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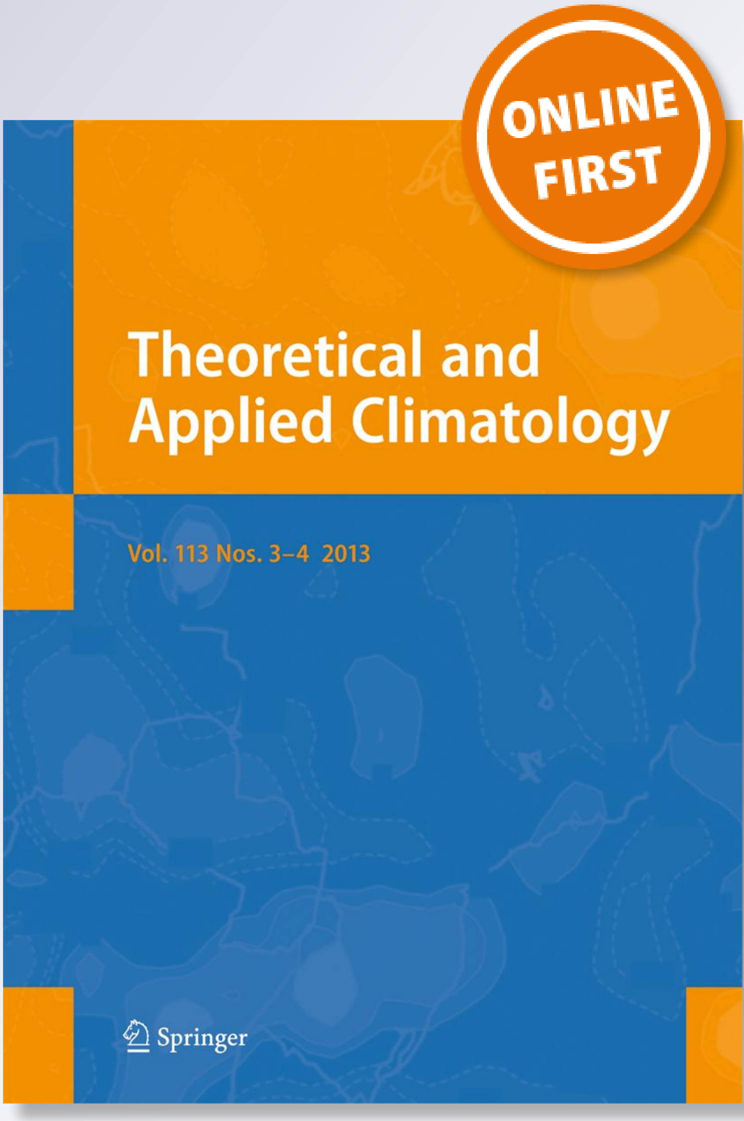

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ORIGINAL PAPER

Revisiting the crop coefficient–reference evapotranspiration procedure for improving irrigation management

Fábio R. Marin[1] · Luiz R. Angelocci[1] · Daniel S. P. Nassif[2] · Murilo S. Vianna[1] · Felipe G. Pilau[1] · Evandro H. F. M. da Silva[1] · Luiz R. Sobenko[1] · Alexandre O. Gonçalves[1,3] · Rodolfo A. A. Pereira[1] · Kassio S. Carvalho[4]

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Abstract

The consumptive use of water by irrigated crops is typically quantified using the crop coefficient–reference evapotranspiration (K_c–ET_o) procedure; yet, recent results showed that K_c might change with ET_o, in response to high atmospheric demand. It is not known if the reduced K_c at high ET_o applies to other crops with different aerodynamic features of the canopies. This paper seeks to provide the K_c values for soybean, wheat and potato, and propose an adaptation to the K_c–ET_o procedure, hypothesising that the inverse relation between K_c and ET_o would be general for all types of crops. Our results showed average K_c values of 0.90, 1.18 and 1.28, respectively, for soybean, wheat and potato cropping systems in the Brazilian cropping systems. However, K_c decreased as ET_o increased, for all crops considered in this study, because of the increase of internal plant resistances to vapour diffusion from the leaves to the atmosphere. When ET_o was above > 4 mm d^{-1}, the water use by such crops was lower than that prescribed by Allen et al. (JAMA, 1998). The time-based K_c curves in Allen et al. (JAMA, 1998) are inappropriate for the studied crops under high demanding conditions and, besides the considerations suggested by Allen et al. (JAMA, 1998) (i.e., crop development stage, presence or absence of weeds), K_c recommendations for practical irrigation management should be based on the average ET_o values of the previous days of the irrigation procedure.

1 Introduction

Irrigation is a useful practice to reduce yield losses in many regions around the world with insufficient precipitation and low soil-holding capacity (Jagtap and Jones 1989). Over the next decades, irrigated agriculture is expected to be affected by climate change while it must also be expanded to feed the world's growing population (Döll 2002).

