simulated vs. observed soil water content values. This allows a good perception of trends or bias in modeling if they occur. A second one was the regression forced to the origin between observed and model-predicted soil water content values. When the regression coefficient (b) is close to 1.0, the covariance is close to the variance of

Table 4
Standard (initial) and calibrated basal crop coefficients, p depletion fractions and M_L parameter for vineyards ET simulation.

	Standard[a]	Calibrated
p_{ini}	0.45	0.59
p_{med}	0.45	0.50
p_{end}	0.45	0.59
$K_{cb\ full\ ini}$	0.20	0.30
$K_{cb\ full\ med}$	0.80	1.15
$K_{cb\ full\ end}$	0.60	0.90
M_L	1.50	

	2008		2009		2010		Mean	
	Potential[c]	Actual[d]	Potential[c]	Actual[d]	Potential[c]	Actual[d]	Potential[c]	Actual[d]
$K_{cb\ cover\ ini}$[b]	0.38	0.38	0.53	0.53	0.60	0.60	0.50	0.50
$K_{cb\ cover\ dev}$[b]	0.49	0.49	0.46	0.46	0.52	0.52	0.49	0.49
$K_{cb\ cover\ mid}$[b]	0.41	0.23	0.36	0.33	0.34	0.20	0.37	0.25
$K_{cb\ cover\ ens\ season}$[b]	0.38	0.25	0.45	0.22	0.44	0.06	0.42	0.18
$K_{cb\ vine\ ini}$	0.11	0.11	0.09	0.09	0.08	0.08	0.09	0.09
$K_{cb\ vine\ mid}$	0.56	0.27	0.63	0.57	0.62	0.37	0.60	0.40
$K_{cb\ vine\ end}$	0.39	0.25	0.52	0.11	0.46	0.07	0.46	0.14
$K_{cb(crop+gcover)\ ini}$	0.49	0.49	0.62	0.62	0.68	0.68	0.60	0.60
$K_{cb(crop+gcover)\ mid}$	0.97	0.49	0.99	0.90	0.97	0.57	0.98	0.65
$K_{cb(crop+gcover)\ end}$	0.90	0.57	0.89	0.20	0.94	0.14	0.91	0.30

[a] From Allen et al. (1998, 2007) and Allen and Pereira (2009).
[b] These $K_{cb\ cover}$ are averages for each period.
[c] Values adjusted to density but not to water stress.
[d] Values adjusted to density and water stress.

the observed values, indicating that predicted and observed values were statistically similar. A coefficient of determination (r^2) close to 1.0 indicated that most of the total variance of the observed values was explained by the model. A set of indicators of residual estimation errors was used as described in previous studies and applications (Legates and McCabe, 1999; Moriasi et al., 2007; Cholpankulov et al., 2008; Popova and Pereira, 2011) – the root mean square error (RMSE) and the average absolute error (AAE) –, as well as indicators of the quality of model fitting: the index of agreement (d_{IA}), developed by Willmott (1981), that represents the ratio between the mean square error and the potential error due to modeling, and the modeling efficiency (EF), a normalized statistic developed by Nash and Sutcliffe (1970) that determines the relative magnitude of the residual variance compared to the measured data variance.

3. Results and discussion

3.1. Model calibration and validation

The SIMDualKc model was calibrated using field data obtained for the subsurface drip irrigation treatment of 2009 and validated for all other treatments and years. The calibrated crop parameters $K_{cb\ full}$, p and M_L are given in Table 4. The p values did not require much adjustments relative to the standard $p = 0.45$ tabled by Allen et al. (1998, 2007), thus it was simply adjusted to local climate conditions according to Allen et al. (1998). The M_L value is expected to vary between 1.5 and 2.0 (Allen et al., 2007), depending on the canopy density and thickness. For a hypothesized vineyard with partial cover, as a result of surface roughness and due to larger amounts of available energy resulting from open inter-row spaces (Paço et al., 2012), $M_L = 1.5$ is a reasonable value for the conditions of the study.

Graphical results representing the model fitting of the observed and simulated soil water content values (θ, %) throughout the season for calibration and validation are presented in Fig. 4. This figure shows that the simulated soil water content adequately followed the observed values along the entire crop seasons of 2008, 2009 and 2010 despite differences in weather conditions for three years (Fig. 1).

