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Evapotranspiration and crop coefficient patterns of an apple orchard in a sub-humid environment

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ABSTRACT

Increasing water use efficiency is one of the main challenges of sustainable fruit tree production. From 2013 to 2015 we measured actual evapotranspiration (*ETa*) using eddy covariance in a well-irrigated apple orchard located in in South Tyrol (Italy), a sub-humid environment. We assessed the experimental crop coefficient (Kc_{exp}) and analyzed the dependency of *Kc* on specific environmental variables at a daily time scale. Kc_{exp} values changed throughout the season following a bell-shaped trend and were generally lower than the FAO tabular values corrected for local climatic conditions. In the mid-season phase, when LAI and tabular *Kc* are supposed to be constant, the average experimental *Kc* ($\bar{K}c_{exp}$) was 1.01, 86% of the *Kc* value reported by FAO (1.18). Mid-season *Kc* residuals (Kc_{exp} - $\bar{K}c_{exp}$) were positively correlated with daily vapor pressure deficit (VPD) (ρ = 0.45), suggesting that the daily *Kc* variability observed is due, at least in part, to changes in the evaporative demands of the atmosphere. We explain these results by considering the relatively humid environment, the high water availability and the fact that leaves on apple trees are more tightly coupled to the atmosphere with respect to a smoother grass surface.

1. Introduction

Water used by the agricultural sector accounts for a high fraction of the fresh water available on Earth (FAOSTAT, 2017). Problems related with water shortage are increasing, affecting not only agricultural production but also the civil and industrial economy. There is a great need to increase knowledge about actual crop water consumption in order to adopt strategies to increase irrigation efficiency. Apples are the main deciduous fruit tree crop worldwide and the Trentino-South Tyrol region (northern Italy) is one the main apple growing regions in Europe, accounting for approximately 65% of the national total and 10% of EU production (FAOSTAT, 2017; ISTAT, 2017).

To obtain high yields, apple trees are often irrigated. The most widely used estimate of water requirements (*ETc*) for a particular crop (Allen et al., 1998; Doorenbos and Pruitt, 1977; Pereira et al., 2015) is obtained multiplying the reference evapotranspiration, *ETo* (the sum of evaporation and transpiration of an homogeneously clipped and well-irrigated grass field, calculated by the FAO Penman-Monteith equation, FAO-PM), by a crop coefficient, *Kc* (*ETc* = *ETo***Kc*). The main advantage of this method is that the assessment of *ETo* is based on meteorological data from reference stations, while tabular *Kc* values account for specific crop types and growing conditions. This method, however, has been questioned when applied to fruit tree crops. The FAO-PM equation uses a constant value for the bulk surface resistance ($r_S = 70\,\mathrm{s\ m^{-1}}$) to assess *ETo*, while many authors (Katerji and Rana, 2006; Lecina et al., 2003) have shown that r_S varies according to environmental drivers such as radiation, water pressure deficit and wind velocity (Damour et al., 2010). As an attempt to take into account these environmental drivers, Allen et al. (2006) recommended the use of separate r_S values for day and night periods, when *ETo* is assessed hourly.

Stomatal control on crop transpiration depends on the coupling between the leaves and the surrounding atmosphere (Jarvis and Mcnaughton, 1986; Monteith, 1981). Jarvis (1985) discussed the degree of coupling of different horticultural crops based on their height and canopy roughness. Tall, well-exposed crop systems like orchards are well coupled to the atmosphere and respond sensitively to small changes in stomatal conductance (g_s), especially in the presence of wind. Short or protected crop systems are, on the contrary, poorly coupled with the atmosphere and their transpiration depends more on radiation than on g_s (Chapin et al., 2011; Jarvis and Mcnaughton, 1986; Sadras et al., 2016). For such systems, a fixed r_S can be assumed as a reasonable simplification.

For several fruit tree species like peach (Paço et al., 2006), kiwifruit

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(Silva et al., 2008), pear (Conceição et al., 2008; Girona et al., 2004), and apple (Dragoni et al., 2005; Marsal et al., 2014; Naor and Girona, 2012; Volschenk, 2017), *Kc* values different from the FAO tabular values have been reported (Allen et al., 1998). In addition to random error and oscillation around the mean, the mismatch between modelled and actual evapotranspiration (*ETc* and *ETa,* respectively) might be partly explained by different characteristics of the boundary layer in well- and in poorly-coupled crop systems. In production regions characterized by unstable meteorological conditions during summer, e.g. in those close to mountains, where driving variables like the vapor pressure deficit (VPD) and radiation (Rg) can change suddenly, high daily variability in *Kc* can be observed (Dragoni et al., 2005; Volschenk, 2017).

In this study, water and energy fluxes were continuously measured during three years (2013–2015) via eddy covariance. Among different methodologies to directly measure crop water consumption such as weighing lysimeters (Girona et al., 2011, 2004; Mauder et al., 2018), sap flow (Fernández, 2014), whole-canopy gas exchange measurements (Dragoni et al., 2005) and water balance, the micrometeorological approach known as eddy covariance is recognized as one of the most reliable (Sun et al., 2008) to the point that it is also used for calibrating other methods (Conceição et al., 2008; Paço et al., 2006; Rana et al., 2005; Villalobos et al., 2009). Eddy covariance tends, however, to underestimate water fluxes due to the incomplete closure of the energy balance (Foken, 2008; Foken et al., 2006; Leuning et al., 2012; Mauder et al., 2018; McGloin et al., 2018; Stoy et al., 2013; Wilson et al., 2002; Wohlfahrt et al., 2016). To be reliable, this method requires the selection of a proper site, preferable flat, where an homogeneous crop cover, turbulent conditions and good control of data quality are present (Aubinet et al., 2000; Soubie et al., 2016).

The objectives of this study were: i) to obtain experimental *Kc* (Kc_{exp}) values from the ratio "measured *ETa* / modelled *ETo"*; ii) to compare the seasonal trends in Kc_{exp} with reference *Kc* adapted for local meteorological conditions and iii) to test the hypothesis that day to day variability of Kc_{exp} within the same growing phase depends, at least in part, upon the variability of key meteorological variables affecting ET.

2. Material and methods

2.1. The experimental site

The experiment was conducted for three years (from 2013 to 2015) in an apple orchard located in the valley of the Adige River (46°21′N, 11°16′E, 224 m above sea level, municipality of Caldaro, Bolzano, Italy). The apple trees (*Malus domestica* Borkh., cultivar "Fuji" grafted on "M9" dwarfing rootstock) were planted in 2000 at distances of 3 x 1 m and managed following organic farming guidelines. The soil in the 1.8 m wide alleys between apple tree rows is covered by actively growing grasses throughout the growing season and mowed three times a year (Fig. A supplemental material). The growth of grasses in the 1.2 m soil stripe below the tree canopy is controlled by alternating mowing and mechanical tillage. The training system is spindle bush, and trees, with heights between 3.5 and 4 m have been in their full production phase since 2005. Seasonal trends in leaf area index (LAI) was assessed by repeated measurement during the three years before this experiment (Zanotelli et al., 2015). Between 2013 and 2015, only LAI-max assessment was carried out in July (2.8, 2.8 and 2.9 m^2 m^{-2} in the three years, respectively). Fruit yields ranged between 63 (2015) and 72 (2014) t ha^{-1}. The loamy soil (USDA classification) has 0.19% total nitrogen, 1.85% organic carbon and a pH of 7.2 (average of the upper 0–30 cm soil layer). The soil water content measured at field capacity is 0.37 ± 0.01 m^3 m^{-3} (average ± s.e.), while the permanent wilting point, estimated according to soil texture is 0.12 m^3 m^{-3}. Soil bulk density is 1.23 ± 0.01 g cm^{-3}. Since planting, the orchard is irrigated using an overhead sprinkler irrigation system. An additional drip irrigation system was implemented in spring 2015 and used in combination with the overhead sprinkler system. The maximum number of days between two successive rainfall and/or overhead irrigation events in 2015 (when also the drip irrigation was applied) was 6 days. Frequent overhead irrigation and rainfall made water available both underneath the trees and in the alleys, demonstrated by the actively growing alley vegetation in summer (Fig. A, supplemental material).