A common procedure for estimating the irrigation requirements of a well-watered agricultural crop, denoted as the crop evapotranspiration (ET_c), is to first estimate the reference evapotranspiration (ET_o) from a standard surface and then apply an appropriate empirical crop coefficient (K_c) (Allen et al. 1989). Thus, K_c is applied to correct ET_o for local soil, plant, climate and management factors not accounted for in the estimation of ET_o; however, since K_c and ET_o are mathematically related for a site, ET_o and, consequently, K_c, will vary according to the method used to predict ET_o (Jagtap and Jones 1989). Allen et al. (1998) addressed this by adopting the Penman–Monteith combination equation as a standard for ET_o and advised on procedures for calculating its parameters. Allen (2000) also suggested a list of K_c values for 126 agricultural crops, which led to the adoption of the Penman–Monteith method as a universal procedure for scheduling and quantifying irrigation, with further developments made by Allen and Pereira (2009).

Over the last decade, irrigation has gained importance in Brazil, as major crops have expanded to new areas with sandy soils, high temperatures, and long and regular dry seasons. In addition, against the background of a changing climate, with an average predicted temperature increase of about 1.25 °C for the period from 2046 to 2065 (Marin et al. 2013), irrigation use and methods in the country are likely to change. With the aim to respond to the rapid increase in the irrigation use in Brazil, we conducted several studies (Marin et al. 2005, Marin &

✉ Fábio R. Marin
fabio.marin@usp.br

1 College of Agriculture "Luiz de Queiroz" (ESALQ), University of São Paulo (USP), Piracicaba, SP, Brazil

2 Federal University of São Carlos (UFSCAR), Buri, SP, Brazil

3 Embrapa Soils, Rio de Janeiro, RJ, Brazil

4 Federal Institute of Mato Grosso, Sorriso, MT, Brazil

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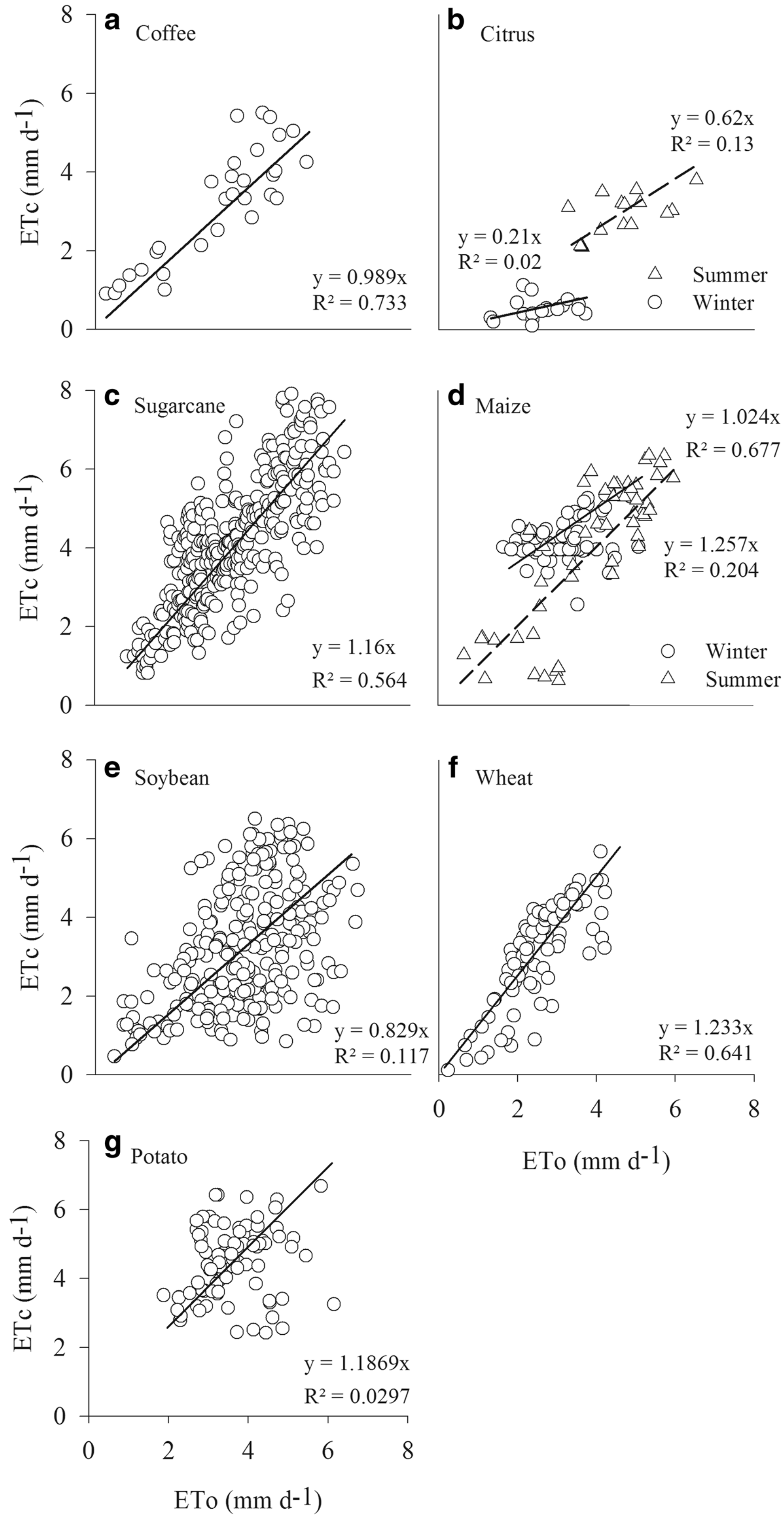