An evaluation of the model fitting was performed using various indicators of goodness of fit, which are presented in Table 5. Results show that the coefficients of regression were close to 1.0 and the coefficients of determination ranged from 0.93 to 0.98 for all treatments; Fig. 5 shows regression results when considering all data. The estimation error RMSE for soil water content ranged from 0.8 to 2.1 mm, representing less than 2% of TAW; the AAE values were lower than 1.8 mm. The indices of efficiency (EF) were higher than 0.85, thus indicating that the residual variance due to modeling is comparable to the measured data variance. The indices of agreement (d_{IA}) were close to 1 for all years and all treatments, which indicate that the modeling potential error is close to the mean square error. When considering all data together indicators are very good, e.g. EF = 0.93 and $d_{IA} = 0.98$. These statistics suggest good model performance and agreement between simulated and observed soil water content, i.e., the ability of the model to predict the soil water content over a wide range of observed values and for rain-fed and irrigated (surface and subsurface drip) conditions.

3.2. Basal crop coefficients

The initial values of the $K_{cb\ full}$ for the initial, mid and end-season stages were taken from Allen et al. (2007) concerning wine grapes, but adjustments performed during the calibration process led to increase the $K_{cb\ full}$ values, that became similar to those for table grapes reported by the aforementioned authors. The $K_{cb\ full}$ values obtained – $K_{cb\ full\ ini}$: 0.3, $K_{cb\ full\ mid}$: 1.15 and $K_{cb\ full\ end}$: 0.9 (Table 4) – are higher than those tabled for wine grapes due to the vines height (about 2 m), which are higher than common wine grapes, and because the vineyard architecture, determined by the trellis system, is similar to many training systems used for table grapes. In addition, the $K_{cb\ full}$ values for table grapes given by Allen et al. (2007) do not include an implicit water stress reduction factor (K_s) contrarily to the $K_{cb\ full}$ for wine grapes (Allen and Pereira, 2009). SIMDualKc simulates with a daily time step the effects of water stress by computing the stress coefficient K_s. When the available soil water in the root zone is less that the readily available soil water $K_s < 1.0$, thus resulting $K_{cb\ act} = K_s\ K_{cb}$ with $K_{cb\ act} < K_{cb}$ (Rosa et al., 2012a); therefore, it is not required that the input values of

