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Periodicity of crop coefficient and soil water depletion fraction in a climatological water balance

Bruno César Gurski[1]*, Jorge Luiz Moretti de Souza[1], Daniela Jerszurki[2], Robson André Armindo[1] and Adão Wagner Pêgo Evangelista[3]

[1]Department of Soil and Agricultural Engineering, Federal University of Paraná, 1540, Rua dos Funcionários street, 80035-050, Curitiba, Brazil.

[2]Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, 84990, Israel.

[3]Department of Agronomy, Federal University of Goiás, Avenida Esperança, s/n., Campus Samambaia, 74690-900, Goiânia, Brazil.

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In comparison to a measured field water balance (FWB), we aimed to evaluate the impact of using different functions to daily estimate the crop coefficient (Kc) and soil water depletion fraction (p) in a climatological water balance (CWB), and verify that the grouping of output variables provides improved results. The FWB was conducted in Telêmaco Borba, Southern Brazil. The data were collected at weekly intervals in 2009, in an area of loblolly pine with 6 years-old. The CWB considers different equations to estimate daily Kc and p values. The output components of the CWB were estimated daily, then weekly and monthly grouped for comparison with the FWB. Linear correlation analysis, index "d" of concordance, index "c" of performance, mean error, mean absolute error and root mean square error were performed in order to compare the water balances, based on the soil-water storage variation (ΔS) and actual evapotranspiration (ETa). The use of a Kc measured weekly improved the CWB, providing high correlation and small errors in relation to a measured water balance, independent of the comparison scale. On the other hand, the use of a Kc that considers climate variables (Kc_k) had the worst levels of accuracy and precision, and the biggest mistakes in all analyzes and all tested variables. There was no significant improvement with the daily variation of p, both grouping weeks as in months. The proposed equations do not represent any gain in the CWB, in comparison with the use of a constant p value over time. The estimate of the CWB and its subsequent grouping in months for comparison provided greater degree of accuracy and precision for the variables analyzed, but caused the biggest mistakes. Therefore, the calculation of CWB should be performed with the highest periodicity possible, and grouping the CWB output variables should only be performed for comparison.

Key words: *Pinus taeda*, crop evapotranspiration, actual evapotranspiration, soil water storage, field water balance.

INTRODUCTION

The field water balance (FWB) is the accounting of inputs and outputs of water at any given volume control over a specific time interval. It can be calculated by means of crop evapotranspiration (ETc) measurement instruments as lysimeters and evapotranspirometers, or by measuring the soil moisture. The monitoring of soil water storage, combined to the understanding about crop needs have been considered important tools to the agroforestry activities planning, improvement of soil water use efficiency by irrigation practices and agroclimatic zoning (Yan et al., 2012; Khazaei and Hosseini, 2015).

The study of water demand in soils under plantation of exotic woods, such as *Pinus taeda*, assists in the development of alternatives to the rational use of water, which implies in no compromising of the environmental balance and promoting the development of silvicultural activity (Rigatto et al., 2005).

Currently, the FWB is more used in scientific researches and their measures are commonly used to verify mathematical models, which are developed to simulate and perform estimations. Thus, many researchers have sought to develop indirect methods to estimate it from climatic variables, in parts because complete field measurements are time consuming, costly and experimentally difficult depending of the size of the area to be monitored (Zhang et al., 2004; Praveena et al., 2012; Yan et al., 2012).

In this context, the estimated climatological water balance (CWB) is required. However, some input components of CWB do not represents the real conditions of the crop in the field, especially for perennial crops, such as forest species, in relation to the variations in time. Due to the lack of specialized studies and local complexity measurements, the water components are usually estimated empirically and are considered constant over time, such as the crop coefficient (Kc) and soil water depletion fraction (p) (Allen et al., 1998). Using a constant value for these variables can significantly affect the output components, such as crop evapotranspiration (ETc); soil water storage (S); actual evapotranspiration (ETa). Since consistent, the highest frequency of the input data in the CWB generally improve their sensitivity to small variations over time (Khazaei and Hosseini, 2015), making it more reliable for the silvicultural planning.