Fig. 1 Relationship between reference grass evapotranspiration (ETo) and crop evapotranspiration (ETc) measured for **a** coffee, **b** citrus, **c** sugarcane, **d** maize, **e** soybean, **f** wheat and **g** potato

Angelocci 2011; Nassif et al. 2014; Marin et al. 2016; Sobenko et al. 2018) to provide K_c values for different Brazilian cropping systems, by following the approach proposed by Allen et al. (1998). Those papers showed that besides the well-known crop variables influencing K_c (e.g., canopy architecture, crop phenology, the fraction of soil covered), the average ET_o values of the previous days of the irrigation procedure should also be considered, for more accurate prescriptions. The justification of this claim was based on the evidence of an inverse relationship between ET_o and K_c in high evaporative demand environments, which would imply an overestimation of crop water requirements in such conditions.

In the present paper, we conducted new experiments for soybean, wheat and potato, and combined the findings with data for coffee, citrus, sugarcane and maize, to establish a robust database of K_c values for crops with different canopy architectures, phenology and root systems. This paper intends to (i) provide K_c values for soybean, wheat and potato, measured in well-designed experiments for Brazilian cropping systems, and (ii) propose an adaptation to the K_c–ET_o procedure, hypothesising that the inverse association between K_c and ET_o would be general for all crops, irrespective of the aerodynamic features of the canopies or any other crop attribute.

Table 1 Values of crop coefficients (K_c) for coffee, sugarcane, citrus, potato, maize, soybean and wheat crops. Crop phases are expressed as initial (ini), middle (mid) and end of cycle (end), as well as for the whole crop cycles

Crop	Crop stage and/or season	K_c
Soybean	Ini	0.82 [0.16]
	Mid	1.08 [0.15]
	End	0.87 [0.18]
	Whole cycle	0.83 [0.39]
Wheat	Ini	1.17 [0.43]
	Mid	1.30 [0.22]
	End	0.52 [0.28]
	Whole cycle	1.23 [0.38]
Potato	Ini	1.31 [0.13]
	Mid	1.40 [0.32]
	End	0.91 [0.33]
	Whole cycle	1.19 [0.34]
Coffee	Whole cycle	0.99 [0.54]
Citrus	Winter	0.21 [0.06]
	Summer	0.62 [0.08]
Sugarcane	Whole cycle	1.16 [0.33]
Maize	Winter/whole cycle	1.26 [0.32]
	Summer/whole cycle	1.02 [0.45]

Values represent means and standard deviations (in brackets)

2 Material and methods

Six crop databases from eleven field experiments were established at the College of Agriculture "Luiz de Queiroz" (ESALQ) of the University of São Paulo (USP), Piracicaba, São Paulo State, Brazil (latitude 22° 42′ S; longitude 47° 30′ W; 546 m above sea level [asl]). The crops included were coffee, citrus (two periods in the same year), sugarcane (four seasons), maize (two seasons), soybean (two seasons), potato (one season) and wheat (one season). One experiment with potato was also conducted at Terra Viva Farm, Vargem Grande do Sul, São Paulo State, Brazil (latitude 21° 51′ S; longitude 46° 59′ W; 720 m asl). The climate of these two experimental sites is characterised as Cwa (high-altitude tropical climate) (Köppen 1931), with rainy summers and dry winters. One soybean experiment was also conducted at the Embrapa Soybean Research Station, Londrina, Paraná State, Brazil (latitude 23° 11′ S, longitude 51° 11′ W, 597 m asl) where the climate is characterised as Cfa (humid subtropical climate).

For all experiments, daily reference grass evapotranspiration (ET_o) values were estimated by the Penman–Monteith equation, as parameterised by Allen et al. (1998), using weather data sampled at 10-s intervals and averaged over 15-min time steps by a meteorological station located next to the experimental fields. The weather station was composed of a datalogger Campbell Scientific, Inc. (Logan, UT, USA) and a sensor kit with a pluviometer (TB4), a thermo-hygrometer (HMP-155), a wind speed and direction meter (034A), a barometer (CS106), a rugged pyranometer (CM3), a net radiometer (NR-LITE2) and a quantum sensor (LI190SB).