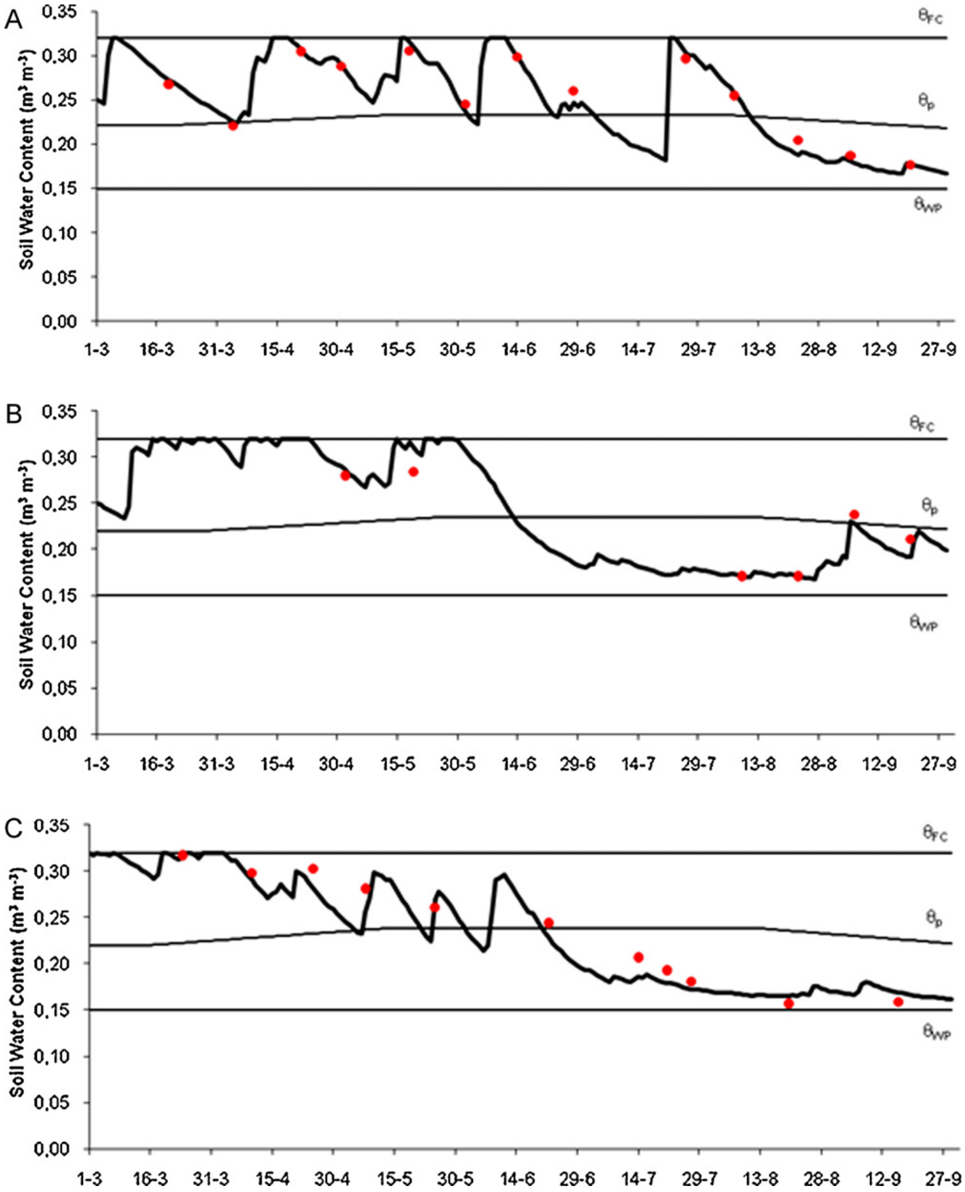

Fig. 4. Simulated soil water content curve and observed values (●) relative to a subsurface drip irrigation for (a) model calibration, 2009 and (b) and (c) validation (2008 and 2010, respectively). Curves θ_{FC}, θ_{WP} and θ_p represent respectively soil moisture at field capacity, wilting point, and when depletion equals the fraction *p*.

Table 5
Indicators of goodness of fit relative to model calibration and validations and all treatments (2008–2010).

Goodness of fit indicators		*b*	r^2	RMSE (mm)	RRMSE (%)	AAE (mm)	EF	d_{IA}
Calibration	R4-27sub	1.00	0.97	0.8	0.8	0.6	0.97	0.99
Validation								
2008	R	1.06	0.97	1.7	1.5	1.4	0.87	0.98
	DI	1.03	0.97	1.3	1.2	1.1	0.96	0.99
	SDI	1.03	0.94	2.1	1.9	1.6	0.86	0.97
2009	R	1.04	0.96	1.7	1.6	1.4	0.88	0.97
	DI	1.04	0.97	1.4	1.3	1.2	0.92	0.98
	SDI	1.06	0.95	2.1	1.8	1.8	0.85	0.97
2010	R	0.99	0.98	1.2	1.1	0.9	0.97	0.99
	DI	0.98	0.96	1.4	1.2	1.1	0.96	0.99
	SDI	1.01	0.93	2.0	1.7	1.5	0.92	0.98
All experiments	1.02	0.94	1.8	1.7	1.4	0.93	0.98	

R, rainfed; DI, surface drip irrigation; SDI, subsurface drip irrigation; b, regression coefficient; r^2, determination coefficient; RMSE, root mean square error; RRMSE, RMSE as a percentage of total available water; AAE, average absolute error; EF, modeling efficiency; d_{IA}, index of agreement.

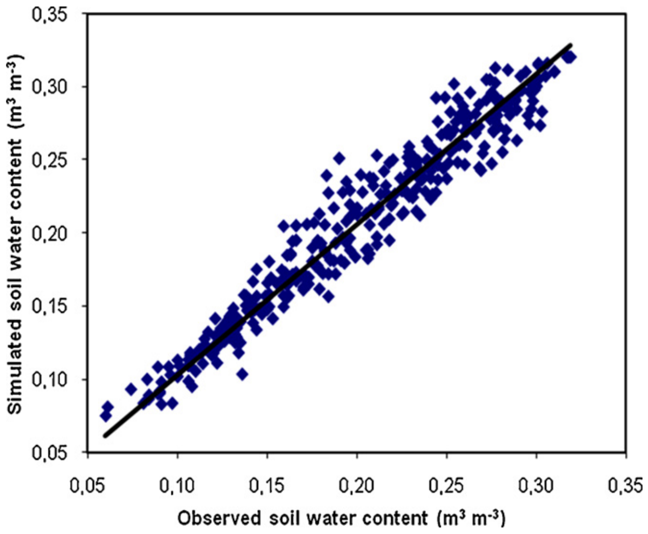

Fig. 5. Comparison between observed and simulated soil water content using all vineyard experiment data (2008–2010).

