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Soil water extraction by roots and evapotranspiration crop coefficients for coffee

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Abstract: Basic information for a rational soil-water management of the coffee crop is still insufficient, mainly under irrigated conditions. Of great importance for the estimation of water requeirements of coffee crops are their root distribuition and evapotranspiration crop coefficients. This study compares soil water extraction by roots of coffee plants variety "Catuaí Vermelho" (IAC-44), grown in Piracicaba, SP, Brazil, 3 to 5 years old, with direct measurements of root dry matter, showing a good agreement between both approaches, and confirming that most of the root system is distributed in the top soil layer (0-0.3m) and that less than 10% of the root system reaches depths greater than 1.0m. Calculated evapotranspiration crop coefficients are in agreement with those found in the literature, with an average of 1.1, independently of shoot dry matter, plant height and leaf area index.

Key words: perenial crop, soil water storage, water balance

Extração radicular de água e coeficiente de cultura para evapotranspiração em cultura de café

Resumo: Informação básica para o manejo racional de água e solo na cultura de café é ainda insuficiente, principalmente em condições de cultura irrigada. A distribuição radicular e os coeficientes de cultura para evapotranspiração são de grande importância para a estimativa da necessidade de água na cultura de café. Esse estudo compara a extração radicular de água de plantas de café, variedade "Catuaí Vermelho" (IAC-44), cultivado em Piracicaba, SP, Brasil, de 3 a 5 anos de idade, com medidas diretas de material seca de raiz, mostrando uma boa relação entre as metodologias e confirmando

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que a maioria do sistema radicular está distribuido na camada superficial de solo (0-0,3m) e que menos de 10% do sistema radicular atinge profundidades maiores que 1,0m. Os coeficientes de cultura medidos estão de acordo com aqueles encontrados na literatura, com uma media de 1,1, independentemente da matéria seca, altura de planta e índice de área foliar.

Palavras-chave: cultura perene, armazenamento de água no solo, balanço hídrico

INTRODUCTION

Coffee is among the most important crops grown in Brazil and, recently, its cultivation reached areas previously considered not adequate due to their pronounced water deficit, which is corrected by supplementary irrigation. This techonology implies in lower risk of production and allows efficient fertilizer use, improving quantity and quality of the product (Silva, 2002). These facts justify research investments to refine management practices in relation to system sustainability and cost/benefit ratio. Due to these facts any improvement in coffee management practices is welcome. Although the actual state of the knowledge on the processes that involve water and nutrient dynamics in coffee crops is well developed, there is still room to generate or improve field practices that lead to a greater sustainability, a greater productivity, and a greater efficiency in the use of the available natural resources.

Camargo & Camargo (2001) recognize that the coffee crop, being a perenial crop, spends two years to complete its phenologic frutification cycle, composed of six distinct phases, starting in September for most climatological conditions in Brazil: 1st, vegetative, from Set. to Mar., exposed to long days; 2nd, also vegetative, from Apr. to Aug., exposed to short days, when vegetative nodes formed during the 1st phase are induced to become reproductive, representing a period of relative rest of the plant, followed by the maturation of the reproductive nodes; 3rd, flowering being induced by rainfall or irrigation, due to an elevation of the water potential in the floral nodes (hydric shock); 4th, fruit filling, from Jan. to Mar.; 5th, fruit maturation, from Apr. to Jun.; 6th, senescence of productive brances which no longer will be induced to flower. During these phases the crop requires soil water to supply 1,100 to 1,300mm for evapotranspiration. Therefore, root distributions and shoot architecture are of great importance for a rational water management of the crop. Santinato et al. (1996), present evapotranspiration crop coefficients for several crops grown in the states of Minas

Gerais and Bahia (Brazil), related to crop line spacing and crop age. In another study Cordeiro et al. (1987) *apud* Rena (1998), observed for 6 year old coffee shrubs, that 90% of the root system explored the 0-0.5m soil layer, presenting a large concentration of absorbing roots in the surface layer, probably due to irrigation and fertilizer application practices. Rena (1998) states that in most Brazilian soils, the coffee plant does not present deep roots, 85% of them being distributed below plant canopie, mostly near the stem. Martins et al. (2006) concluded that coffee irrigated with 80 to 100% of the Class A pan evapotranspiration, present larger values of root dry matter as compared to non irrigated plants. In relation to evapotranspiration crop coefficients, Arruda et al. (2000), Rena & Maestri (2000), and Villa Nova et al. (2002) indicate the importance of crop management conditions like plant population, spacing, interrow condition.