For all experiments, except for the citrus experiment, in which overall ET_c was determined via the aerodynamic method (Thom et al. 1975), ET_c was computed via the surface energy balance–Bowen ratio (β) method. Daily ET_c was calculated via scanned data at 10-s intervals and averaged 15-min values were recorded via a data logger (Campbell Scientific, Inc.). To estimate ET_c, we used Eqs. (1) and (2). Reliability of the Bowen ratio (β) data was tested, according to Perez et al. (1999).

$$\beta = \gamma \frac{\Delta T}{\Delta e} \tag{1}$$

$$\mathrm{ETc} = \frac{Rn - G}{\lambda(1+\beta)} \tag{2}$$

where γ is the psychrometric constant (kPa °C^{-1}); β is the Bowen ratio (dimensionless); ΔT and Δe are, respectively, air temperature (°C) and partial vapour pressure difference (kPa) between two heights; Rn is the surface radiation balance (MJ m^{-2} d^{-1}); G is soil heat flux (MJ m^{-2} d^{-1}); ET_c is the crop evapotranspiration (mm d^{-1}); and λ is the latent heat of vaporisation (MJ m^{-2} d^{-1}).

To determine the canopy–atmosphere coupling interaction, diurnal courses of leaf conductance to water vapour (g_S) (the inverse of leaf resistance, r_S) were determined along several days of each experiment, using porometers or an infra-red gas

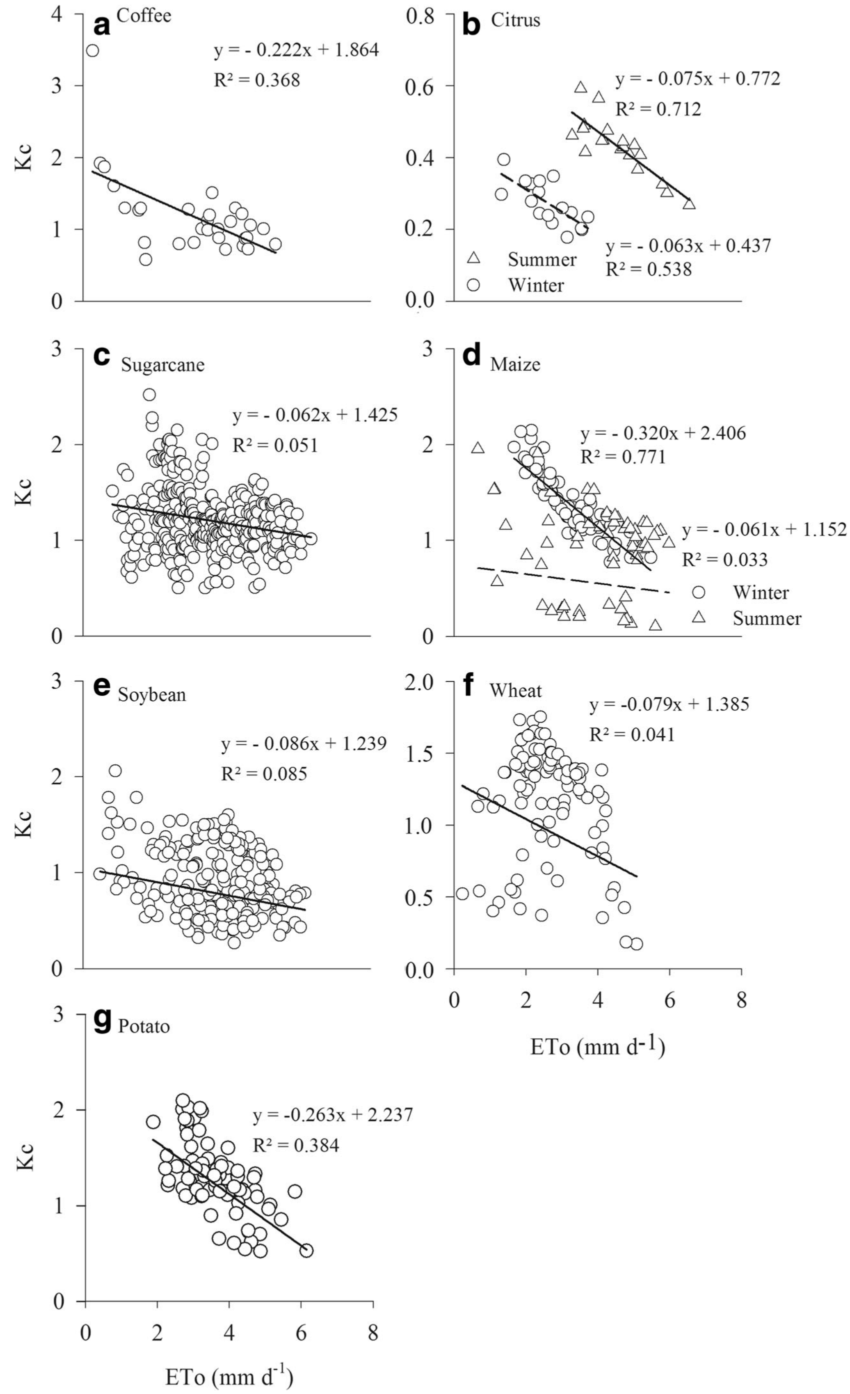


Fig. 2 Relationship between reference grass evapotranspiration (ETo) and measured crop coefficients (K_c) for **a** coffee, **b** citrus, **c** sugarcane, **d** maize, **e** soybean, **f** wheat and **g** potato