2.2. Meteorological measurements

Meteorological variables were measured using instruments installed on the eddy covariance tower at 8 m height (4 m above the tree canopy). The four components of net radiation (incoming and outgoing short- and long-wave radiation) were measured by CNR1 (Kipp & Zonen, Delft, Holland), air temperature and relative humidity by a CS215 (Campbell Scientific Incorporated, Logan, Utah, United States, CSI hereafter), photosynthetic active radiation by SKP215 (Skye Instruments Ltd, Powys, UK), wind speed by a 3D sonic anemometer Gill R3-50 (Gill-Instruments, Lymington, UK) and precipitation by a professional rain gauge RAIN-O-MATIC (Pronamic, Silkeborg, Denmark). Six TDRs (CS616, CSI) placed at 50 cm distance from the apple trees were used to assess the soil water content (SWC). Three of them were vertically oriented starting from soil surface so that they integrated the soil moisture in the first 30 cm of soil. Three additional probes were oriented horizontally at depths of 10, 30 and 60 cm to assess the SWC soil profile. Two soil heat flux plates HFP01 (Huxeflux, Delft, Holland) were placed at 5 cm depth in the opposite sides (South and North) of the 1.2 m wide weed free soil strip below the trees, to measure the soil heat transfer (G). A CR3000 (CSI) logged all meteorological data half-hourly. A comparative analysis between air temperature, relative humidity, wind velocity and vapour pressure deficit data collected in the experimental site and in a standard meteorological station located approximately 3 km away from the experimental orchard (Laimburg Research Centre, LRC, http://www.laimburg.it/en/services/weather-data.asp) was carried out (Fig. B in supplemental material). Unfortunately, net radiation data were not recorded at the LRC. A correlation analysis for each variables was performed to calculate the intercept and slope of the ordinary least square linear regression model (a and b, respectively), the coefficient of determination (R^2) and the root mean square error (RMSE). The linear model fitted the two series of data very well (intercept and slope close to 0 and 1, respectively, Fig. B of supplemental material*)*. For this reason, and given the need to synchronize radiation data with aerodynamic parameters at half-hourly calculation time steps (Pereira et al., 2015), we decided to calculate reference ET (*ETo*) using the data collected at the eddy covariance site, after having adapted the daily net radiation (Rn) data from the orchard, adjusted to include outgoing shortwave radiation corresponding to an albedo of 0.23, typical of a grass field (Allen et al., 1998); we also assumed that the long wave radiation did not significantly differ between the two sites. More information are reported in Fig. C of supplemental material.

2.3. ETo estimation

Reference evapotranspiration (*ETo*, mm half-hour^{-1}) was calculated at half hourly time steps by adopting a modified version of Eq. 53 from FAO 56 (Allen et al., 1998) as reported by Allen et al. (2006):

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma\frac{C_n}{T_{hh} + 273}u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (1)$$

where *Rn* is the net radiation at the canopy surface (MJ m^{-2} half-hour^{-1}) adapted to provide an albedo of a reference grass surface, *G* is soil heat flux density (MJ m^{-2} half-hour^{-1}), T_{hh}, is the mean half-hourly air temperature (°C), *RH* is the relative humidity and u_2 the half-hourly average of wind speed (m s^{-1}) downscaled to a height of 2 m. All these variables were measured at the eddy covariance site. The saturation vapour pressure at T_{hh} (e_s, kPa), the slope of the saturation vapour pressure temperature relationship at T_{hh} (Δ, kPa °C^{-1}), and the average half-hourly actual vapour pressure (e_a, kPa) were calculated based on the relative standard equations (Allen et al., 1998). γ is the psychrometric constant (kPa °C^{-1}), while C_n and C_d are respectively numerator and denominator coefficients that differ in reason of computation time step. At the half-hour time step C_n was equal to 18.5. Regarding C_d, it was decided to follow Allen et al. (2006), who suggested to consider a different bulk surface resistance (r_S) for the day (50 s m^{-1}) and the night (200 s m^{-1}) period when the equation is applied at hourly (or lower) time step. This means that C_d, instead of being constantly equal to 0.34, assumes a value of 0.24 when Rn is > 0 and 0.96 when Rn is < 0.

2.4. Eddy covariance measurements

An 8-meter tower was installed at the experimental site in the spring 2009, in an area that proved to satisfy the requirements of flatness and homogeneity of surface cover (Zanotelli et al., 2013). H_2O concentrations were measured by a LI-7200 (Li-Cor Biosciences, Lincoln, Nebraska, USA) infrared gas analyzer. Instantaneous gas and wind data were taken 4 ms above the canopy with a frequency of 20 Hz. Raw data were collected and H_2O flux data (*ETa*) computed every 30 min with Eddysoft software (Kolle and Rebmann, 2007). Low quality data for turbulence and stationarity were screened out according to the Foken and Wichura (1996) quality test, as described by Zanotelli et al. (2013). The gaps in the original dataset due to maintenance and instrument failure, and the data that did not pass the quality check process, were replaced using the online gap-filling and flux-partitioning tool provided by the Max Plank Institute (http://www.bgc-jena.mpg.de/-MDIwork/eddyproc/) applying the approach described in Reichstein et al. (2005). This approach considers both the co-variation of fluxes with meteorological variables and the temporal auto-correlation of the fluxes. On average, in the three years of the study, this process was used to fill approximately 30% of daylight data.

2.5. Correction of the eddy measured ETa

Measured *ETa* data were corrected to account for the underestimation involved with the closure failure of the energy balance. The energy balance closure ratio (EBR) was calculated at daily timescale as follows:

$$EBR = \frac{\sum(\lambda E + H)}{\sum(R_n - G - S)} \tag{2}$$

where λE and H are the eddy covariance-measured latent and sensible heat fluxes, respectively, while R_n is net radiation and G the soil heat transfer. All the terms of Eq. (2) were measured every half hour as energy fluxes (W m^{-2}) and converted to MJ m^{-2}d^{-1}. We did not measure the heat storage term (S), which in our system can be considered negligible (Leuning et al., 2012; Stoy et al., 2013; Wilson et al., 2002).

Following previous research on the topic (Foken, 2008; Jung et al., 2010; Mauder et al., 2018; Twine et al., 2000) we forced the closure of the energy balance by means of the Bowen ratio method:

$$Res_{EB} = R_n - G - \lambda E - H \tag{3}$$

where Res_{EB} is the absolute energy balance residual, calculated at a daily base and added proportionally to H and λE according to the daily value of the Bowen ratio. To improve the interpretation of the seasonal course of *ETa* in the three years (as well as fo Kc_{exp}) the local polynomial regression fitting (loess function, R Core Team, 2017) was used with the default span of 0.75.