$K_{cb\ full}$ are previously corrected for water stress. The values obtained for $K_{cb\ full\ mid}$ and $K_{cb\ full\ end}$ are equal to those tabled by Allen et al. (2007) for table grapes. However, $K_{cb\ full\ ini} = 0.30$ is slightly higher than the one tabled by the same authors and resulted close to the $K_{cb\ full\ ini}$ relative to fruit trees, e.g., apples, avocado, apricots, pears and peaches (Allen et al., 2007; Allen and Pereira, 2009).

The K_{cb} of the active groundcover ($K_{cb\ cover}$) was not obtained via calibration-validation of standard/tabled data, but computed by the model using the procedure referred above (Fig. 3) based upon observations of $f_{r\ g\ cover}$, density and $h_{g\ cover}$ throughout the crop growing season, i.e., at the beginning of the simulation and immediately before and after the cultivation operations (Table 3). The daily actual $K_{cb\ cover}$ values were corrected by the same water stress coefficient (K_s) used for adjusting $K_{cb(crop+gcover)}$, as discussed below. Their values throughout the 2009 growing season are presented in Fig. 6b. The abrupt decreases of actual $K_{cb\ cover}$ observed in Fig. 6b are due to mowing and/or application of herbicides, while smoother decreases are caused by water stress. The average daily actual and potential $K_{cb\ cover}$ values (i.e., respectively corrected and not corrected for K_s) during each crop development stage of 2008, 2009 and 2010, are presented in Table 4.

The daily potential (non-stressed) $K_{cb\ cover}$ values were combined through Eq. (5) with $K_{cb\ full}$ and the density coefficient (K_d) referring to the vine crop, to obtain the combined potential (non-stressed) $K_{cb(crop+gcover)}$. Every time that the soil water content decreased below the no stress depletion fraction p the actual $K_{cb(crop+gcover)}$ was reduced by a water stress coefficient (K_s), thus becoming much smaller than the potential $K_{cb(crop+gcover)}$. The actual $K_{cb(crop+gcover)}$ values, as well as the soil evaporation K_e values for the 2009 vine growing season, are presented in Fig. 6a. It may be observed that the K_e values decreased from the initial stage, when the vine canopy shading is negligible, to the mid season stage, when the vine canopy is fully developed. The average K_e during the full growing seasons of 2008–2010 was 0.09; such a small value is due to the combined soil shading effects of the vine canopy and the active ground cover.

Fig. 6a shows for the 2009, that the initial values of actual $K_{cb(crop+gcover)}$ are quite high due to a great vigor of the active groundcover that produces then a high $K_{cb\ cover}$ (Fig. 6b). During the period of rapid growth of the vine plants $K_{cb(crop+gcover)}$ increases substantially from 0.6 at the end of the initial period to about 1.0 at the start of the mid-season. This is mainly due to the vine canopy development and not to the ground cover because $K_{cb\ cover}$ slightly increases during a first short time to decrease immediately after due to cultivation practices (Fig. 6b). During the mid-season, the actual $K_{cb(crop+gcover)}$ would remain equal to 1.0 if a serious water stress did not occur by the mid of the season. An actual $K_{cb(crop+gcover)}$ of ~0.2 was observed by the end of the season (Table 4) much smaller than the potential $K_{cb(crop+gcover)}$ (0.89); this was due to low soil water avaliability conditions prevailing during the entire late season.

Analyzing results from all experiments and years (Table 4), the average actual $K_{cb(crop+gcover)}$ during the initial and mid-season periods were 0.60 and 0.65, respectively, while $K_{cb(crop+gcover)}$ by the end of the season (at harvest) decreased to 0.30. Thus, actual $K_{cb(crop+gcover)\ mid}$ and $K_{cb(crop+gcover)\ end}$ are far below the correspondent non-stressed values of 0.98 and 0.91, respectively (Table 4). Actual $K_{cb(crop+gcover)\ ini}$ is similar to the initial K_c obtained by Yunusa et al. (1997) in Australia, referring to an experiment in a 'Sultana' vineyard with a cover crop covering 85% of the ground surface, and which $K_{c\ ini}$ values were mainly dominated by the cover crop transpiration. Relative to $K_{cb(crop+gcover)\ mid}$ and $K_{cb(crop+gcover)\ end}$, the lack of studies reporting for a separate analysis of $K_{cb(crop+gcover)}$ during each crop development stage does not enable to compare the values achieved in this research with other studies.