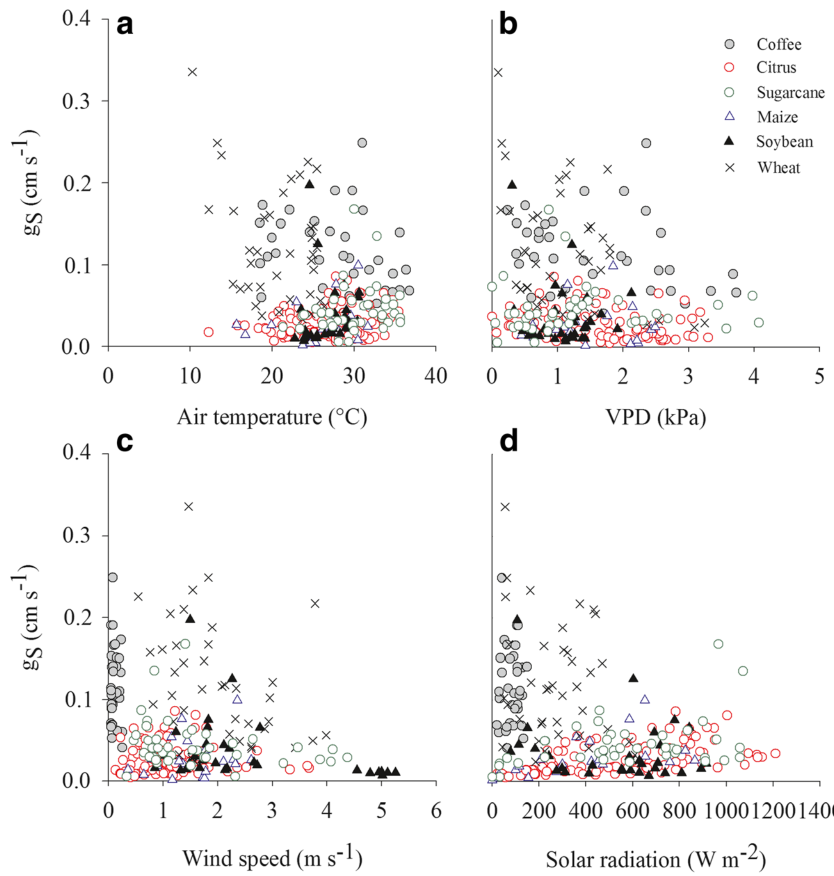
Table 2 Average values of decoupling factor (Ω) for coffee, citrus, sugarcane, maize, soybean and wheat plantations under experimental conditions

Crop	Ω
Coffee	0.09
Citrus	0.11
Sugarcane	0.22
Maize	0.18
Soybean	0.59
Wheat	0.54

analyser (ADC Bioscientific Ltd., Hoddesdon, UK) on exposed and shaded leaves from 09:00 to 16:00–18:00 h (local time). Therefore, the decoupling factor (Ω) was calculated, according to Eq. (3) (McNaughton and Jarvis 1983):

$$\Omega = \frac{1}{1 + \left[\frac{\gamma}{(s+\gamma)} \frac{r_S}{r_a}\right]} \tag{3}$$

Fig. 3 Relationship between leaf diffusion conductance to water vapour (g_s) and **a** air temperature, **b** vapour pressure deficit (VPD), **c** wind speed and **d** solar radiation for several crops. Values of g_s for wheat, sugarcane and maize were multiplied by 10



where Ω is the decoupling factor (dimensionless); s is the slope of the saturation vapour pressure curve (kPa °C^{-1}); r_S is the stomatal resistance to vapour diffusion (s m^{-1}), measured with porometers; and r_a is the bulk aerodynamic resistance (s m^{-1}). The conceptual interpretation of Ω is described in Marin et al. (2016).

2.1 Datasets 1 (coffee), 2 (citrus), 3 (sugarcane) and 4 (maize)

The four experiments that produced the datasets 1 to 4 are fully described in Marin et al. (2005), Marin and Angelocci (2011), Marin et al. (2016) and Sobenko et al. (2018), respectively.