In comparison to a measured field water balance, we aimed to evaluate the impact of using different equations to daily estimate the crop coefficient (Kc) and soil water depletion fraction (p) in a climatological water balance, and verify that the grouping of output variables provides improved results.

MATERIALS AND METHODS

A field water balance (FWB) was conducted in Telêmaco Borba, state of Paraná, Southern Brazil, 24°13′19"S, 50°32′33"W, 700 m altitude (Figure 1). The region has a climate type transitional wet subtropical to temperate ("Cfa/Cfb") with an average temperature in the coldest month below 16°C including frost events, and an average temperature in the warmest month above 22°C (Alvares et al., 2013).

This experiment served as a witness, being considered the actual values for comparison with the models proposed in this manuscript. The data were collected at weekly intervals in 2009, in an area of 12.5 ha of 6-years old *Pinus taeda* planting, with standard spacing of 2.0 × 3.0 m (1,667 trees/ha) in a clay Oxisol with undulated relief. For details of the methodology (Souza et al., 2016).

The output components (ΔS - soil-water storage variation and ETa - actual evapotranspiration) of the FWB, were compared with a climatological water balance (CWB). ETa in the FWB was calculated as follows:

$$ETa = -\Delta S + P - D + U \quad (1)$$

Where: ETa is actual evapotranspiration (mm week^{-1}); ΔS is soil-water storage variation at the root zone (mm week^{-1}); P is precipitation (mm week^{-1}); D is downward drainage out of the root zone (mm week^{-1}); U is upward capillary flow across root zone (mm week^{-1}).

Soil water storage (S) was calculated preliminarily, with the ΔS obtained from the difference between previous (S_j) and current water storage (S_{j+1}):

$$S_j = \theta_1 \cdot z_1 + \sum_{i=1}^{n} \frac{(\theta_i + \theta_{i+1}) \cdot z_i}{2} \quad (2)$$

Where: S_j is soil water storage in j-th week year (mm); θ_i is volumetric moisture in i-th soil depth (cm^3/cm^3); z_i is soil depth (m); j is weeks over year that samples were taken ; I is sample collection depths (m).

A daily climatological water balance (CWB) was estimated according to Thornthwaite and Mather (1945) methodology. The daily data series of precipitation (P) used in the simulations were the same used in FWB (Souza et al., 2016). Reference evapotranspiration (ETo) was estimated by Penman-Monteith method (Allen et al., 1998). Daily climatological data were provided by an automatic weather station. Soil water storage (S) was estimated from cosine equation (Rijtema and Aboukhaled, 1975). The initial value of S for 2009 was recorded on December 31, 2008, being equal to 52.5 mm, and was considered an average of total available water (TAW) equal to 174 mm, with no variation in the effective root depth (z = 0.80 m).

Different methodologies and functions to estimate the Kc were used to calculate the CWB (Figure 2). A basic value that did not change over time was used (Kc_A), this value was proposed by Allen et al. (1998) to conifers species. In addition, measured values were used, obtained in the FWB cited, which were grouped weekly and monthly (Kc_m and Kc_{month}, respectively). Finally, we tested an equation, proposed by Allen et al. (1998), that uses climate variables to estimate the daily Kc_k:

$$Kc(DAP)_k = Kc_A + [0.04 \cdot (u_2 - 2) - 0.004 \cdot (RH_{\min} - 45)] \cdot \left(\frac{h}{3}\right)^{0.3} \quad (3)$$

Where: Kc_k is crop coefficient (dimensionless); Kc_A is crop coefficient recommended by Allen et al. (1998) (dimensionless); u_2 is daily average wind speed at 2 m height (m s^{-1}); RH_{min} is minimum daily average relative humidity (%); h is average plant height (m).

*Corresponding author. E-mail: brunogurski@ufpr.br.