The average actual $K_{cb(crop+gcover)}$ over the entire vine growing season was 0.65, which is substantially higher than the value derived from the paper of Yunusa et al. (1997). It is close to the value approximated from the results of Celette et al. (2010) in south of France (0.50). The small value of $K_{cb(crop+gcover)}$ obtained by Yunusa et al. (1997) was due to small energy interception by the vines canopy (low f_c) and to the short period when the cover crop was present.

In order to analyze separately the K_{cb} for the vine ($K_{cb\ vine}$) and that of the active groundcover, the first was calculated by subtracting the known $K_{cb\ cover}$ from $K_{cb(crop+gcover)}$, whose actual values throughout the growing season are presented in Fig. 6b. It may be observed that actual $K_{cb\ vine}$ increases from 0.1 at the end of the initial period to about 0.7 at the start of the mid-season. During the first month of the mid-season, an intense growth of the groundcover, hence of the actual $K_{cb\ cover}$, resulted in a pronounced decrease of $K_{cb\ vine}$ until mowing and herbicide application by mid June. These practices greatly reduced $K_{cb\ cover}$ and favored a quick increase of $K_{cb\ vine}$. This sudden and pronounced increase in $K_{cb\ vine}$ shows the positive impacts of reducing the competition for water when groundcover is reduced, thus augmenting the transpiration of the vines. This opposed behaviors of $K_{cb\ cover}$ and $K_{cb\ vine}$ were also apparent in the periods of 18-06 to 04-07 and 22-07 to 10-08 (Fig. 6b) and justify the use of cover crops and active ground cover by native vegetation for reducing the vigor of the vines as reported in other studies (Lopes et al., 2011; Monteiro and Lopes, 2007). The reduction of $K_{cb\ vine}$ observed during the first three weeks of July and from 10-08 forward (Fig. 6), was also due to low soil water avaliability, which also caused a reduction of $K_{cb\ cover}$.

The average values of actual $K_{cb\ vine}$ for the initial and mid-season periods, and at the end of the season are presented in Table 4. The value obtained for actual $K_{cb\ vine}$ during the mid-season, $K_{cb\ vine\ mid} = 0.40$, considering both the high fraction of ground covered and the vines height ($f_c = 0.5$, $h = 2.0$ m), was mainly determined by water stress and competition for water by the active groundcover. Yunusa et al. (2004) found even lower $K_{cb\ vine\ mid}$ values for a 40% ground cover 'sultana' vineyard in Australia (about 0.17), while Trambouze and Voltz (2001) obtained a similar value (0.36) for 'Shiraz' vines in south of France. However, other researchers reported higher values for $K_{cb\ mid}$ in wine grapes vineyards with f_c varying 30–50%: Intrigliolo et al. (2009) reported $K_{cb\ mid}$ around 0.50 in a 'Riesling' vineyard in the state of New York, USA; Zhang et al. (2011) obtained $K_{cb\ mid} = 0.53$ for a 'Merlot' vineyard in northwest China; Poblete-Echevarría and Ortega-Farias