In order to contribute to the knowledge of coffee soil-water relationships, this study used field water balance data (Silva et al., 2006; Silva et al., 2007), established during one complete phenologic cycle of the coffee crop, to estimate root distribution and crop coefficients from plant soil water extraction data.

MATERIAL AND METHODS

A water balance experiment was carried out in Piracicaba, SP, Brazil (22°42' S, 47°38' W, 580m above sea level) on a Rhodic Kandiudalf, locally called "Nitossolo Vermelho Eutroférrico" (Embrapa, 1999), under a "Cwa" climate (Köppen, 1931). A three year old coffee crop (*Coffea arabica L.*), cultivar "Catuaí Vermelho" (IAC-144) was used to evaluate soil water extraction and evapotranspiration crop coefficients during two years (Sept 01, 2003 to Aug 31, 2005). Plant rows followed contour lines on a 10% slope land, with a spacing of 1.75 m between rows and 0.75 m between plants. In an area of approximately 0.2 ha, five plots of about 120 plants were selected randomly for water balance establishment, which can be found elsewhere (Silva et al., 2006). The classical water balance equation was used integrated over 14 day periods ($\Delta t = t_{i+14} - t_i$):

$$P + I - ER \pm \Delta S_L - RO - Q_L = 0 \qquad (1)$$

in which P = rainfall (mm); I = irrigation (mm); ER = actual evapotranspiration (mm); ΔS_L = soil water storage changes (mm) in the z = 0 to z = L = 1.0 m soil layer; RO = run-off (mm) and Q_L = drainage soil water fluxes at the lower soil volume limit, taken as z = L = 1.0m, all during periods t_i and t_{i+14}, i being the time index

corresponding to days after beginning (DAB); i = 1 stands for September 1, 2003. From this date on, 52 fourteen day water balances were established (Silva et al., 2006), up to 720 DAB.

Soil Water Extraction by roots

In order to estimate the extraction of water by roots (RE) only balances for which P, I, RO and Q_L were null, were selected so that Eq. 1 is reduced to ER = ΔS. Assuming that the evapotranspiration from the soil surface is negligibe in relation to plant transpiration, ΔS would represent RE. This assumption is here accepted based on the fact that the soil surface was always almost completely covered by dead coffee leaf mulch, and that a good weed control was maintained in the interrows during the whole experimental period. At the end of the experiment, interrows were already shaded by coffee branches, so that the canopy represented a full green cover.

Soil water storage changes ΔS were calculated from soil water content θ (z_j, t_i), ($m^3.m^{-3}$) measurements obtained using a neutron probe (Bacchi et al., 2002), set at depths z_j (j corresponding to a depth index, j = 0 for soil surface, using $\Delta z = 0.2$m). The chosen depths for measurements were j = 1 for z = 0.2; j = 2 for z = 0.4; j = 3 for z = 0.6; j = 4 for z = 0.8 and j = 5 for z = 1.0 m from the soil surface, made at times t_i and t_{i+14}. Using the trapezoidal rule, we have:

$$\Delta S_{(j=L;t=i+14)} = S_{L,i+14} - S_{L,i} = \left(\overline{\theta}_{ti+14} - \overline{\theta}_{ti}\right)L = \left[\sum_{j=1}^{5} \theta_{j,i+14} - \sum_{j=1}^{5} \theta_{j,i}\right]\frac{L}{5} \qquad (2)$$

whith L taken as 1,000 mm in order to obtain ΔS in mm.

To estimate coffee root distribuition, ΔS was also estimated by layers for the periods $\Delta t = t_{i+14} - t_i$. Since neutron probe measurements of θ are averages of a soil volume corresponding to spheres of 0.20 to 0.30m diameter (depending on soil water content), it was assumed that each θ measurement represents the average of the following soil layers: $\theta_{j=1}$ represents the 0 – 0.3 layer; $\theta_{j=2}$ the 0.3 – 0.5 layer; $\theta_{j=3}$ the 0.5 – 0.7 layer; $\theta_{j=4}$ the 0.7 – 0.9 layer; and $\theta_{j=5}$ the 0.9 – 1.0 layer. In this way, it is assumed that the $\theta_{j=1}$ measurement includes measuremets at the soil surface, which were not made, and that $\theta_{j=5}$ corresponds only to the 0.9 – 1.0m layer. These averages, multiplied by each respective layer thickness in mm, yield layer soil water storages.