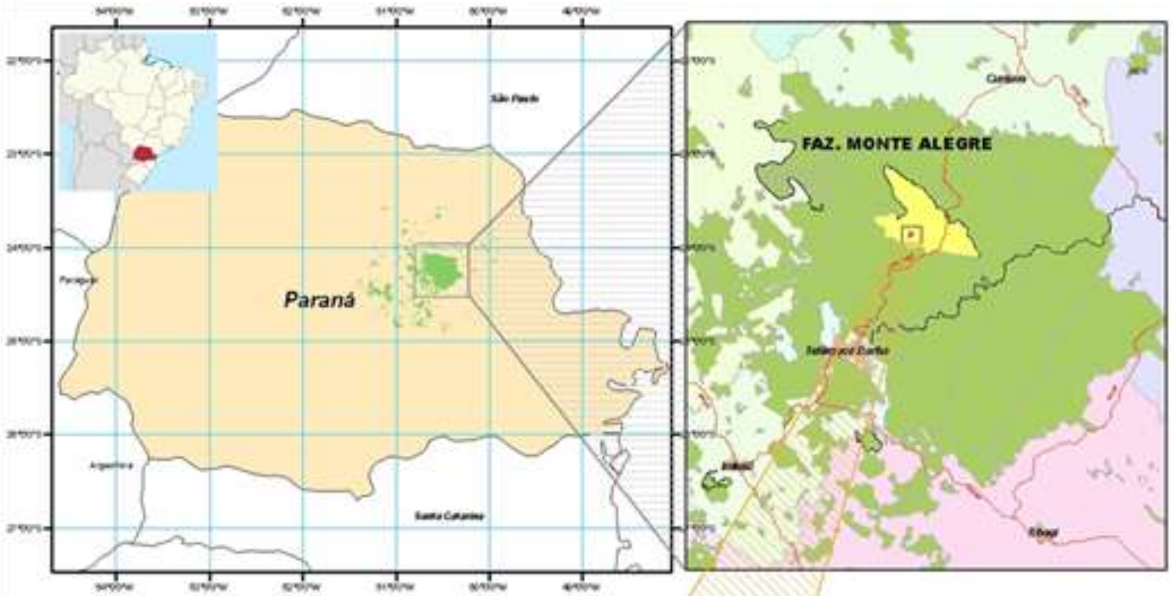

Figure 1. Location of the study area in Southern Brazil.

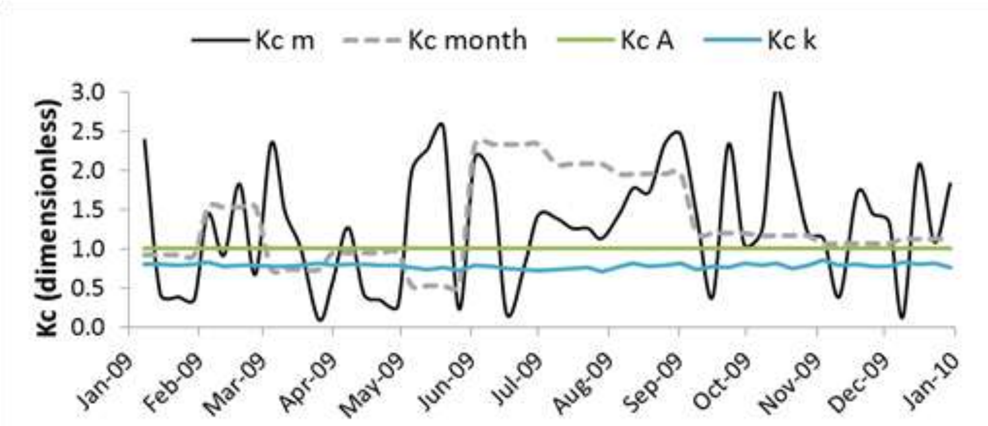

Figure 2. Different crop coefficients (Kc's) used in 2009 for pine, as follows: Kc proposed by Allen et al. (1998) (Kc_A); Kc measured in a soil water balance (Kc_m); Kc measured, but grouped monthly (Kc_{month}); Kc obtained by climatic variables (Kc_k).

