Advances in Forestry Science
Original Article

Crop coefficient in different densities of Pinus taeda

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Received: 23 August 2017 / Accepted: 19 December 2017 / Published: 31 March 2018

Abstract

We analyzed the crop coefficient (Kc) of *Pinus taeda* within different planting densities in order to understand the effect of density population over the maximum water consumption, which will help us to improve its general values presented in the literature. The soil water balance was carried out over a year in a six years-old commercial pine forest in Southern Brazil. Soil water content was measured at different depths and Kc was estimated by the well-known ETc/ETo ratio, and by an alternative method based on wind speed, relative humidity, and plant height. The treatments consisted of different tree cover proportions: T100 (100% cover – standard planting cover, spacing 2.0 x 3.0 m – 1667 trees ha^{-1}), T75 (75% cover), T50 (50% cover), T25 (25% cover), and T0 (no cover – clearcutting). Analysis of variance was carried out with Tukey's test at 1% of probability. Tree cover did not affect the Kc for *Pinus taeda*. However, we observed significant lower Kc under full cover. As opposed to the recommended value for pine (Kc = 1), our results indicated average Kc equal to 2.12 in subtropical humid climate type. However, it was not possible to estimate a satisfactory value of Kc from climatic variables for the subtropical humid climate type.

Keywords: Loblolly pine, Conifer, Crop evapotranspiration, Tree cover

Introduction

Water balance is accounted as the water inflows and outflows in a given soil volume over certain period of time. Estimation of water fluxes from land-to-air are needed to the improvement of soil and irrigation management (Khazaei and Hosseini 2015; Jerszurki et al. 2017). The crop evapotranspiration (ETc) is considered the main outflow of water from land to air, because it represents the maximum crop water demand. Assessing ETc in situ, such by use of evapotranspirometers or lysimeters, can be costly, time consuming, and depending on the method, those measurements are subject to large uncertainties (Liu and Luo 2010, Zhang et al. 2011). Thus, consistent estimations of ETc by different methods, such as based on soil water content measurements, are widely accepted, and the use of crop coefficient (Kc), estimated by the ratio between ETc and reference evapotranspiration (ETo) (Kc = ETc/ETo), is widely used in the management of forest crops (Alves et al. 2013). In addition, Kc can be estimated by variables that directly influence it, such as leaf area index (LAI).

Attempts to obtain reasonable Kc values for forest crops had been made (Allen et al., 1998). Accordingly, the experimentally proved Kc for the conifers group is equal to 1, and have been widely used for *Pinus spp.* regardless of planting density.

However, many studies have found significant differences when comparing the Kc obtained by measured ETc for different crops to the values proposed by Allen et al. (1998). These inconsistent results can be explained by the wrong use of a single value that do not accounts for differences in soil and climate conditions (Liu and Luo 2010; Zhang et al. 2011; Arif et al. 2012; Zapata et al. 2012). Indeed, Allen et al. (1998) already required attention for the use of the Kc values and suggested local studies to improve the estimates. Despite the large-scale pine cultivation, to the best of our knowledge, the suggested Kc values for conifers group are not consistent, and thus can not be used in pine plantations in Southern Brazil. Accordingly, here we determine the crop coefficient of *Pinus taeda* with different planting densities in order to understand the effect of density population over the maximum water consumption, which will help us to improve its general values presented in the literature.

Materials and methods

The soil water balance (SWB) was conducted in Telêmaco Borba, Southern Brazil, 24°13'19"S, 50°32'33"W, and 700 m altitude. Data was collected over 2009, totaling 53 weeks, in a six years-old *Pinus taeda* plantation of 12.5 ha, over clayey oxisol (Souza et al. 2016). The area is located in the transitional subtropical humid to tempered climate (Cfa/Cfb), with an average temperature in the coldest month below 16°C, frosts and average temperature in the warmest month above 22°C, with hot summers (Álvares et al. 2013).