Since the number of balances that attend the restriction ΔS = RE is small, it was decided to include also balances of small values of P, those in which P would not have

reached the depth z = 0.3m, the limit of the first layer used in the calculations. When P is large and reaches depths greater than z = 0.3m, it would not be possible to diferenciate the water extracted from the 0 – 0.3m layer from that of the 0.3 – 0.5 layer. To choose these balances, the criterium of P<DEF (0 – 0.3) was used, , in which DEF (0 – 0.3) is the deficit of soil water (mm) in relation to field capacity, determined under field conditions.

Evapotranspiration Crop Coefficients

The actual evapotranspiration ER was taken as an unknown in eq (1) and estimated from the difference of all other components. The reference evapotranspiration (ET_o) of a green grass surface was estimated through the Penman-Monteith model (Pereira et al., 1997) using meteorological data colleted by an authomated weather station, located about 200 m from the experimental plots. The crop coefficient (K_c) for coffee was calculated by the ratio ER/ET_o, only for balances in which the soil was close to field capacity, RO = 0 and Q_L = 0. For these particular balance periods P was of the same order of magnitude of ER, to assure that there was no restriction of soil water, so that ER could be considered equal to ET_c.

Crop Growth and Development

The study also involved growth and development analyses of the coffee plants, sampling every 60 days the aerial part of whole plants to evaluate dry matter, plant hight and total leaf area (TLA, m^2) using an area integrator model LAI – 3000. The leaf area index (LAI) was calculated by the ratio of TLA and the area occupied by one plant (0.75 x 1.75 = 1.313m^2). Data were interpolated using a spline curve adjustment, in order to obtain intermediate values for all balances.

The direct measurement of the root system was performed only at the end of each cropping year (366 and 720 DAB), in order to minimize plot disturbance during the experimental period, and was made through auger samplings performed in the same layes as those used to estimate ΔS changes.

RESULTS AND DISCUSSION

From the 52 consecutive water balances made over the two year period (2003 – 2005), only 15 attend to the criteria used for the calculation of RE (Table 1). The values of RE, calculated for each soil layer and averaged for each year (Table 2), indicate the importance of the surface layer (0 – 0.3m) in contributing to the total RE. Although the coffee root system development is bound primarily to plant genetic characteristics, other factors can also alter its spatial distribution, like the available water in the soil (Franco & Inforzato, 1946 cited in Barreto et al. 2006) and the nutrient availability for the plant (Amaral, 2002 cited in Barreto et al. 2006). Irrigation practices may also affect primary and secondary root growth in the different soil layers (Barros et al., 1997). In our case, irrigation was applied only once a year, at the end of the dry winter season, when plants were suffering a severe water deficit and a flower fall could occur, affecting productivity. Therefore, irrigation most likely did not affect root distribution, which is a result of the water regime in Piracicaba.

The contribution of each layer decreases drastically with depth, the value for the last layer (0.9 – 1.0m) being very small for both years, showing that the root system did not extend significantly bellow the 1.0 depth. The high values of the stardard desviations (SD) and, consequently of the coefficients of variation (CV), are the result of the temporal variability of the microclimatic conditions of the periods used for their evaluation, which can be appreciated through the values of ER shown in Table 1. In terms of percent (Fig 1), RE data show a great consistency in relation to year and to the direct root dry mass measurements. On average, the 0 – 0.3 m layer contributes with 58% in the total, giving evidence to the importance of this soil layer in the water management of the coffee crop.

Table 1 – Water balances selected for the calculation of root extraction (RE).