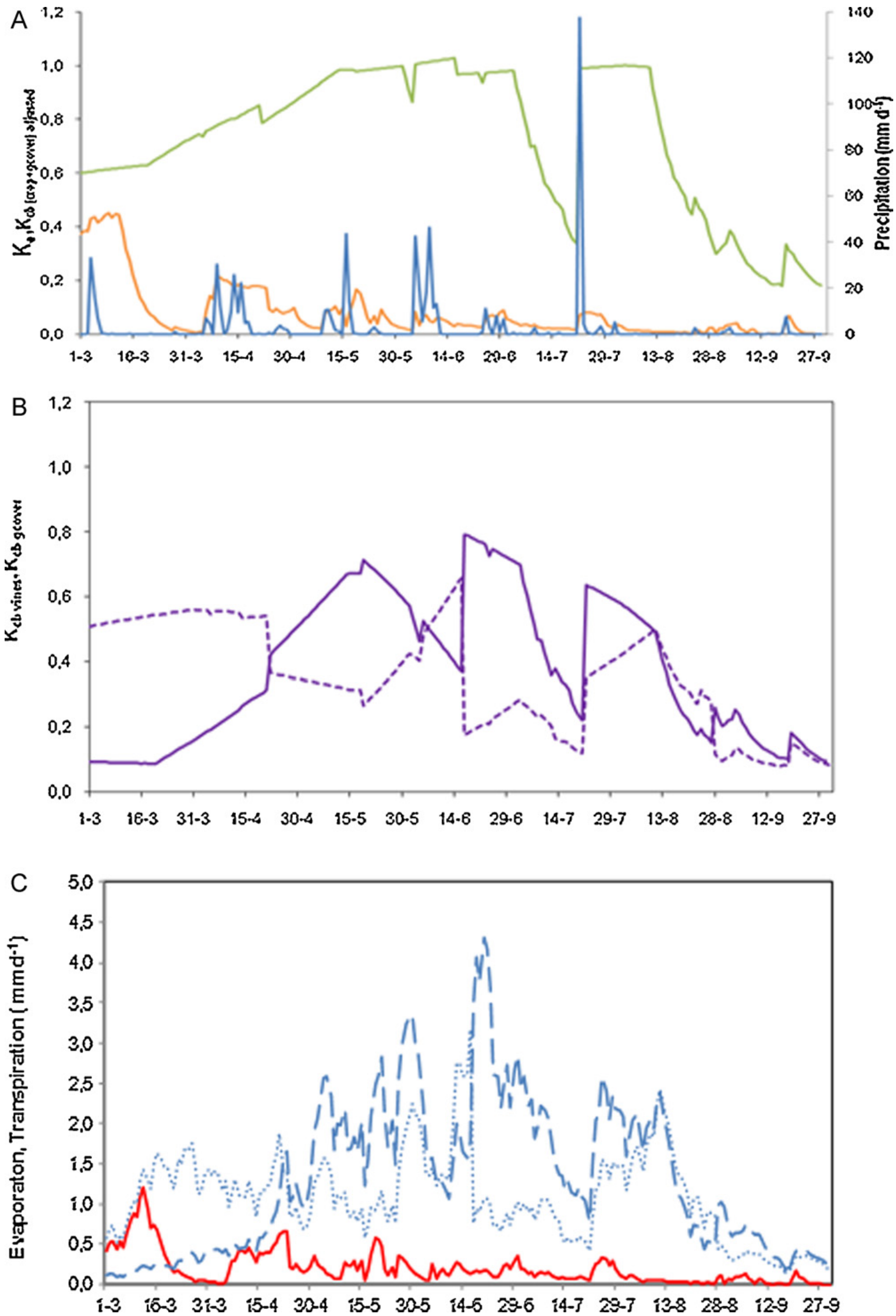

Fig. 6. Variation of (a): K_e (▬), adjusted $K_{cb(crop+gcover)}$ (▬) and precipitation (▬); (b) adjusted $K_{cbvines}$ (▬) and adjusted $K_{cbgcover}$ (▬ ▬ ▬); and (c) soil evaporation (▬), vine transpiration (▬ ▬) and active groundcover transpiration (┅) for the subsurface drip irrigation in 2009.

(2009) found $K_{c\ mid} = 0.55$ in a 'Merlot' vineyard in Chile, i.e., including soil evaporation, which corresponds to a $K_{cb\ vine\ mid}$ similar to that obtained in this study. Results in Table 4 show that when water stress during the mid-season is moderate, like in the experiments of 2009, $K_{cb\ vine\ mid}$ averaged 0.57, which is even higher than the $K_{cb\ mid}$ values reported by the aforementioned authors, and closer to $K_{cb\ mid}$ found by Moratiel and Martínez-Cob (2012) and by Teixeira et al. (2007).

The actual $K_{cb\ vine\ end} = 0.14$ is much smaller than values reported by Intrigliolo et al. (2009) and Zhang et al. (2011), who found $K_{cb\ vine\ end}$ values of about 0.55 and 0.45, respectively. These values are close to the non-stressed $K_{cb\ vine\ end}$ values obtained in this study (Table 4), where water stress conditions during the late season were quite important.

3.3. Soil evaporation, vine transpiration and active ground cover transpiration

Exploring the results of the model when applied to the experimental data, the transpiration of the vine plants transpiration (T_v), of the active ground cover (T_g) and soil evaporation (E) were computed for all treatments. Results in Table 6 show that in a traditional

Table 6
Crop evapotranspiration and respective components separating vineyard and active ground cover transpiration for all treatments and the three seasons (2008–2010).