Three scenarios of p estimation were tested as follow (Figure 3): Constant over time (p_A), value recommended by Allen et al. (1998); Doorenbos and Kassan (1979) (p_{DK}); and an equation proposed by Allen et al. (1998) (p_{Ai}):

$$p_{DK_i} = 0.0025 \cdot ETc_i^2 - 0.0869 \cdot ETc_i + 1 \text{ for } 0 \leq ETc \leq 17 \text{ mm day}^{-1} \quad (4)$$

$$p_{Ai} = p_A + 0.04 \cdot (5 - ETc_i) \text{ for } p_A \leq 0.8 \quad (5)$$

Where: ETc_i = crop evapotranspiration in the i-th day (mm day^{-1}); p_A = *soil* water depletion fraction recommended by Allen et al. (1998) (dimensionless).

The output components were calculated daily in the CWB (ΔS_{CWB} and ETa_{CWB}), and then grouped in weeks and months for comparison with the FWB (ΔS_{FWB} and ETa_{FWB}). The evaluation was performed using the coefficient of determination (R^2), index "d" Willmott et al. (1985), index "c" of Camargo and Sentelhas (1997): c > 0.85 = great accuracy; c from 0.85 to 0.76 = very good; c from 0.75 to 0.66 = good; c from 0.65 to 0.61 = average; c from 0.60 to 0.51 = tolerable; c from 0.50 to 0.41 = bad; and c ≤ 0.40 = very bad. Mean error (ME) were also used; mean absolute error (MAE) and root mean square error (RMSE). It is important to note that the comparisons were made with the ΔS instead S, because the differences between methodology of FWB and CWB, and the ΔS_{CWB} and ETa_{CWB} results were demonstrated in mm month^{-1} and mm day^{-1}, respectively, to facilitate discussion and comparison to

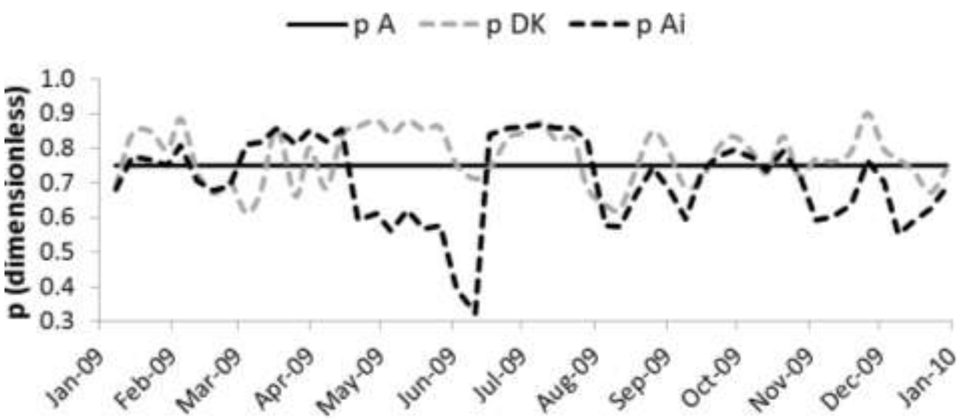

Figure 3. Different soil water depletion fraction used in 2009 for pine, as follows: Constant over time (p_A); value recommended by Doorenbos and Kassan (1979) (p_{DK}); and depending on the daily crop evapotranspiration (p_{Ai}).