Balance Nº	DAB	P	DEF (0-0,3)	S_{Li}	ΔS	ER
		(mm)	(mm)	(mm)	(mm)	(mm)
2	14 -28	5.8	41.4	257.4	-8.1	-13.9
5	56 -70	25.3	30.4	271.0	-10.7	-36.1
15	196 - 210	14.0	13.7	348.5	-52.3	-66.3
21	280 - 294	7.2	9.3	348.7	-14.6	-21.8
22	294 - 308	1.9	14.6	336.2	-16.9	-18.8
25	336 - 350	0.0	16.6	329.3	-11.9	-11.9
27	364 - 378	0.0	24.8	308.9	-32.6	-32.6
28	378 - 392	6.5	35.1	276.4	-18.0	-24.5
34	462 - 476	18.9	29.4	288.3	-25.8	-44.7
40	546 - 560	1.4	23.2	273.5	-28.3	-29.7
43	588 - 602	0	32.3	265.3	-16.4	-16.4
45	616 - 630	12.4	37.8	260.4	-1.5	-13.9
49	672 - 686	0	17.3	310.3	-19.6	-19.6
50	686 - 700	8.7	27.8	293.7	-7.3	-16.0
51	700 - 714	0	30.5	287.2	-15.8	-15.8

DAB = days after beginning; 14 to 350 DAB = 1st year; 344 to 714 = 2nd year. P = rainfall; DEF (0 – 0.3) = soil water deficit of the 0 – 0.3m soil layer at the beginning of each balance, S_{Li} = initial soil water storage of the 0 – 1.0m layer; ΔS_L = change in water storage; ER = actual evapotranspiration.

Table 2 – Average values of the extraction of water by roots (RE) with respective standard deviations (SD) and coefficients of variation (CV), as a function of depth.

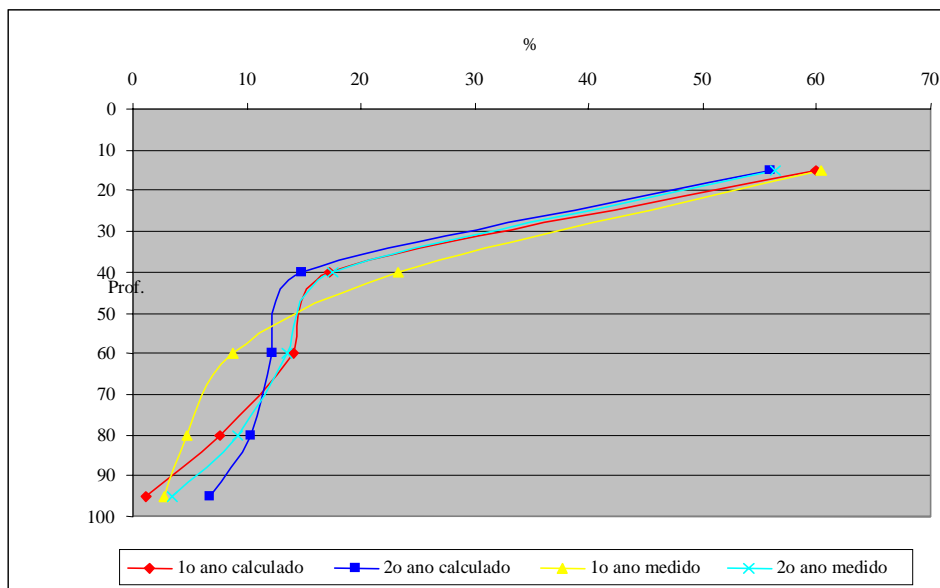|	1st year			2nd year		
	Average (mm/day)	SD	CV	Average (mm/day)	SD	CV
RE_{0-30}	-1.25	0.96	-77.44	-0.99	0.46	-46.27
RE_{30-50}	-0.30	0.26	-84.79	-0.25	0.13	-52.79
RE_{50-70}	-0.26	0.25	-97.84	-0.21	0.12	-60.16
RE_{70-90}	-0.16	0.21	-128.54	-0.20	0.17	-89.08
RE_{90-100}	-0.04	0.09	-227.31	-0.13	0.10	-80.36
RE_{0-100}	-2.01	1.47	-73.08	-1.76	0.75	-42.58

Figure 1 – Average % values of root extraction (RE) of each layer in relation to the total, comparing calculated values through eq. 2 with field measured values.

Table 3 – Water balances selected for the calculation of the evapotranspiration crop coefficient (K_c) for coffee.