2.6. Assessment and interpretation of crop coefficient (Kc)

Given the independency of *ETa* and *ETo* assessments, the single crop coefficient (*Kc*) for the studied apple orchard was experimentally obtained as:

$$Kc_{exp} = \frac{ETa}{ETo} \tag{4}$$

where *ETa* (corrected by forcing the energy balance closure) and *ETo* were considered for the period of active vegetative growth (March – October) at daily timescale, to obtain an assessment of experimental *Kc* for three consecutive years. Following the FAO56 approach, the growing season was divided into four phases, adapting the suggested values (Table 11, FAO56, Allen et al., 1998) to our experimental conditions. The four phenological phases were set as follows: the initial phase (phase 1, *ini*), indicatively the period from bud burst to fruit set, was between DOY 60 to DOY 99; the phase of leaf development (phase 2, *dev*) ranged between DOY 100 and DOY 165; the mid-season phase (phase 3, *mid*),when the canopy is fully expanded, ranged from DOY 166 to DOY 258; while phase 4 (*late*), was between DOY 258 to DOY 304, just before initial leaf fall (*end*).

The tabular Kc_{ini} value for the apple orchard was not modified as the climatic conditions were not different from those assumed as reference. *Kc* values in the mid and end season phases were adapted to our specific climatic conditions using the equation proposed by Allen et al. (1998):

$$Kc_{mid/end} = Kc_{mid/end(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{5}$$

where Kc_{mid} and Kc_{end} (*Tab*) were derived from table n. 12 reported in FAO56 (apples with active ground cover and killing frost), u_2 is the mean value for daily wind speed in the considered growing stage taken at 8 m in the experimental site (given the good correlation with the wind speed measured in the near meteo station, figure A in supplemental material), RH_{min} is the mean value for daily minimum relative humidity in mid- or end-season stage and h is the mean plant height (4 m). These reference *Kc* values were substantially confirmed by Allen and Pereira (2009) for the category of apple orchards that matches our growing condition: active ground cover, killing frost, high density and higher effective fraction of ground cover ($f_{c\ eff}$ = 0.7). Due to the fact that the orchard was irrigated regularly and that soil moisture rarely dropped to 25% in volume (Fig. 1), no stress coefficient was adopted (Ks = 1).

To study the effects of environmental variables on the variability of *Kc* in the mid-season phase where LAI and *Kc* are supposed to be constant, the difference $Kc_{exp} - \bar{K}c_{exp}$ (later “residuals”) was calculated, where $\bar{K}c_{exp}$ represents the three-year average of the experimental daily *Kc* for this phase (Eq. (4)). Then, the existence of a correlation between these residuals values with the following meteorological variables was tested: mean daily air Temperature (Tair, °C), global radiation (Rg, *MJ* $m^{-2}d^{-1}$), vapor pressure deficit (VPD, *kPa*) and wind velocity (u_2, *m s*$^{-1}$). A multiple regression model was first tested on Kc-residuals, considering the four meteorological variables as initial predictors and following the backward elimination process to assess the minimum adequate model. The relative importance of the significant parameters was tested with the aid of the R package “Relaimpo” (Grömping, 2006) using the standard “lmg” metric. Single linear regression analysis between meteorological parameters and the Kc-residuals was also performed, and the *p-value* of the intercept and slope parameters, the coefficient of determination and the Spearman correlation coefficient (ρ) used to test the robustness of the linear models.

To examine the effect of VPD on Kc, the dataset was divided according to four classes of VPD (< 0.5, 0.5–1, 1.0–1.5 and > 1.5 kPa), used as different levels of the factor VPD in a non-parametric Kruskall Wallis test, followed by the Wilcoxon test when significant differences were observed. All computation were carried out with the R statistical software (R Core Team, 2017).

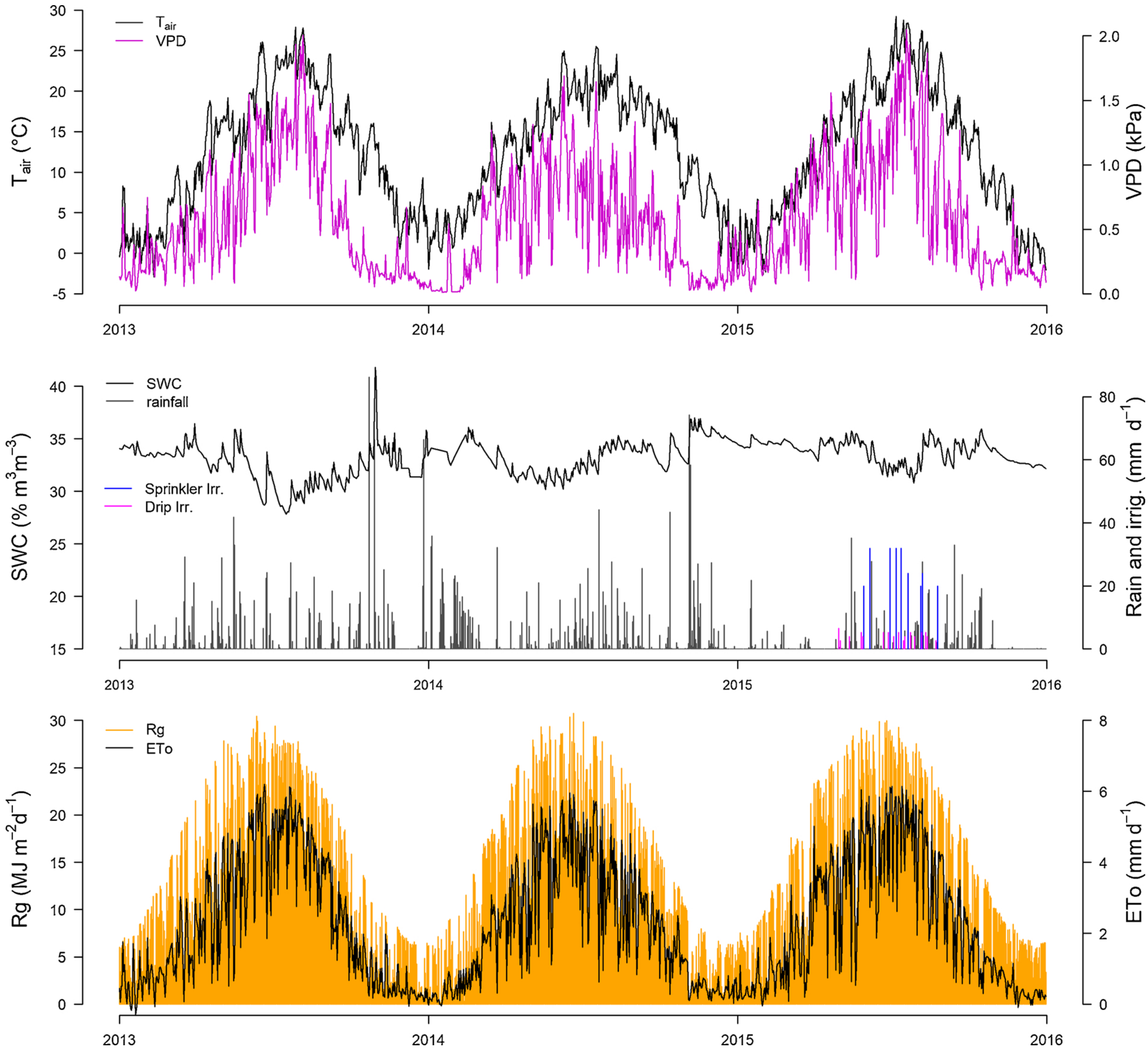

Fig. 1. Time series of the main environmental variables over the three years (2013–2015) considered in the study. The upper panel reports air temperature (Tair, °C) and vapour pressure deficit (VPD, kPa). In the central panel the volumetric soil water content (SWC, $m^3 m^{-3}$, average of three probes), the precipitation (rainfall, mm d^{-1}), and the irrigation (either with sprinkler and drip system, mm) are shown. The bottom panel reports the seasonal course of reference evapotranspiration (*ETo*, mm d^{-1}) and global radiation (Rg, MJ $m^{-2}d^{-1}$).