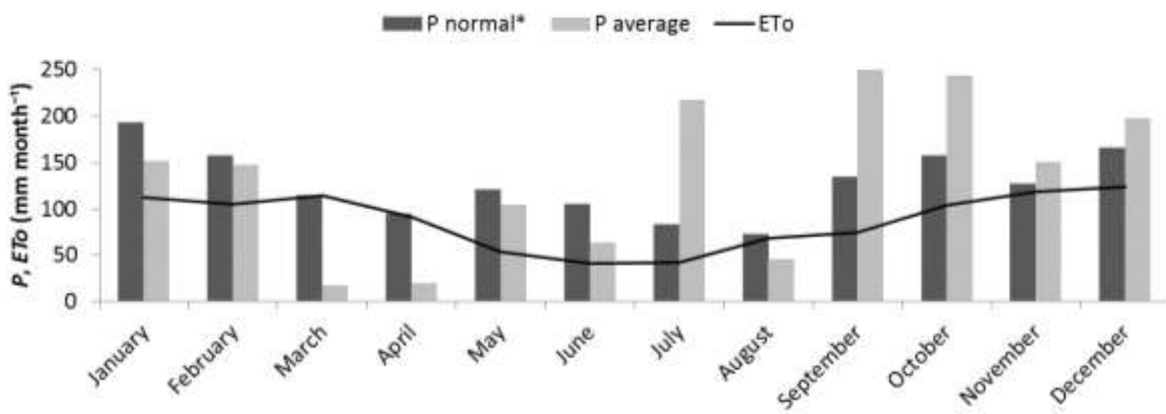

Figure 4. Monthly normal average precipitation (P_{normal}), precipitation ($P_{average}$) and reference evapotranspiration (ETo), in Telêmaco Borba, Southern Brazil, in 2009. *Standard climatological series observed between 1947 and 2005 for Telêmaco Borba, Southern Brazil.

the literature:

$$ME = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(E_i - O_i\right) \tag{6}$$

$$MAE = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(\left| E_i - O_i \right|\right) \tag{7}$$

$$RMSE = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} \left(E_i - O_i\right)^2} \tag{8}$$

Where: *ME* = mean error; *MAE* = mean absolut error; *RMSE* = root mean square error; *n* = number of observations (dimensionless); E_i = estimated value in the i-th day; O_i = observed value in the i-th day.

RESULTS

As expected, the ETo in 2009 showed typical trend throughout the year, with the lowest and highest values in winter and summer, respectively. Despite, $P_{average}$ was atypical regarding P_{normal} of Telêmaco Borba region (Figure 4).

The annual $P_{average}$ was higher than P_{normal} presenting a total value of 1,608.1 and 1,490.0 mm, respectively, with poor distribution of precipitation throughout 2009 and significant accumulation from September to December. Historically characterized as a month of low precipitation, July presented mean $P_{average}$ 38% higher than P_{normal}. It is important to note that 2009 may be considered as an

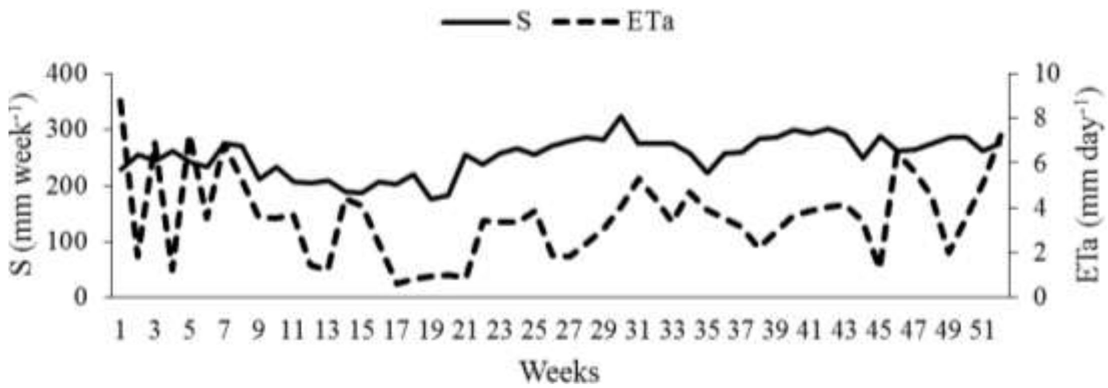

Figure 5. Soi water storage (S) and actual evapotranspiration (ETa) in the field water balance for pine, in Telêmaco Borba, in 2009.

atypical year, especially in relation to observed precipitation (Figure 4), in which there has been much lower values (March and April) or higher values (July, September and October) in relation to P_{normal}. The major occurrence of inaccuracies was related to the atypical series of $P_{average}$, when the precipitation was much higher or lower than the historical data.

There were larger differences in ΔS_{CWB} compared to ΔS_{FWB} when the mean $P_{average}$ was higher, and ETa_{CWB} in relation to ETa_{FWB} when $P_{average}$ was lower (Figure 5). The poorly adjustment of the ΔS_{CWB} occurred in July and September, when $P_{average}$ overcame P_{normal} by 38 and 52%, respectively. However, there were also minor differences when the situation was the opposite.