Balance Nº	DAB	P (mm)	ER (mm)	ET_0 (mm)	K_c	LAI	SDM kg	PH m
6	70 - 84	75.06	-62.3	-60.3	1.03	4.0	0.85	1.30
7	84 - 98	89.74	-72.0	-50.5	1.43	4.5	0.95	1.33
8	98 - 112	49.30	-57.5	-62.4	0.92	5.4	1.00	1.35
9	112 - 126	85.60	-68.1	-57.5	1.18	5.6	1.07	1.36
10	126_140	50.60	-52.2	-63.2	0.83	6.2	1.18	1.39
15	196_210	14.00	-62.4	-55.3	1.13	9.1	1.80	1.53
16	210_224	65.20	-64.2	-47.7	1.35	9.4	1.88	1.57
17	224_238	52.30	-51.7	-36.1	1.43	9.6	1.95	1.60
18	238_252	23.20	-29.6	-35.6	0.83	9.5	2.01	1.61
19	252_266	25.50	-25.6	-24.4	1.05	9.1	2.20	1.63
31	420_434	11.80	-52.2	-53.9	0.97	4.0	1.70	1.81
32	434_448	87.36	-72.1	-57.8	1.25	4.3	1.80	1.82
33	448_462	32.78	-73.1	-64.6	1.13	4.6	1.90	1.83
34	462_476	18.88	-45.1	-59.9	0.75	5.0	2.05	1.85
35	476_490	75.20	-64.8	-54.5	1.19	5.3	2.20	1.86
38	518_532	30.00	-88.9	-71.3	1.25	8.1	3.01	1.89
39	532_546	46.50	-74.5	-68.2	1.09	8.5	3.15	1.91

DAB = days after beginning; 70 DAB to 266 DAB = 1st year; 420 DAB to 546 DAB = 2nd year; P = rainfall; ER = actual evapotranspiration; ET_o = Penman-Monteith potencial evapotranspiration; K_c = crop coefficient for coffe, LAI = leaf area index; SDM = shoot dry matter; PH = plant height.

Also from the 52 consecutive water balances, only 17 could be selected to calculate the evapotranspiration crop coefficients K_c (Table 3) using the adopted criteria. The variability of the K_c data, oscilated between 0.75 and 1.43, with averages for the 1st year: 1.12; SD = 0.23; CV = 20.4%, and for the 2nd year: average = 1.09; SD = 0.18; CV = 16.3%, so that an overall average of K_c = 1.11; SD = 0.20; CV = 18.4, could represent well this coffee variety grown under the experimental conditions. This value is in agreement with other found in the literature, eg Villa Nova et al. (2002), which present a new approach to estimate Kc, taking into account plant population, spacing and interrow condition. They however do not indicate number of replicates and estimation errors, so that it is not possible to judge if their Kc values differer for field conditions. They conclude that Kc varies with plant growth, despite the fact that they include leaf area measurements in the Kc calculation. Silva et al. (2006) shows that the variability of all water balance components is of great importance, specially that of ER, in their case with very high coefficients of variation, which lead to a high variability in Kc calculations. Due to the phenologic frutification cycle (Camargo & Camargo, 2001) our crop

invested more in leaf production during first year, which is reflected in higher values of LAI towards the end of this year (Table 3). It was also observed that the total shoot dry matter (SDM) also had a much higher contribution from leaves during the first year as compared to the 2nd year, during which the higher contribution was due to fruits. The SDM decrease from one year to the other is due to the physiological fall of old leaves and to harvest, during which fruit and some leaves are exported. Althoug for each year the values of LAI increase consistently, the correspondent Kc values oscilate randomically. Linear regressions between LAI and K_c, and SDM and K_c presented very low and non significant regression coefficients, so that K_c could not be related to the growth of the plants, evaluated through leaf area and shoot dry matter accumulation.

CONCLUDING REMARKS

Coffee plants, variety "Catuaí Vermelho" (IAC-44), 3 to 5 years old, grown in Piracicaba, SP, showed a root distribution that covers mainly the top layer (0-0.3m) 58%, with less than 10% bellow the 1.0m depth. The variability of the evapotranspiration measurements made from field water balances did not allow the observation of the dependence of Kc on plant growth parameters. An average value of 1.1, with a coefficient of variation of 18.4

% was obtained.

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