2.2 Dataset 5: soybean

Three experiments were conducted with soybean crops. Two of them were sown in Piracicaba: the first from October 2016 to March 2017 and the second from December 2017 to April 2018. Both of these experiments were irrigated by a centre pivot, and the 3-ha experimental field (on Eutric Rhodic Ferralic Nitisol) was planted with the soybean cultivar BRS399-RR at a row spacing of 0.45 m, with 18 seeds per linear metre, resulting in a plant density of 35.5 plants m^{-2}. The irrigation frequency and the amount of water were scheduled to ensure a soil moisture content above 80% field capacity. Diurnal courses of g_S were determined in three exposed leaves, respectively, during 2 days of the vegetative stages (V2 and V5) and 3 days of the reproductive stages (R2, R3 and R6), using an AP4 cycling porometer (Delta-T Devices Ltd., Cambridge, UK); r_a was calculated according to Eq. (4) (Allen et al. 1998):

$$r_a = \frac{\left[ln\left(\frac{z-d}{z_0}\right)\right]^2}{u\,k} \quad (4)$$

where k is the von Kármán constant (0.40), z is the measurement height u (m), z_0 is the surface roughness length (m) and u is the wind speed (m s^{-1}).

The third soybean experiment was carried out from October 2007 to March 2008, at Embrapa Soja Research Station in Londrina, on a 0.28-ha experimental field (Eutric Rhodic Ferralic Nitisol soil) with the soybean cultivar Coodetec–CD206, at a row spacing of 0.50 m, and with 18 seeds per linear metre, resulting in a plant density of 35.5 plants m^{-2}. There were no g_S measurements in this experiment. In all three experiments, ET$_c$ was calculated by a β system connected to a CR1000 data logger (Campbell Scientific, Inc.).

2.3 Dataset 6: wheat

This experiment was conducted from May to September 2017 at the University of Sao Paulo-ESALQ in Piracicaba, with the wheat cultivar TBIO-Sossego, in an area of 2.7 ha. The soil was classified as Eutric Rhodic Ferralic Nitisol. The wheat was sown with a row spacing of 0.17 m, and 53 seeds per linear metre, resulting in a plant density of 308.7 plants m^{-2}. The irrigation frequency was based on a water balance to avoid insufficient water supply, as done in maize (dataset 4) and soybean experiments (dataset 5).

The overall ET_c was determined by a β system connected to a CR1000 data logger (Campbell Scientific, Inc.). Rn was recorded using a NR-LITE2 net radiometer (Kipp & Zonen, Delft, Netherlands). G was determined at 0.05 m below the ground, using HFP01 soil heat flux plates (Hukseflux, Delft, Netherlands). ΔT and Δe were measured at the same levels as used in datasets 4 and 5, using a HMP155 probe (Vaisala, Vantaa, Finland).

For this experiment, g_S was determined during the stages of head development, flowering, grain formation and maturation, using an AP4 cycling porometer (Delta-T Devices Ltd.). In total, eight measurements were carried out: three in the head development phase, three in the flowering phase, one during grain formation and one during maturation. As described for the maize and soybean crops, the r_a of wheat was calculated by Eq. (4).

2.4 Dataset 7: Potato

This experiment was conducted at the commercial farm Terraviva in Vargem Grande do Sul, Sao Paulo State, Brazil, from May 2016 to Sept 2016, with the potato cultivar Agria, on a total area of 140 ha (Eutric Rhodic Ferralic Nitisol soil), with a row spacing of 0.80 m, and three plants per linear metre (25,000 plants ha^{-1}). Irrigation was performed using the centre pivot method; there were no g_S measurements in this experiment. The ET_c was calculated by a β system connected to a CR1000 data logger (Campbell Scientific, Inc.).

3 Results and discussion

The K_c values, given by the angular coefficient of the line forced to pass through the origin (Fig. 1), reasonably agreed with the reference values proposed by FAO-56 (Allen et al. 1998), as shown in Table 1. The average K_c during the soybean cycle was 0.83, similar to the values found by Allen et al. (1998), Suyker and Verma (2009) and Payero and Irmak (2013), but 20% lower than that recommended by the FAO-56 (Allen et al. 1998) (Table 1). The average K_c for wheat was 1.18, consistent with the values reported in the literature for similar climates (Kjaersgaard et al. 2008; Gao et al. 2014) and those recommended by Allen et al. (1998) for each crop stage during winter wheat cultivation (Table 1). The potato crop presented a mean K_c value of 1.28, corroborating the values presented by Franke and Konig (1994) for the same environmental conditions. Conversely, this value was 16 and 22% lower than that proposed by Allen et al. (1998) and Doorenbos and Pruitt (1977), respectively. The relationships found for coffee, sugarcane, maize and citrus were analysed in previous papers (Marin et al. 2005; Marin and Angelocci 2011; Nassif et al. 2014; Marin et al. 2016; Sobenko et al. 2018) and, in general, their averages agreed with those proposed by Allen et al. (1998).