Regarding the ETa_{CWB} the greatest errors occurred when the mean $P_{average}$ was below P_{normal}, especially in March and April. The ETa_{CWB} had its highest values in the same periods when the largest precipitation occurred (Figures 4 and 5). This relation is similar to obtained by Silva et al. (2009) with corn in Piracicaba, Southestern Brazil.

There was no significant improvement, in both the S and ETa, with the daily variation of p, both grouping weeks as in months. The use of the proposed equations does not represent any gain in the CWB, in comparison with the use of a constant p value over time (Tables 1 and 2).

The use of Kc_m represented the highest degree of accuracy and precision, and minor errors, both to S and ETa,, independent of the comparison scale. On the other hand, Kc_k had the worst levels of accuracy and precision, and the biggest mistakes in all analyze and all tested variables. The use of the equation proposed to daily estimate Kc was inadequate and did not contribute to the CWB, on the contrary, because the equation showed worse results than even Kc_A, which is constant over time.

The estimate of the CWB and its subsequent grouping in months for comparison provided greater degree of accuracy and precision for the variables analyzed, but caused the biggest mistakes.

DISCUSSION

There is definitely influence of precipitation on S and ETa. Zhang et al. (2004) report that the *S* directly influences *ETa*, in the extent that the soil water deficits reduces the ETa. On the other hand, Praveena et al. (2012) found that the excess water leads to increase in *ETa.* Farré and Faci (2006) found that the factors that most influence ETa are the S and P. The reason is due to a higher evaporation in the surface layers up to 0.40 m deep (Cruz et al., 2005). When ETa_{CWB} was very low (March, April and May) there was small P, and low variations within the months came from deeper layers (0.60 and 0.80 m), which have a higher water retention capacity, contributing to the root water uptake (Souza et al., 2013).

According to Souza et al. (2013) when long periods without precipitation occurs, there is the process of soil water drying, with variation of the humidity, especially within the first 0.20 m deep. In this condition, a large evaporative demand by atmosphere cannot be attended by soil, because the amount of water available on the surface is restricted, and the water conductivity begins to influence evaporation. At this stage, the evaporation rate is controlled by the vapor transfer mechanisms and adsorption on the soil solid matrix.

Many authors attested the influence of p in crop productivity (Doorenbos and Kassan, 1979; Tao et al., 2003; Steduto et al., 2009), however, there was no improvement in the adjustment of the component values of the CWB to the FWB, even varying p daily (p_{DK} and p_{Ai}) in relation to the constant value (p_A) over time. It may be that $P_{average}$ allowed high S throughout the year. As a consequence, the soil was constantly in the wet zone (in other words, when $S \geq TAW\ (1 - p)$), and ETa and crop evapotranspiration (ETc) have been showed almost the same values under this condition.

Bruno et al. (2007) using a Kc obtained by lisymeter and then grouped in four phenological phases, to estimate the CWB for coffee in Piracicaba,

Table 1. Comparison of soil-water storage variation (ΔS) obtained in a field (FWB) and climatological (CWB) water balances, grouped weekly and monthly, with different crop coefficients (Kc) and soil water depletion fraction (p) for pine in Telêmaco Borba, in 2009.