Treatment	T (mm)	T_v (mm)	T_g (mm)	E_s (mm)	$E_s/ET_{a\ (\%)}$	ET_a (mm)	ET_o (mm)	$K_{c\ adj}$ (aver.)	ET (mm d^{-1})
2008									
R	329.9	137.1	192.8	65.5	17	395.5	644.6	0.61	1.8
DI	350.4	153.1	197.3	57.7	14	408.1		0.63	1.9
SDI	362.7	159.0	203.7	63.4	15	426.2		0.66	2.0
2009									
R	493.3	258.1	235.2	43.2	8	536.2	682.4	0.79	2.5
DI	508.2	271.6	236.7	45.2	8	553.4		0.81	2.6
SDI	521.7	277.7	244.0	45.9	8	567.6		0.83	2.7
2010									
R	353.9	175.0	178.9	42.8	11	396.7	754.9	0.53	1.9
DI	380.5	195.1	185.4	43.2	10	423.8		0.56	2.0
SDI	398.8	205.2	193.6	46.5	10	445.3		0.59	2.1

R, rainfed; DI, surface drip irrigation; SDI, subsurface drip irrigation; T, total transpiration; T_v, vineyard transpiration; T_g, active ground cover transpiration; E_s, evaporation from the soil; ET_a, actual crop evapotranspiration; ET_o, reference evapotranspiration; $K_{c\ adj}$, actual crop coefficient.

“semi-trellised” vineyard of *V. vinifera* cv. Albariño with active groundcover, about 8–17% of the water use during the crop season was evaporation from the soil, which is substantially smaller than the 48% reported by Yunusa et al. (1997) although the cover crop was temporary (3–5 months). Differently, E was closer to the 20% value reported by Celette et al. (2010) for a permanent cover crop. Soil evaporation (E) averaged 17 and 11% of ET_a in 2008 and 2010, respectively, due to high rainfall in the initial and development crop stages when canopy cover is less: 661 and 267 mm (respectively 75 and 65% of total crop season precipitation); differently, in 2009 soil evaporation reduced to 8% since rainfall in the initial and development crop stages was only 40% of total precipitation.

The remaining 83–92% total ET consists of transpiration of both vines (T_v) and active groundcover (T_g), with T_v representing 37, 49 and 45% of total ET in 2008, 2009 and 2010, respectively. T_g, ranged from 43% in 2009 to 48% in 2008. Both the T_v average amount (204 mm) and percentage in total ET (44%) are substantially higher than the values reported by Yunusa et al. (1997) but similar to those referred by Celette et al. (2010). The percentage of T_g in total ET (≈45%) is considerably higher than values reported by Yunusa et al. (1997) although similar in quantity, and is similar to values reported by Celette et al. (2010).

For all experimentation years, the vineyard crop transpiration from the subsurface drip irrigation plots was higher than T_v for surface drip irrigation, and the latter was higher than T_v of the rain-fed treatment. These may be explained by the fact that subsurface drip irrigation plots received more water than surface drip irrigation.

The average ET rates over the full crop seasons of 2008–2010 ranged 1.8 to 2.7 mm d^{-1}, which are not far from the ET rates reported by Singleton and Maudsley (1996), Yunusa et al. (1997), Poblete-Echevarría and Ortega-Farias (2009), Celette et al. (2010), Zhang et al. (2011), Trambouze and Voltz (2001), and Intrigliolo et al. (2009). However, the last authors refer to base-line ET rates, i.e., not considering soil evaporation. Differently, the average ET rates obtained in our study are smaller than those reported by Moratiel and Martínez-Cob (2012), Rana et al. (2004), Teixeira et al. (2007) and Netzer et al. (2009) due to differences in climatic demand, canopy architecture and irrigation management. For instance, ET rates during 2008 and 2010 averaged 2.0 mm d^{-1} with an average $K_{c\ adj}$ of about 0.63 and 0.56 (Table 6), respectively, while during 2009 only moderate water stress occurred resulting in an ET rate of 2.6 mm d^{-1} and $K_{c\ adj} = 0.81$, which is close to the K_c values obtained by Moratiel and Martínez-Cob (2012) and Teixeira et al. (2007).