The experimental design was a randomized block with four replicates. Each block was 3.125 ha and each treatment comprised 0.625 ha. The treatments consisted of tree cover proportions: T100 (100% cover – standard planting cover, spacing 2.0 x 3.0 m – 1667 trees ha^{-1}), T75 (75% cover), T50 (50% cover), T25 (25% cover), and T0 (no cover – clearcutting) These cuts began the experiment (Figure 1).

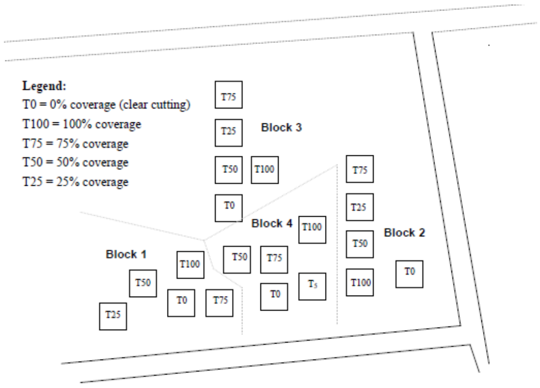

Figure 1 - Distribution of treatments in the experimental area of loblolly pine in Southern Brazil (Adapted from Souza et al. 2016).

Disturbed soil samples were taken weekly at 0-0.1, 0.1-0.2, 0.2-0.4, 0.4-0.6 and 0.6-1.0 m depth for gravimetric moisture determination in drying oven (EMBRAPA, 2011). The samples were collected with an auger hole. After, were transported in waterproof and sealed containers to the laboratory. The samples were then weighed and dried at 105-110°C for 24 hours. After that time, the samples were placed in a desiccator to cool and weighed at the end. These samples were performed in duplicate at each depth (one in the row and one between rows). The gravimetric water content was obtained based on the average of the two samples. During

2009, a total of 10,800 samples were collected to determine gravimetric moisture.

Undisturbed samples were collected in two trenches of 1.5 x 3.0 x 1.8 m, with volumetric rings, in the same depths that disturbed soil samples were taken, with three repetitions at each depth, to determine the soil physical properties (density, hydraulic conductivity of saturated soil, soil water retention curve) (EMBRAPA, 2011) (Table 1). Only two trenches were sampled, because the area was homogeneous.

Table 1 - Physical and hydraulic soil characteristics at different depths in the experimental area (Adapted from Souza et al. 2016)

Depth	Sand	Silt	Clay	C organic	ρ (1)	Macropores	Micro pores	α (2)	K_0(3)
(m)		%		(kg m^{-3})		(m^3 m^{-3})		(mm day^{-1})	
0-0.1	41	10	49	1.70	1100 a	0.200 a	0.395 c	0.598 a	15607.34 a
0.1-0.2	40	11	49	1.20	1210 a	0.137 ab	0.403 bc	0.541 a	4097.95 b
0.2-0.4	40	11	50	0.89	1210 a	0.140 ab	0.395 c	0.537 a	5651.00 ab
0.4-0.6	36	11	53	0.68	1230 a	0.08 b	0.46 a	0.54a	957.20 b
0.6-1.0	36	11	53	0.45	1160 a	0.116 ab	0.443 ab	0.561 a	904.80 b
CV (%)(4)	-	-	-	5.8	6.0	24.8	3.5	4.0	71.2

(1)Soil bulk density; (2)Total porosity; (3)Soil saturated hydraulic conductivity; (4) Coefficient of variation.

* Means followed by the same letter do not differ by Tukey (p <0.05).

Only vertical water fluxes were accounted in the SWB. As the study area is relatively flat, it was considered null surface flow, and there was no irrigation in the area. The actual evapotranspiration (ETa) was calculated from the following expression:

$$ETa = -\Delta S + P - DD + CR$$

In wish: ETa – actual evapotranspiration (mm week^{-1}), ΔS – soil water storage variation (mm week^{-1}), P – precipitation (mm week^{-1}), DD – deep drainage (mm week^{-1}), CR – capillary rise (mm week^{-1}).