Analyses	Weekly			Monthly		
Kc; p	Kc_k; p_{DK}	Kc_k; p_{Ai}	Kc_k; p_A	Kc_k; p_{DK}	Kc_k; p_{Ai}	Kc_k; p_A
R^2	0.35	0.35	0.36	0.21	0.21	0.21
"*d*"*	0.74	0.74	0.74	0.65	0.65	0.65
"*c*"*	0.44	0.44	0.44	0.30	0.30	0.30
Performance	Bad	Bad	Bad	Terrible	Terrible	Terrible
ME*	1.17	1.17	1.17	10.12	10.12	10.12
MAE*	16.35	16.35	16.06	37.23	37.26	37.91
RMSE*	20.00	20.00	19.84	47.72	47.72	47.70
Kc; p	Kc_{month}; p_{DK}	Kc_{month}; p_{Ai}	Kc_{month}; p_A	Kc_{month}; p_{DK}	Kc_{month}; p_{Ai}	Kc_{month}; p_A
R^2	0.37	0.37	0.36	0.89	0.89	0.90
"*d*"	0.77	0.77	0.76	0.94	0.94	0.95
"*c*"	0.47	0.47	0.46	0.89	0.89	0.90
Performance	Bad	Bad	Bad	Great	Great	Great
ME	1.39	1.42	1.42	9.84	9.84	9.84
MAE	18.06	17.98	18.07	20.79	19.83	19.07
RMSE	4.21	4.20	4.21	26.96	26.97	24.93
Kc; p	Kc_m; p_{DK}	Kc_m; p_{Ai}	Kc_m; p_A	Kc_m; p_{DK}	Kc_m; p_{Ai}	Kc_m; p_A
R^2	0.33	0.34	0.34	0.85	0.85	0.84
"*d*"	0.74	0.75	0.75	0.93	0.93	0.93
"*c*"	0.43	0.44	0.44	0.86	0.86	0.86
Performance	Bad	Bad	Bad	Great	Great	Great
ME	1.37	1.37	1.37	10.12	10.12	10.12
MAE	18.04	17.56	17.26	21.03	21.68	21.96
RMSE	0.30	0.34	0.34	27.44	28.31	27.40
Kc; p			Kc_A; p_A			Kc_A; p_A
R^2	-	-	0.38	-	-	0.33
"*d*"	-	-	0.76	-	-	0.73
"*c*"	-	-	0.47	-	-	0.42
Performance	-	-	Bad	-	-	Bad
ME	-	-	1.27	-	-	10.08
MAE	-	-	16.43	-	-	32.59
RMSE	-	-	0.38	-	-	42.90

*"d", Index of Willmott et al. (1985); "c", index of Camargo and Sentelhas (1997); ME, mean error; MAE, mean absolut error; RMSE, root mean square error.

Southeastern Brazil, with 14-days intervals, obtained, on average, R^2 = 0.75 for ΔS_{CWB} and R^2 = 0.84 for ETa_{CWB}. For pine, we found for Kc_m and Kc_{month}, which were the best in accuracy, R^2 = 0.85 and 0.89 for ΔS_{CWB}, and R^2 = 0.76 and 0.64 for ETa_{CWB}, respectively, when monthly compared. These results demonstrate that the use of a variable Kc, unlike Kc_A, significantly improves the ETa, including the pine, but because it is a perennial crop, it did not show significant difference between Kc_m and Kc_{month} for ΔS_{CWB}. It may be that in plants with smaller cycles and higher phenological changes, this difference existed for ΔS.

Probably, the ΔS_{CWB} have been influenced by the litter of Pinus taeda, due to its low density and high potential for water retention. The litter forms a layer of dissipative energy, reducing evaporation losses from soil to the atmosphere, but has the disadvantage of intercepting and storing water from precipitation, which is subsequently lost to the atmosphere before infiltrates in the soil profile. According to Silva et al. (2006), the evaporated water in the soil-plant system correlates significantly with water initially stored in the litter. The authors found that 1,000; 4,000 and 8,000 kg/ha of corn straw with 412, 255 and 260% humidity in relation to its volume, respectively, have lost large amounts of stored water, reaching 0, 41 and 53%, respectively. Water storage in the litter is another source of error in the CWB, because all the water from precipitation (less interception) was considered as

Table 2. Comparison of actual evapotranspiration (ETa) obtained in a field (FWB) and climatological (CWB) water balances, grouped weekly and monthly, with different crop coefficients (Kc) and soil water depletion fraction (p) for pine in Telêmaco Borba, in 2009.