3. Results

3.1. Meteorological conditions and soil water status

Year 2015 was warmer and drier than 2013, while 2014 was anomalously rainys (Conte et al., 2019), especially in summer (Fig. 1). Mean annual VPD was lowest in 2014 (0.51 kPa) intermediate in 2013 (0.58 kPa) and highest in 2015 (0.63 kPa). Annual precipitation was 1113, 1277 and 573 mm in 2013, 2014 and 2015, respectively. During the experimental period, the soil water content was always kept within an optimal range as a consequence of natural precipitation (in 2014) and irrigation (in 2013 and 2015). Data from the three, vertically-oriented TDR probes showed soil water contents in the first 30 cm of soil depth from 0.27 to 0.41 m^3 m^{-3} (0.33 ± 0.02 m^3 m^{-3} average ± st. dev.). In the growing season period (from March to October), the average daily available photosynthetically active radiation was 31.3, 31.2 and 31.4 photon mol m^{-2}, the average air temperature was 16.5, 16.6 and 17.1 °C and VPD was 0.76, 0.70 and 0.83 kPa in 2013, 2014 and 2015, respectively.

3.2. ETo and ETa

Annual patterns of *ETo* is shown in Fig. 1. The cumulated amount of *ETo* was 828, 790 and 851 mm y^{-1} in 2013, 2014 and 2015, respectively, while the *ETo* calculated for the growing season only (from DOY 60 until DOY 304) amounted to 762, 735 and 788 mm, respectively. The average energy balance ratio (*EBR*) of the experimental site, calculated by means of Eq. (2) was 0.60, with higher values recorded during the summer months (from 0.56 in July 2014 to 0.75 in July 2015, Table 1). Despite the high determination coefficients observed between the available energy (*Rn-G*) and the surface energy fluxes ($H + \lambda E$, average $R^2 = 0.93$), the average slope of the linear regression ranged between 0.68 in 2014 and 0.77 in 2015 (Fig. 2). With the aim to close the energy balance, the missing energy was assigned either to H or LE based on the daily Bowen ratio values. Average Bowen ratio values at the monthly scale for the three seasons are reported in Table 1. The cumulated *ETa* obtained via eddy covariance and corrected by forcing the energy balance closure was 764, 683 and 745 mm in 2013, 2014 and 2015, respectively. The closure of the energy balance increased the

Table 1
Energy balance ratio (EBR) obtained via Eq. (2), the Bowen ratio (*H/LE*), and the albedo (shortwave outgoing/ shortwave incoming radiation), presented at a monthly scale in the three considered growing seasons.

Month	EBR				Bowen Ratio				Albedo			
	2013	*2014*	*2015*	*Av. ´13-´15*	*2013*	*2014*	*2015*	*Av. ´13-´15*	*2013*	*2014*	*2015*	*Av. ´13-´15*
Mar	0.57	0.60	0.56	0.58	0.86	0.42	0.93	0.74	0.13	0.14	0.14	0.14
Apr	0.59	0.61	0.58	0.59	0.51	0.34	0.28	0.38	0.14	0.15	0.16	0.15
May	0.60	0.60	0.52	0.57	0.27	0.27	0.20	0.25	0.16	0.16	0.17	0.16
Jun	0.64	0.58	0.67	0.63	0.14	0.11	0.17	0.14	0.16	0.15	0.15	0.15
Jul	0.66	0.56	0.75	0.65	0.09	0.12	0.10	0.10	0.14	0.14	0.15	0.14
Aug	0.67	0.61	0.65	0.64	0.15	0.18	0.13	0.15	0.14	0.14	0.14	0.14
Sep	0.65	0.61	0.57	0.61	0.17	0.22	0.21	0.20	0.14	0.15	0.15	0.15
Oct	0.43	0.53	0.52	0.49	0.37	0.49	0.52	0.46	0.15	0.16	0.16	0.16
Average season	***0.60***	***0.59***	***0.60***	***0.60***	***0.32***	***0.27***	***0.32***	***0.30***	***0.14***	***0.15***	***0.15***	***0.15***

measured *ETa* by approximately 25%. Considering only the growing season (March-October), the mean daily *ETa* in the three years was 2.9, 2.7 and 2.9 mm d^{-1} while the maximum daily *ETa,* recorded always in July, was 6.7, 6.3 and 6.8 mm d^{-1} in 2013, 2014 and 2015, respectively (Fig. 3).

3.3. Kc values

The linear correlation between *ETa* and *ETo* in the mid-season phase was highly significant (Fig. 4). The non-parametric regression line fitted on the seasonal course of Kc_{exp}, showed a bell-shaped curve with some differences among the years (Fig. 5). The trend of the curve was similar in 2013 and in 2015, with a slightly higher peak in the latter year, while it was smoother and lower in the wetter and cooler 2014 season. With the exception of some isolated spikes, the highest Kc_{exp} values (between 1.00 and 1.25) associated with the peak of the non-parametric curve, were obtained around DOY 200, when the highest mean daily temperatures were also recorded.

The seasonal course of $\bar{K}c_{exp}$ obtained by applying Eq. (4), schematized according to the four-phases approach proposed in FAO56, is shown in Fig. 6, together with the tabular *Kc* values (FAO56) corrected for local environmental condition according to Eq. (5). $\bar{K}c_{exp}$ was 30% higher than the values proposed by FAO56 in the initial phase and both were of similar magnitude at the end of the season. In the mid-phase, the $\bar{K}c_{exp}$ averaged 1.01, approximately 15% lower than the 1.20 proposed as default by FAO. The differences were confirmed even after Kc_{mid} was adapted to the local growing meteorological conditions, with $\bar{K}c_{exp}$ always lower than the tabular values (Table 2).

In the mid-season phase, the *Kc* residuals (Kc_{exp} - $\bar{K}c_{exp}$) were positively correlated with both T_{air} and VPD (Fig. 7 a and c). In both cases, both intercept and slope parameters of the fitted linear model were highly significant, and the Spearman correlation coefficient confirmed the existence of a moderate monotonic positive correlation (ρ = 0.45), although the coefficients of determination were rather low (R^2 = 0.15). No significant correlation between the residuals and Rg or wind speed was, on the contrary, observed (Fig. 7 b and d). Given the high level of autocorrelation between VPD and T_{air} (R^2 = 696%, ρ = 0.83), the backward elimination procedure applied to the fitted multiple regression models with four variables, excluded T_{air} and kept only VPD, Rg and wind as significant predictors. The amount of variance explained by the model increased with respect to the single linear models (R^2 = 27.7%) and the analysis on the relative importance of the parameters, confirmed VPD as the most influential (78%), followed by Rg (16%) and wind speed (6%, Table 4). The sign of the coefficient indicated that VPD has a positive influence on Kc residuals, while Rg and wind speed affect negatively the results.