Results for E, T_v and T_g relative to the various crop growth stages are presented in Table 7. E and T_g were the main ET_a components during the initial crop growth stage, representing about 90% of ET_a for that period. The large E component (≈36%) resulted from high water content in the soil evaporation layer and a relatively low fraction of soil covered by the vegetation (f_c) during the initial stage (cf. Table 2). T_g was higher during 2009, despite the $K_{cb\ cover\ ini}$ was similar to that of 2010, since ET_a was greater in 2009. During the crop development stage, i.e., the transition between the initial and the midseason periods, important rains occurred, thus keeping the upper soil layer wet, but E decreased to about 13% of ET_a due to the increase in ground cover and vine transpiration, which increased from 10% in the initial crop stage to 35% due to the development of the vines’ canopy.

During the midseason period the fraction of wet soil exposed to radiation was low, thus the evaporation (E) during this period

Table 7
Soil evaporation (E_s), vine transpiration (T_v) and active ground cover transpiration (T_g) (2008–2010).

Treatment	Initial stage			Vegetative growth			Mid season			End season[a]		
	E_s (mm)	T_v (mm)	T_g (mm)	E_s (mm)	T_v (mm)	T_g (mm)	E_s (mm)	T_v (mm)	T_g (mm)	E_s (mm)	T_v (mm)	T_g (mm)
2008												
R	22	5	17	30	45	82	6	66	65	6	15	15
DI	18	5	17	25	47	81	8	76	69	6	18	16
SDI	21	5	17	26	47	81	9	82	74	6	18	17
2009												
R	14	4	22	13	52	67	15	162	102	1	36	40
DI	13	4	22	14	53	67	17	170	102	2	40	42
SDI	13	4	22	13	53	67	17	173	105	2	43	46
2010												
R	8	2	14	18	51	83	14	115	72	1	3	3
DI	5	2	14	17	53	82	19	130	76	2	6	6
SDI	6	2	14	17	52	82	20	139	82	2	7	7

R, rainfed; DI, drip irrigation; SDI, subsurface drip irrigation.

[a] From end of mid-season to harvest.

continued to decline, especially for the rainfed treatment. Differences among years were mainly related to rainfall. The T_v for this period was close to 55% of ET_a, representing between 52 and 68% of total T_v in the season. During mid-season, the percentage of T_g in relation to total ET had its minimum values. 2008 was an exception due to a longer water stress period in this year. During the late season, because f_c decreased as the crop senesced, the proportion of E relative to ET_a increased relative to the mid-season period, also due to a small rain during this end season. The exception was 2009 where no rain occurred. The proportion of T_g relative to ET_a during the late season decreased relative to the mid-season period in 2008, but increased for the other years following the behavior of T_v. As expected, E was smaller for the rainfed crop because the soil evaporation layer was dry during much of the crop season.

The dual-K_c approach using a $K_{\text{cb full}}$ and a $K_{\text{cb cover}}$ to take into consideration both the vine crop and an active ground cover transpiration showed to be promising in separately estimating transpiration of the crop and of the active ground cover, as well as the soil evaporation. However, further tests may be required through measuring the soil evaporation and/or T_g.

4. Conclusions

Adopting the dual crop coefficient approach for the estimation of the soil water balance of a vineyard with active ground cover allows a better understanding of water use because it provides for the partition of ET into soil evaporation and crop and active ground cover transpiration. With this objective, the SIMDualKc model was calibrated and validated for drip-irrigated/fertigated vineyards with active ground cover, under conditions of the traditional "semi-trellised" vineyards of *V. vinifera* cv. Albariño in Galicia. Results showed that computations using the density coefficient and the height relative to both the vine canopy and the active ground cover were appropriate for deriving the actual basal crop coefficients $K_{\text{cb vine}}$, $K_{\text{cb gcover}}$ and $K_{\text{cb(crop+gcover)}}$. Results obtained for K_{cb} and depeletion fraction p can provide support irrigation to management in similar vineyards, including with variable ground cover management.

Results for K_{cb} compare well with other reported research on vineyards under different water management practices. Moreover, the model allows to analyze actual and potential (non-stressed) K_{cb} values for all growth periods and therefore to understand when water stress occurred and how severe it was. Similarly, results for soil evaporation, and vine and ground cover transpiration also compare well with results from vineyards in other locations. Differences are explained by the crop architecture, the ET demand, ground cover management, as well as irrigation management. Results of the current study show that the calibrated $K_{\text{cb full}}$ correspond to the commonly tabled values for table grapes due to crop architecture and height. However, the adjusted actual K_{cb} values are smaller due to water stress and competition by the active ground cover, mainly when rainfall is largely insufficient. Despite good results of model fit were obtained when calibrating and validating it, further specific tests of the model relative to the active ground cover may be desirable.

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