The component DD or CR was calculated by the soil water flux density (q_z) using the Darcy-Buckingham equation, between 0.8 and 1.0 m depth. The value of the effective depth of the root system was considered constant (z = 0.8 m). As flow occurs between soil layers in different days, the Darcy-Buckingham equation was adapted to weekly flow. The flow resulted of the product between the average values of unsaturated hydraulic conductivity $K(\theta)$, and total potential gradient $\Delta\overline{H} / \Delta z$ of *i-th* weeks (Souza et al. 2016).

Unsaturated soil hydraulic conductivity $K(\theta)$ was estimated according to Mualem (1976) with regression parameters obtained from the model described in Van Genuchten (1980). Soil water retention values, for each depth, were obtained between –0.006 and –1.500 MPa with a pressure plate apparatus by desorbing the saturated cores at several pressure steps. The saturated cores were used to obtain water retention values over the entire range studied; i.e., under –0.006 MPa (pressure table) and –0.010 to −1.500 MPa (Richard's pressure chamber). Water content at each pressure was calculated from the volume of outflow between pressure steps, the final water content, and the weight of oven-dried soil. Volumetric water content and soil-water pressure potential, obtained for each depth, were adjusted as proposed by Van Genuchten (1980), using the *Soil Water Retention Curve* program (Dourado Neto et al. 2001).

The soil water storage (S) was calculated by the trapezoidal rule, with the variation of the soil water storage (ΔS) obtained from the difference between the previous storage (Sj) and current (Sj + 1):

$$S_j = \int_0^{z_n} \frac{\partial\theta}{\partial t} dz \cong \sum_{i=0}^{n-1} \frac{(\theta_i + \theta_{i+1}) \cdot z_{i+1}}{2}$$

In wish: S_j: soil water storage in j-th week (mm), θ_i: volumetric moisture in *i*-th soil depth (cm^3 cm^{-3}), z_i: soil depth (mm), *j*: weeks over year that samples were taken (53 weeks), *i*: sample collection depths: 1: 0-0.1, 2: 0.1-0.2, 3: 0.2-0.4, 4: 0.4-0.6, and, 5: 0.6-1.0 mm.

Precipitation (P) was measured daily by 60 acrylic gauges with 80 mm of water capacity installed within the experimental area. Two rain gauges were installed at 0.50 m from the edge of the trees and 1.30 m above the ground. A third rain gauge was placed at the midpoint between the rows of trees. The mean *P* was calculated as the average of the three rain gauges. 2009 was chosen precisely because it's been an atypical year, based on the normal P for the region (climatological normal observed between 1947 and 2005), with a total value of 1608 mm in 2009 and 1490 mm for P normal. This allowed average S remained high during almost every year, above field capacity (θ_{CC}). Thus, the soil was in the wet zone (i.e., when S ≥ Available Soil Water . (1 – *p*)) almost all the time, and the ETa ≅ ETc, which enabled us measure the Kc throughout the year (Figure 2).

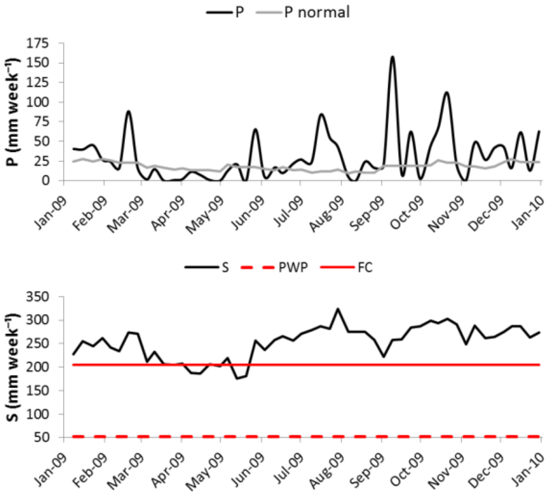

Figure 2 - Average soil water balance parameters in the experimental area over 2009, as follows: (a) precipitation (P) and regular periodic precipitation (P normal); (b) soil water storage (S), field capacity (FC) and permanent wilting point (PWP)

The Kc was calculated by the following relation:

$$Kc_{measured} = \frac{ETc_i}{ETo_i}$$

In wish: $Kc_{measured}$ – crop coefficient measured in the *i-th* week (dimensionless), ETc_i – crop evapotranspiration in the *i-th* week (mm week^{-1}), ETo_i – reference evapotranspiration in the *i-th* week (mm week^{-1}).