Coherently with the analysis of the residuals, average Kc_{exp} values obtained when VPD values were below 0.5 kPa, were significantly lower (0.91 on average) with respect to those recorded when VPD was between 0.5 and 1.5 kPa (1.01 and 1.02). The highest Kc_{exp} values were recorded with VPD values above 1.5 kPa (1.12 on average, Table 3).

4. Discussion

A reliable assessment of *ETo* and a precise measurement of *ETa* are of a pivotal importance for the purposes of this work, as both directly

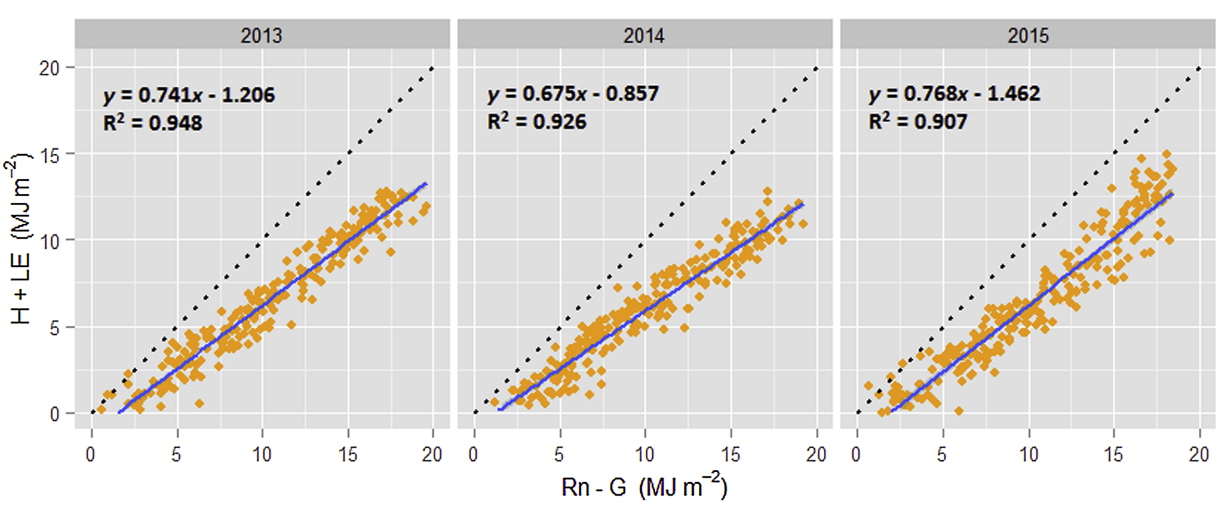

Fig. 2. Energy balance closure during the growing seasons (March-October) of the three years considered in the study. The *x* axis reports the available energy given by net radiation (*Rn*) minus soil heat transfer (*G*), while in the *y* axes are reported the eddy covariance measured surface energy fluxes given by the sum of latent (*LE*) and sensible heat (*H*). Data reported are cumulated at a daily base (MJ m^{-2}).

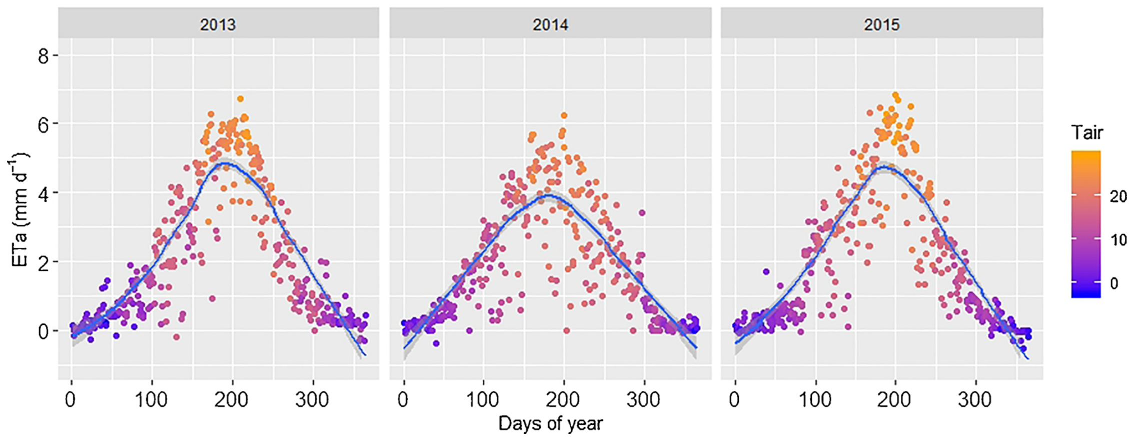

Fig. 3. Seasonal trend of evapotranspiration (*ETa*, mm day^{-1}) measured via eddy covariance in the tree years of the study. The color of the dots reflects the mean air temperature of the single days. The regression line and the relative 95% confidence intervals (gray area around the line) are obtained using the loess function with the default span of 0.75.

influence Kc_{exp} (Eq. (4)). The method reported in FAO56 (Allen et al., 1998) for modelling *ETo* has been questioned by several authors, who showed that using fixed - instead of a varying canopy (or surface) resistance (r_S) - may limit the predictive capacity of the model, especially when applied at hourly (and shorter) time scales (Damour et al., 2010; De Medeiros et al., 2005; Katerji and Rana, 2006; Lecina et al., 2003; Steduto et al., 2003; Ventura et al., 1999). To account for this, *ETo* was calculated at half-hourly time steps, considering a varying r_S: 50 s m^{-1} during daytime (Rn > 0 Wm^{-2}) and 200 s m^{-1} at night (Allen et al., 2006; Pereira et al., 2015).