For all of them, K_c decreased with increasing ET_o values (Fig. 2), even though irrigation was well managed to ensure a high soil water content during the entire crop cycles. The K_c notably decreased with increasing ET_o values for corn, coffee and citrus (represented by the negative slope of the straight

Table 3 Values of crop coefficients (K_c and/or K_{cb}) for different ranges of reference grass evapotranspiration (ETo) for coffee, sugarcane, citrus orchards, maize, potato, soybean and wheat crops

Crop	ETo range (mm d^{-1})	K_c	K_{cb}
Coffee	< 2.0	1.57 [0.84]	1.27 [0.48]
	2.0–4.0	1.03 [0.23]	0.87 [0.18]
	> 4.0	0.94 [0.20]	0.67 [0.08]
Citrus (winter)	< 2.0	0.39 [0.16]	0.46 [0.09]
	2.0–4.0	0.31 [0.15]	0.35 [0.06]
	> 4.0	0.22 [0.05]	0.24 [0.03]
Citrus (summer)	< 2.0	0.74 [0.14]	0.53 [0.11]
	2.0–4.0	0.71 [0.12]	0.45 [0.03]
	> 4.0	0.68 [0.10]	0.37 [0.06]
Sugarcane	< 2.0	1.26 [0.46]	–
	2.0–4.0	1.15 [0.27]	–
	> 4.0	1.10 [0.20]	–
Maize (winter)	< 2.5	1.78 [0.20]	–
	2.5–4.0	1.29 [0.22]	–
	> 4.0	0.89 [0.24]	–
Maize (summer)	< 2.0	1.26 [0.48]	–
	2.0–4.0	0.86 [0.53]	–
	> 4.0	0.84 [0.35]	–
Soybean	< 2.0	0.96 [0.53]	–
	2.0–4.0	0.93 [0.36]	–
	> 4.0	0.85 [0.32]	–
Wheat	< 2.0	1.16 [0.41]	–
	2.0–4.0	1.30 [0.28]	–
	> 4.0	0.75 [0.40]	–
Potato	< 3.0	1.55 [0.33]	–
	3.0–4.5	1.26 [0.28]	–
	> 4.5	0.98 [0.28]	–

Values represent means and standard deviations (in brackets)

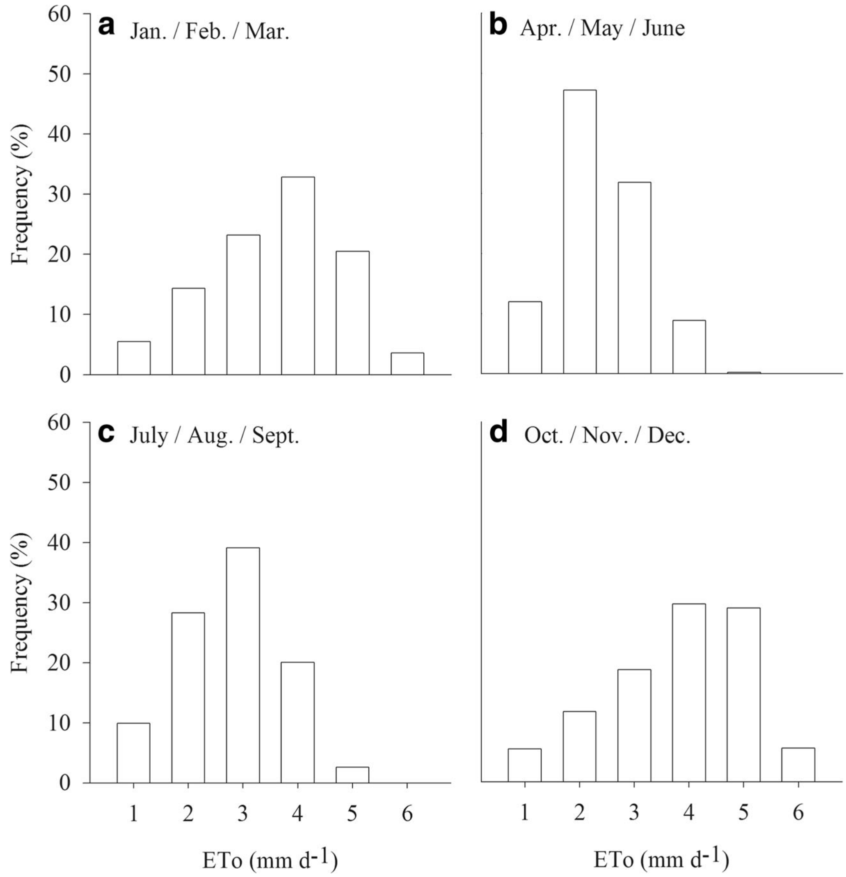


Fig. 4 Quarterly frequency distribution, based on a 30-year daily weather series of grass reference evapotranspiration (ETo) for Piracicaba, SP, Brazil

line). For sugarcane, wheat and soybean, K_c also decreased with increasing ET_o values, albeit at lower rates than those observed for corn, coffee and citrus.

In general, Ω values were low, indicating that the crop canopies were strongly coupled to the atmosphere. Exceptions were found for soybean and wheat, in which *Ω* was comparatively higher than those for other crops (Table 2), indicating a relative decoupling from the atmosphere; however, K_c values also decreased with increasing ET_o values (Fig. 2d, e).