We also performed Kc estimates considering the value proposed by the Food and Agriculture Organization (FAO) of Kc_{FAO} = 1.0 for conifers, as well as an equation that considers regional climate variables, called $Kc_{climatic}$ (Allen et al. 1998):

$$Kc_{climatic} = Kc_{FAO} + [0.04 \cdot (u_2 - 2) - 0.004 \cdot (RH_{min} - 45)] \cdot \left(\frac{h}{3}\right)^{0,3}$$

In wish: $Kc_{climatic}$ - climatic crop coefficient (dimensionless), Kc_{FAO} – crop coefficient recommended by Allen et al. (1998) (dimensionless), u_2 - average wind speed at 2 m height (m s^{-1}), RH_{min} – average minimum relative humidity (%), h – average plant height (m).

To perform the calculations described above, we relied on daily observations of maximum, minimum, and average air temperature (ºC), relative humidity (%), daily sunshine hours (MJ m^{-2} d^{-1}), and wind speed (m s^{-1}) measured at ten meters above the ground level, from January 2009 to January 2010, obtained from the automatic weather station located within the experimental area. Wind speed measurements were transformed to wind speed at 2 m height by the wind profile relationship (Allen et al. 1998).

The differences between treatments were analyzed by ANOVA and Tukey's test at 1% of probability.

Results

The average values were 2.12, 1.00 and 0.78 to Kcmeasured, KcFAO, Kcclimatic, respectively (Figure 3). T100 was the only treatment that statistically differed from the others, corresponding to a lower water consumption (Table 1).

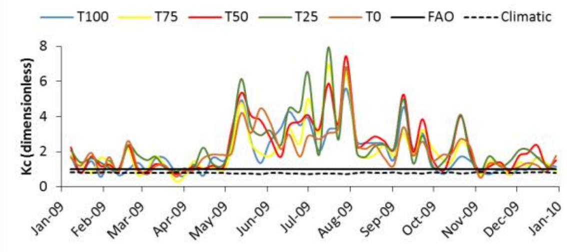

Figure 3 - Average crop coefficients (Kc) for *Pinus taeda*, in different cover treatments, FAO-Kc (Kc = 1) and Kc estimated by the alternative climatic model (Climatic) proposed by Allen et al. (1998)

T25 stood out, with the highest value of Kc. Thereby, the water consumption and wood productivity will be higher which, by demanding greater planning and crop treatments, will provide the ideal growth conditions for the tree (White et al. 2010).

Similar results were reported by Van Dijk and Keenan (2007), who found greater evapotranspiration consumption in a pine forest after thinning. This finding is due to the increased growth of the remaining trees, especially the leaf area index (LAI), because of the greater light and space availability.

Several authors have concluded that Kc has a direct significant relationship with LAI and productivity, especially in perennial crops, such as forest crops, coffee and sugarcane (Silva et al. 2012, Silva et al. 2013, Rezende et al. 2014). Those relationships have direct implications for crop management, such as irrigation strategies or number and degree of pruning.

Table 2 - Average comparison test of crop coefficients (Kc) for *Pinus taeda*, in different cover treatments

Treatment	Average	
T25	2.37	a
T50	2.31	ab
T75	2.00	ab
T0	1.99	ab
T100	1.91	b

Treatments with the same letter do not differ statistically at 1% probability by Tukey Test (p<0.01).