Eddy covariance has been used successfully as a reference method to assess *ETa* in several fruit trees crops such as olives (Orgaz et al., 2006; Testi et al., 2006, 2004), citrus (Rana et al., 2005; Villalobos et al., 2009), pear (Conceição et al., 2008; Girona et al., 2004), peach (Paço et al., 2006) and apple (Braun et al., 2000). A matter of debate in eddy covariance studies is the closure of the energy balance. Convective energy fluxes, made by the sum of the sensible (*H*) and the latent (λE) heat, are frequently underestimated; imbalances between the available energy, represented by the net radiation (*Rn*) minus the heat transfer to the soil (*G*), may be greater than 30% (Foken, 2008; Foken et al., 2006; Leuning et al., 2012; Stoy et al., 2013; Wilson et al., 2002; Wohlfahrt et al., 2016). The energy balance closure of 0.60 – an imbalance of 40% - found in our site is slightly lower than average data reported by Wilson et al. (2002) from more than 20 sites (0.84, ranging from 0.34 to 1.69). Foken (2008) reported energy imbalances from 37 to 10%, similar to what reported later by Stoy et al. (2013), who found the worst average closures in crops, deciduous broadleaf forests, mixed forests and wetlands. These findings are substantially confirmed in a variety of ecosystems in eastern Europe, where the lowest EBR (0.61) was found in cropland (McGloin et al., 2018). Recent literature lists the heterogeneity of vegetation cover and morphology at landscape scale (characterized by vegetated mountains), associated with mesoscale eddies, as well as the turbulence conditions present at the site, among the most relevant causes of the energy closure failure (Eder et al., 2015; Gao et al., 2017; Mauder et al., 2018; McGloin et al., 2018). Other processes, like the biological energy assimilation and heat storage, which are rarely taken into account, also partially explain the energy balance closure failure (Chapin et al., 2011; Lindroth et al., 2010; Moderow et al., 2009). We cannot fully exclude that our measurements of soil heat flux could have underestimated *G* due to the fact that the probes were positioned only along the tree line. When considered at a daily time scale, however, the contribution of G can be considered negligible since the heat transferred into the soil during the day is released back to the surface at night (Chapin et al., 2011). Other possible sources of uncertainty are related to the possible underestimation of eddy covariance fluxes under rainy conditions (Van Dijk et al., 2015). To provide a more quantitatively-sound estimate of *ETa,* we forced the closure of the energy balance, adopting the Bowen ratio (Foken, 2008; Jung et al., 2010; Twine et al., 2000) to assign the missing energy to the *H* and λE components. It is important to keep in mind that this procedure, which increased the magnitude of *ETa*, also increased Kc_{exp}, thus reducing the gap with the FAO´s tabular data in the mid-season phase.

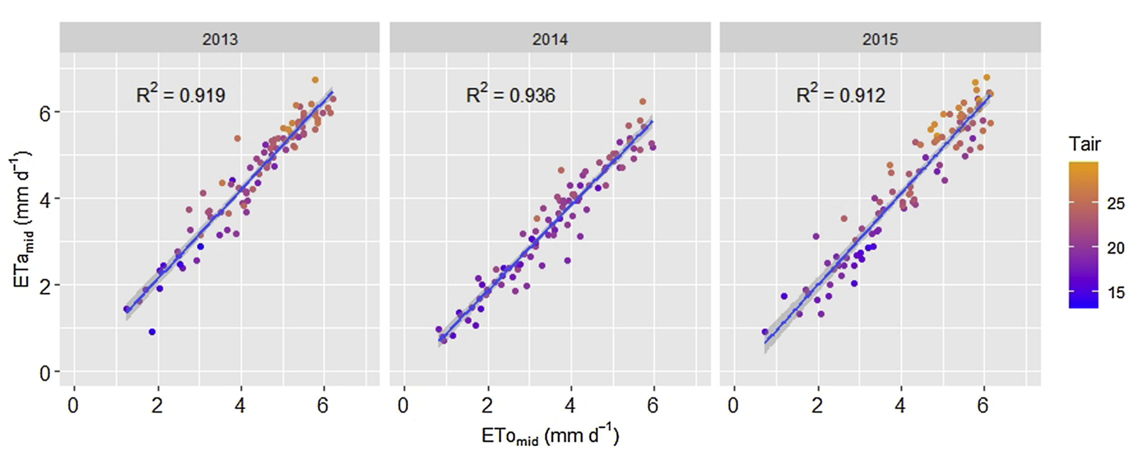

Fig. 4. Correlation of actual evapotranspiration (*ETa*, mm d^{-1}), measured via eddy covariance against reference evapotranspiration (*ETo*, mm d^{-1}), simulated using the FAO-modified Penman Monteith equation (Eq. (1)), in the mid-season phase of three years of the study. The colour of the dots reflects the mean air temperature of the single days. The result of the linear regression is presented with a 95% confidence interval (grey area around the line) and the relative R^2.

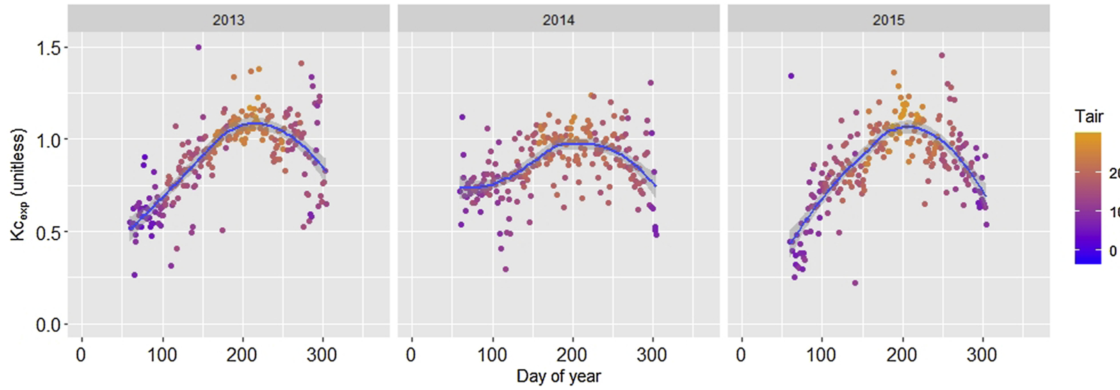

Fig. 5. Daily values of *Kc* (Kc_{exp}) over the vegetative period (March-October) of three years. The colour of the dots reflects the mean daily air temperature. The trend-line for each year (presented with 95% confidence interval – grey area around the line) is obtained by the loess non-parametric regression method with the default span of 0.75.

Kc_{exp} values showed a bell-shaped pattern (Fig. 5) in line with the literature (Girona et al., 2004; Gong et al., 2007; Naor and Girona, 2012; Testa et al., 2011; Volschenk, 2017). Some significant differences among the absolute *Kc* values were observed in the three years. The highest *Kc* values were reached in 2015, in correspondence with the highest summer temperatures (mid-season phase), while the peak was less pronounced in 2014, when the summer was unusually rainy and mild. Kc_{exp} values were generally lower than those proposed by FAO56 (Fig. 6) for a mature apple orchard with active ground cover and killing frost (Allen et al., 1998), even when the tabular values were corrected for local climatic conditions. In the mid-season phase, $\bar{Kc}_{exp}$ reached only 85% of what indicated in FAO56 (Table 2). Several authors reported significant deviation of locally-assessed *Kc* with respect to FAO reference for different horticultural crops. For mature pear trees growing on large weighing lysimeters, Girona et al. (2004) found a *Kc* 30% lower than the FAO's reference, and attributed this difference mainly to a reduced ground cover and to the "palmette" training system used in that orchard. Similar results are reported by Conceição et al. (2008) in a pear orchard in Portugal, where mean *Kc* values for the mid-season stage ranged from 42 to 52% of FAO's reference *Kc*. Paço et al. (2006) in a young peach orchard, measured *Kc* values 25% lower the tabular values (Allen et al., 1998), and were successively adopted as standard Kc for young peach trees (Allen and Pereira, 2009). The *Kc* reported for young olive trees by Testi et al. (2004), regardless the fact that *ETc* was measured via eddy covariance or simulated by water balance, were often less than half the FAO56-*Kc* for mid and late season (0.7), while Testi et al. (2006) reported simulated *Kc* values of 0.57 and 0.64 in two commercial olive orchards for the month of July. In contrast, Rana et al. (2005) reported experimental *Kc* for citrus growing under Mediterranean conditions higher (0.8–1.2) than those reported by Allen et al.(1998). Also for apple orchards, contrasting results are available: Dragoni et al. (2005) found lower *Kc* values with respect to