The mean value of K_c obtained for all crops reasonably agreed with the values proposed by FAO-56 (Allen et al. 1998) for the climate conditions and crop stages during the experimentation periods. In all experiments, K_c decreased with increasing ET_o values (Fig. 2), even at very high soil water contents. So, for these crops, ET_c has reached a ceiling value at some high critical ET_o value and, conversely, ET_c exceeded the grass ET_o, only when ET_o was low.

Regarding the reason for the inverse K_c–ET_o relationship, as we pointed out in a previous study, this only occurs at a high canopy–atmosphere coupling (Marin et al. 2016), but the new experimental data revealed an inverse relationship between K_c and ET_o even for partially decoupled canopy–atmosphere crops (Table 2), such as soybean and wheat (Fig. 1e, f; Fig. 2e, f). This observation leads us to infer that a decline in K_c occurs for all crops at high-evaporative demand environments (representing high ET_o values).

Denmead and Shaw (1962) state that even with high water content in the soil, and under high atmospheric water demand, the relationship between g_s and weather variables showed that maize canopies restrict water loss by closing their stomata as the atmospheric water demand increases. Such a response pattern was also supported by our experimental data, which showed crop g_s responding non-linearly to air temperature (*T*), vapour pressure deficit (VPD) and solar radiation (Srad), and reached maximum values at optimum *T*, VPD and Srad levels. Afterwards, g_s rapidly decreased after evapotranspiration rates reached critical values (Fig. 3) of around 4 mm d^{-1} (Marin et al. 2016). This evidence contrasts with the approach for bulk stomatal resistance parameterisation proposed by Allen et al. (1998), in which a fixed value (~ 70 s m^{-1}) is assumed, which is not affected by climate variables. Instead, several studies mention the dependence of g_s on air temperature and VPD, with stomatal closure in response to increased climate variables, as demonstrated for citrus (Cohen and Cohen 1983; Syvertsen and Lloyd 1994; Angelocci et al. 2004), coffee (Fanjul et al. 1985; Barros et al. 1995), sugarcane (Roberts et al. 1990), maize (Turner 1968; Choudhury 1983; Tardieu et al. 1993), soybean (Teare and Kanemasu 1972; Sionit and Kramer 1976; Choudhury 1983; Oosterhuis and Walker 1987;

Buttery et al. 1993), wheat (Neukam et al. 2016) and potato (Voz and Oyarzún 1987; Liu et al. 2005). These studies corroborate our experimental data (Figs. 1 and 2), suggesting that the same process occurs for the seven species analysed here because leaf diffusive conductance relates to environmental variables restricting water loss under high atmospheric water demand. In turn, an inverse relationship exists between ET_c and ET_o because of increased plant resistance to water transport under high atmospheric water demand conditions.

This inverse association between K_c and ET_o represents an important aspect for irrigation management since major K_c reductions occur when ET_o is higher than 4 mm d^{-1} (Table 3), meaning a high atmosphere water demand from crops and natural water sources, which are usually under pressure because of high pumping rates. Also, under these conditions, energy costs are generally high and could be reduced by following our recommendations, without yield losses. Several papers (e.g., Allen et al. 2006; Allen and Pereira 2009; Allen et al. 2011) have analysed and suggested improvements on the procedures of FAO-56 (Allen et al. 1998) for estimating the ET_o and K_c values. However, our paper shows that the K_c–ET_o inverse relationship occurs in a wide range of species, irrespective of the canopy–atmosphere coupling level. Accepting this inverse association as a valid postulation for modifying the irrigation management in the tropical region of Brazil, it would imply an expressive reduction of water used for irrigation. The reasons are that ET_o values often exceed 4 mm d^{-1} (Fig. 4a, d) during the main growing season (October–March), and such high ET_o values are commonly associated with dry periods when irrigation is required. However, the K_c values above 4 mm d^{-1} were always lower than those prescribed by Allen et al. (1998), suggesting that the time-based K_c curves in Allen et al. (1998) are inappropriate for the studied crops under tropical conditions, and K_c recommendations for practical irrigation management should be based on the average ET_o values of the previous days of the irrigation management.

4 Conclusions

Water use by the studied crops under high evaporative water demand (> 4 mm d^{-1}) was limited and exceeded grass ET_o, only for low ET_o values. This study follows our other four investigations for coffee (Marin et al. 2005), citrus (Marin and Angelocci 2011), sugarcane (Marin et al. 2016) and maize (Sobenko et al. 2018). It differs, however, in that it is the only one to use data for crops that were not strongly canopy-coupled to the atmosphere, suggesting that canopy coupling is not the cause for the observed relationship between ET_c and ET_o. Instead, our results suggest that in the tropical region analysed, the inverse relationship between K_c and ET_o occurs independent of the crop and soil, even for canopy–atmosphere uncoupled crops.

Therefore, the K_c recommendations for practical irrigation management should be based on the average ET_o values of the previous days, as suggested by Allen et al. (1998) (i.e., crop development stage, presence or absence of weeds), to save water and energy and obtain high yields. Our results contribute to the improvements in irrigation projects and management strategies, with potential benefits for farmers and the natural environment, by reducing the amounts of water and energy used for irrigation.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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