Although not statistically different, T0 was higher than T100 because the trunks and roots were not removed from experimental area. Thus, the remained roots may had formed infiltration pores and channels, causing runoff out of the experimental control volume. The precipitation fluxes were computed as evapotranspiration in the SWB, because it was not stored in the soil of the experimental volume control (Souza et al. 2016).

We observed higher average Kc in all treatments compared to Kc_{FAO}. The average of $Kc_{measured}$ (Kc = 2.12) suggests that ETc of loblolly pine, for climate type Cfa/Cfb, is more than 100% higher than the recommended by Allen et al. (1998). This fact corroborates with the statements of Trinidad et al. (2002), showing that *Pinus* has high transpiration rates when soil moisture is close to field capacity. Dolman et al. (1998), also suggests higher water consumption by forest crops, which may indicate that the trees have higher Kc than commercial annual crops. However, such considerations are contested by Verstraeten et al. (2005). Accordingly, the Kc of trees, particularly adult pine trees, is generally less than 1.0, for the climatic type Cfb. For Allen et al. (1998), conifers have substantial stomatal control due to the reduced aerodynamic resistance, which affects the decrease of Kc values under non-stressed conditions and in wide forests.

Verstraeten et al. (2005) had Kc values between 0.71 and 0.97 for *Pinus sylvestris* and *Pinus nigra*, respectively, in a temperate climate type in Belgium (Cfb), by use of WAVE model. These values are similar to the $Kc_{climatic}$ obtained in our experiment, which showed values between 0.7090 and 0.8532. Meiresonne et al. (2003) found Kc = 0.70 for scots pine. The methodologies used by these authors in the estimated water balance consider the Kc's proposed by Allen et al. (1998) for conifers. Therefore, the soil water balance used in our work outperformed the estimated water balance methodology, which overlooks variables of high influence on Kc.

In other forest species, Edraki et al. (2004) reported Kc = 0.85 for *Eucalyptus spp.*, calculated with evapotranspirometer, in Australia; while Alves et al. (2013) found value of 0.82 in Minas Gerais, Brazil, for irrigated *Eucalyptus spp.* seedlings. Schaap et at. (1997) found Kc between 0.75 and 1.0 for a spruce forest in the center of Netherlands. Generally, Kc’s seedlings are close to 1.0 because the leaf area index is low, however, this does not apply to adult forests.

The lack of agreement between Kc_{FAO} values indicated that climatic and crop aspects change and decisively influence Kc over crop cycle (Zhang et al. 2011, Zapata et al. 2012). However, $Kc_{climatic}$ values did not correlate with $Kc_{measured}$ (Figure 3) (R^2 = 0.0047), suggesting that the equation proposed by Allen et al. (1998) to estimate the Kc from climatic variables was not satisfactory to weekly estimations of ETc for loblolly pine in Southern Brazil.

The estimation of Kc in forests is extremely complex and controversial, because ETa may has been influenced by Pinus litter, due to its low density and high potential for water retention. The litter forms a layer of dissipative energy, reducing evaporation losses from the soil to the atmosphere, but has the disadvantage of intercepting and storing water from precipitation, which is subsequently lost into the atmosphere. The higher the density of planting, the greater the influence of this phenomenon.

According to Silva et al. (2006), the evaporated water in the soil-plant system correlates significantly with the water initially stored in the litter. The authors found that 1000, 4000 and 8000 kg ha^{-1} of corn straw with 412, 255 and 260% of moisture in relation to its volume, respectively, have lost large amounts of stored water, reaching 0, 41 and 53%, respectively. Arif et al. (2012) consider that the Kc values also vary with the crop variety, management, irrigation system, soil type, plant cover, and ETo estimative method adopted

Conclusions

Tree cover did not affect the Kc for *Pinus taeda*. However, we observed significant lower Kc under full cover.

As opposed to the recommended value for pine (Kc = 1), our results indicated an average Kc equal to 2.12 in subtropical humid climate type.

It was not possible to estimate a satisfactory value of Kc from climatic variables for the subtropical humid climate type.

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