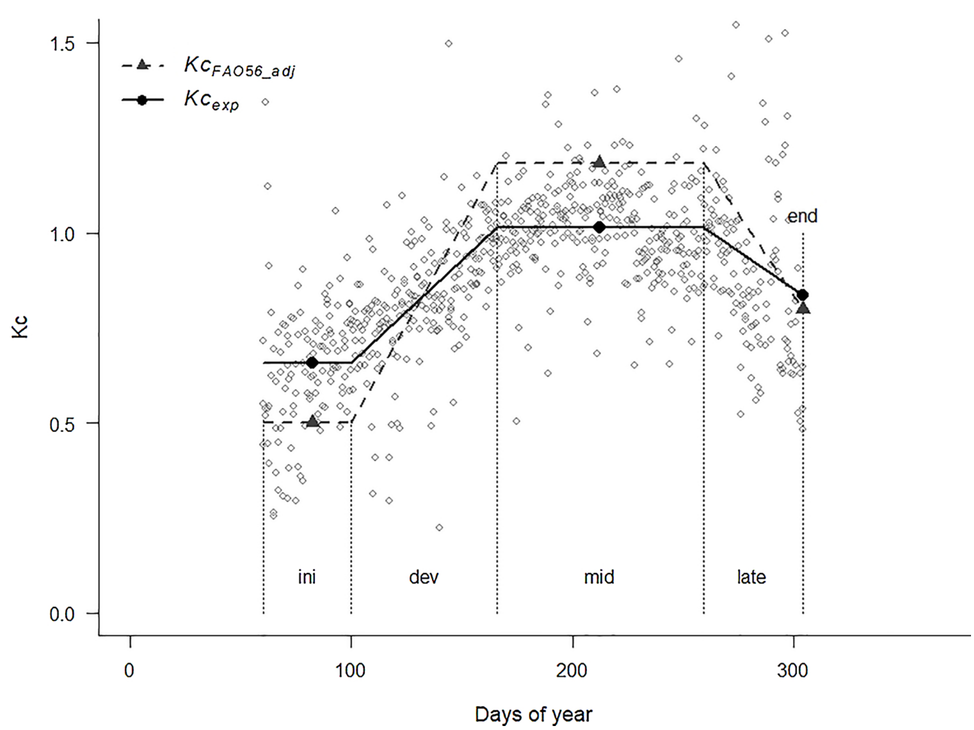

Fig. 6. Seasonal course of *Kc* following the four-stage scheme proposed by FAO. The dashed line was reconstructed based on FAO56 tabularized values for apple crops adjusted for the local climatic conditions, while the solid line is fitted to our experimental data (Kc_{exp}, grey empty dots) in the March-October period of the three years. Consistently with FAO56 scheme, the three black dots represent average Kc_{exp} ($\bar{Kc}_{exp}$)in the initial, mid- and end-season phase (Kc_ini, Kc_mid and Kc_end), whose respective values are reported in Table 2, together with parameters of the *Kc* lines in the development (dev) and late stage of the season.

Table 2
Kc values obtained from FAO56 as they are (Kc_{FAO56}), adjusted for the local climatic conditions (Kc_{FAO56_adj}) and from the experimental data of the three years of this study ($\bar{Kc}_{exp}$), according to Eq. (4) and the four stage scheme proposed by FAO.

Kc	DOY Intervals	Phenological phase	Kc_{FAO56} *	Kc_{FAO56_adj} **	$\bar{Kc}_{exp}$ *mean ± se*
Kc_ini	60-99	Bud burst	0.50	0.500	0.657 ± 0.021
Kc_dev	100-165	Leaf development	*−0.5607 + 0.0106 DOY*	*−0.5096 + 0.0102 DOY*	*0.1170 + 0.0054 DOY*
Kc_mid	166-258	Maximum LAI	1.20	1.183 ± 0.011	1.013 ± 0.008
Kc_late	259-304	Harvest time	*2.6389-0.0056 DOY*	*3.3398-0.0084 DOY*	*2.0142-0.0039 DOY*
Kc_end	304	Before leaf fall	0.95	0.799 ± 0.014	0.835 ± 0.022

* Coefficients reported in table 12 of FAO56 paper for apple trees with a maximum height of 4 m, active ground cover and killing frost (Allen et al., 1998).
** The values of Kc_{mid} and Kc_{end} are adjusted to the local climatic conditions based on Eq. (5). The last seven days of the season (DOY 298–304) are considered for adjusting Kc_{end} (n = 21).

the reference ones for apple trees growing in the relatively cool climate of the New York State; Volschenk (2017) reported maximum *Kc* ranging from 0.8 to 1.1 in South Africa, Australia, Israel and Spain, while Gong et al. (2007) obtained experimental *Kc* values of 1.2 in the semi-arid China´s Shaanxi area. The fact that *Kc* depends on ground cover and crop characteristics and may vary quite substantially among locations (Orgaz et al., 2006) makes difficult the application of the single crop coefficient method where no experimental information exists (Villalobos et al., 2000). Although there is an increasing interest within the scientific community to apply the dual crop coefficient approach (Poblete-Echeverría and Ortega-Farias, 2013), especially when crops are drip irrigated and the soil partially covered by a vegetation, we preferred to adopt the single *Kc* approach because the eddy covariance methods does not allow the separation of transpiration from soil evaporation, and because the orchard floor vegetation was actively growing during the entire vegetative season. So far, no specific indications about *Kc* values for apple trees are available for Trentino Alto-Adige region, the main Italian district and one of the most relevant in Europe (Dalla Via and Mantinger, 2012; FAOSTAT, 2017; ISTAT, 2017), where apple trees are generally irrigated using generous amounts of water.

In summer, when most *ET* losses occur and irrigation is more frequent, the classic FAO56 approach suggests use of a fixed *Kc*, assuming that the estimate of *ETo* accounts for the changes in weather conditions. Our evidence, however, in line with Marsal et al. (2013) and Volschenk (2017), highlights that experimentally-measured *Kc* values significantly vary (up to 25%) within a short period, as well as from year to year, in relation to the meteorological conditions. We demonstrated that the strongest influence on Kc is attributable to VPD (positively correlated), followed, with a lower importance, by Rg and wind speed (negatively correlated). When daily VPD values are below 0.5 kPa, the actual Kc is generally lower with respect to the reference $\bar{Kc}_{exp}$, so the use of $\bar{Kc}_{exp}$ generates an overestimate of *ETc*, while the opposite occurs with VPD > 1.5 kPa (Fig. 7, Table 3). If VPD determines an increment of crop ET more than proportional with respect to reference ET, global radiation and and wind speed instead, when considered in the multiple regression models with VPD, reduce *Kc,* demonstrating to have a greater influence on *ETo* than *ETc,* and highlighting their different effect on the two ecosystem types (Chapin et al., 2011). These results support the hypothesis expressed by Jarvis (1985); Jarvis and Mcnaughton (1986), and Dragoni et al. (2005) of a tighter coupling between the tree canopy and the surrounding atmosphere with respect