Analyses	Weekly			Monthly		
Kc; p	Kc_k; p_{DK}	Kc_k; p_{Ai}	Kc_k; p_A	Kc_k; p_{DK}	Kc_k; p_{Ai}	Kc_k; p_A
R^2	0.09	0.09	0.11	0.28	0.29	0.32
"*d*"*	0.48	0.48	0.50	0.56	0.56	0.57
"*c*"*	0.14	0.14	0.16	0.30	0.30	0.33
Performance	Very Bad	Very Bad	Very Bad	Terrible	Terrible	Terrible
ME*	-1.25	-1.25	-1.27	−1.19	−1.20	−1.22
MAE*	1.77	1.77	1.75	1.32	1.32	1.32
RMSE*	2.08	2.08	2.07	1.55	1.55	1.55
Kc; p	Kc_{month}; p_{DK}	Kc_{month}; p_{Ai}	Kc_{month}; p_A	Kc_{month}; p_{DK}	Kc_{month}; p_{Ai}	Kc_{month}; p_A
R^2	0.29	0.29	0.28	0.65	0.64	0.65
"*d*"	0.72	0.72	0.72	0.89	0.88	0.88
"*c*"	0.39	0.39	0.38	0.72	0.71	0.71
Performance	Very Bad	Very Bad	Very Bad	Good	Good	Good
ME	-0.12	-0.10	-0.13	−0.10	−0.09	−0.11
MAE	1.23	1.25	1.25	0.62	0.64	0.66
RMSE	1.10	1.11	1.11	0.76	0.81	0.84
Kc; p	Kc_m; p_{DK}	Kc_m; p_{Ai}	Kc_m; p_A	Kc_m; p_{DK}	Kc_m; p_{Ai}	Kc_m; p_A
R^2	0.36	0.39	0.40	0.76	0.77	0.73
"*d*"	0.78	0.80	0.80	0.93	0.93	0.91
"*c*"	0.47	0.50	0.50	0.81	0.82	0.78
Performance	Bad	Bad	Tolerable	Very good	Very good	Very good
ME	-0.17	-0.14	-0.16	−0.1557	−0.13	−0.15
MAE	1.01	1.01	1.10	0.50	0.50	0.57
RMSE	0.30	0.30	0.30	0.61	0.63	0.75
Kc; p			Kc_A; p_A			Kc_A; p_A
R^2	-	-	0.19	-	-	0.43
"*d*"	-	-	0.57	-	-	0.69
"*c*"	-	-	0.25	-	-	0.45
Performance	-	-	Very Bad	-	-	Bad
ME	-	-	-0.91	-	-	−0.86
MAE	-	-	1.50	-	-	1.03
RMSE	-	-	1.22	-	-	1.25

*"d", Index of Willmott et al. (1985); "c", index of Camargo and Sentelhas (1997); ME, mean error; MAE, mean absolut error; RMSE, root mean square error.

input in the system. The same does not occur in accounting for FWB. In addition, other factors are influenced by litter, such as entering solar radiation in the system, temperature, runoff, ETc, among others.

The precision and accuracy increased, when comparing values grouped together, because the average decreases the variability in the data. However, this analysis is performed to identify trends or cyclicity in series data, and not to statistical inference (Morettin and Toloi, 1981). So that when the data were grouped monthly to compare this generated higher R^2, "d" and "c", but also the biggest mistakes.

Overall, the CWB and FWB are subject to other sources of error, such as the frequency of calculations that always influences the results (Bruno et al., 2007). In FWB performed, the frequency was weekly, that is, data relating to the sum or mean of values obtained along the week, and it is not possible to determine exactly the time of data sampling. In the calculation of both CWB and FWB some simplifications were needed. It was considered a homogeneous experimental area, without input or output of water from the system via surface and subsurface drainage. However, it is known that there is spatial variability of soil physical parameters (Yan et al., 2012).

Conclusions

The use of a crop coefficient (Kc) measured weekly improved the climatological water balance (CWB), providing high correlation and small errors in relation to a measured water balance, independent of the comparison scale. On the other hand, the use of a Kc that considers climate variables (Kc_k) had the worst levels of accuracy and precision, and the biggest mistakes in all analyzes and all tested variables.

There was no significant improvement with the daily variation of soil-water depletion fraction (p), both grouping weeks as in months. The proposed equations do not represent any gain in the CWB, in comparison with the use of a constant p value over time.

The estimate of the CWB and its subsequent grouping in months for comparison provided greater degree of accuracy and precision for the variables analyzed, but caused the biggest mistakes. Therefore, the calculation of CWB should be performed with the highest periodicity possible, and grouping the CWB output variables should only be performed for comparison.

Conflicts of interests

The authors have not declared any conflict of interests.

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