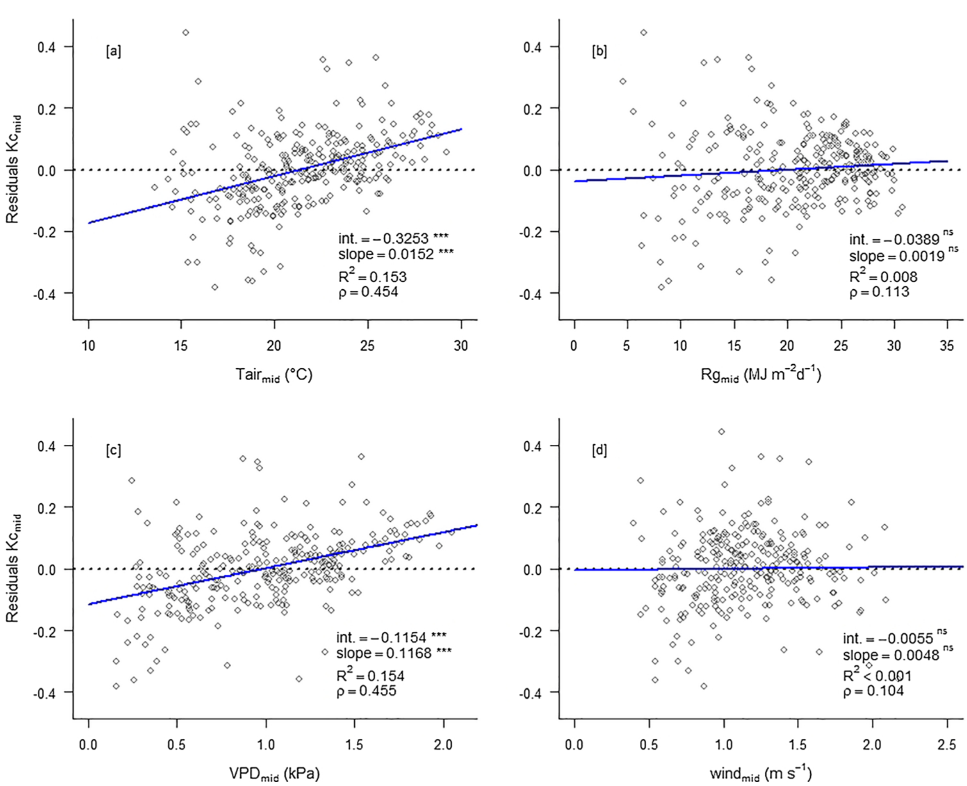

Fig. 7. Sensitivity of *Kc* residuals to key meteorological variables in the mid-season phase: a) air termperature (Tair, *°C*); b) global radiation (Rg, $MJ\ m^{-2} d^{-1}$); c) vapour pressure deficit (VPD, *kPa*) and wind speed (wind, $m\ s^{-1}$). Intercept and slope of the ordinary least square linear model are reported in each panels together with their statistical significance (*** p-value < 0.001; *ns* not significant), the coefficient of determination (R^2), and the Spearman´s correlation coefficient (ρ).

Table 3
Analysis of Kc_{exp} of the mid-season phase in the three considered seasons, divided in four classes of vapour pressure deficit (VPD, *kPa*). The columns "*n*" report the numerosity of the sub-samples. The last row contains the weighted average of the of *Kc* and VPD and the total days of each VPD class. The letters report statistically significant differences of 2013–2015 *Kc* (p-value = 0.05) among VPD classes, after performing a Wilcoxon test.

Year	VPD classes											
	< 0.5 kPa			0.5 – 1.0 kPa			1.0 – 1.5 kPa			> 1.5 kPa		
	n	*VPD*	*Kc*	*n*	*VPD*	*Kc*	*n*	*VPD*	*Kc*	*n*	*VPD*	*Kc*
2013	*6*	*0.42*	0.93	*26*	*0.79*	1.06	*53*	*1.27*	1.04	*8*	*1.75*	1.16
2014	*24*	*0.34*	0.88	*45*	*0.72*	0.97	*23*	*1.15*	0.98	*1*	*1.64*	1.09
2015	*13*	*0.30*	0.94	*26*	*0.75*	1.03	*32*	*1.26*	1.02	*22*	*1.73*	1.11
2013-2015	*43*	*0.34*	0.91 *(c)*	*97*	*0.75*	1.01 *(b)*	*108*	*1.24*	1.02 *(b)*	*31*	*1.74*	1.12 *(a)*

Table 4
Parameters and significance of the minimum adequate multiple regression model to predict Kc residuals. The relative contribution of the single predictor in determining the total variance explained by the model (R^2 = 28%) was calculated using the R package "relaimpo", metric "lmg".

Predictors	Estimated coefficient	Standard error	*p-value*	Relative importance (%)
Intercept	0.0286	0.0270	0.2904	–
VPD *(kPa)*	0.2400	0.0238	< 0.001	77.8
Rg *($MJ\ m^{-2}d^{-1}$)*	–0.0092	0.0017	< 0.001	16.4
Wind *($m\ s^{-1}$)*	–0.0655	0.0222	< 0.01	5.8

to the reference grass surface. It is important, however, to limit these considerations to the sub-humid and not water-limited conditions of this study. In drier environments, where greater water uptake lowers water potential close to the roots, the opposite can happen. The water uptake limitations occurring even from relatively moist soils, determine a decrease in transpiration rate, which is thought to be more accentuated in tall crops than on grass, thus lowering the *Kc* (Denmead and Shaw, 1962; Lobet et al., 2014; Steudle, 2000). Several authors (Annandale and Stockle, 1994; Dragoni et al., 2005; Dragoni and Lakso, 2011; Jarvis, 1985; Testi et al., 2004) have stressed that variable *Kc* should be used when modeling *ET* of tall crops, in order to enhance its ability to cope with specific atmospheric conditions. This suggests that for many tree crops with fully expanded canopy, the evapotranspirative fluxes (*ETc*) are more responsive than *ETo* to short-time variations of the meteorological conditions. In other words, in the presence of summer days with high air temperature (and high VPD), water consumption of the orchard will increase more than proportionally when compared with the reference grass surface. The apple tree height (approximately 4 ms considering summer vegetation), the training system, the fact that most of the canopy was well exposed to direct radiation and thus to the free-atmosphere, are all factors that contribute to increase the roughness of the orchard canopy, to decrease the boundary layer surrounding the vegetation, and to make the evapotranspiration of trees more dependent from the actual environmental conditions in comparison to short and dense canopies of a meadow (Jarvis, 1985; Jarvis and Mcnaughton, 1986; Sadras et al., 2016).

5. Conclusions

This study provided a quantitative assessment of water losses by evapotranspiration from a mature apple orchard over three growing seasons. These measurements allowed the calculation experimental crop coefficients, $\bar{Kc}_{exp}$. Since $\bar{Kc}_{exp}$ in the mid-season phase were generally lower than the reference FAO56 values, applying these findings may save significant amounts of irrigation water. Moreover, we demonstrated that in such a sub-humid environment $\bar{Kc}_{exp}$ is related to T_{air} and VPD and, in summer, it may vary by more than 20% from cold and humid days (with VPD < 0.5 kPa) to warm and dry days when VPD exceeds 1.5 kPa. More research is needed to evaluate whether the VPD-dependency of *Kc* values holds true in other apple growing regions or for other tree crops.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2019.105756.

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