Agricultural Water Management 148 (2015) 130–140

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Deep drainage modeling for a fertigated coffee plantation in the Brazilian savanna

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ARTICLE INFO

Article history:
Received 5 February 2014
Accepted 16 September 2014
Available online 27 October 2014

Keywords:
Brazil
SWAP
Deep drainage
Water productivity
Savanna

ABSTRACT

Modeling in agriculture represents an important tool to understand processes as water and nutrient losses by drainage, or to test different conditions and scenarios of soil and crop management. Among the existing computational models to describe hydrological processes, SWAP (Soil, Water, Atmosphere and Plant model) has been successfully used under several conditions. This model was originally developed to simulate short cycle crops and its use also to cover longer cycles, e.g. perennial crops, is a new application. This report shows a SWAP application to a mature coffee crop over one-production cycle, focusing on deep drainage losses in a typical soil–plant–atmosphere system of the Brazilian savanna (Cerrado). The estimated annual deep drainage $Q = 1019$ mm obtained by SWAP was within 99% of the value determined by the climatologic water balance of 1010 mm. Monthly results of SWAP for Q compared to the estimative using the climatological method presented a determination coefficient of 0.77. A variety of coffee fertigation scenarios were simulated using SWAP and compared to farmer's management scenario, leading to the conclusion that larger irrigation intervals result in lower Q losses, better water productivity and higher crop yield.

1. Introduction

The savanna ecoregion (Cerrado) prevails in central Brazil, also reaching the northeast part of the country and including part of the state of Bahia. The savanna domain in Bahia is highly suitable for irrigated agriculture due to the great availability of surface and underground water resources. According to Brazil's National Grain Supply Company (CONAB), western Bahia is an important food (grain) provider and holds, for example, the highest coffee yield under savanna conditions in the country. However, there are some concerns in respect to the modern agriculture practiced in this producer region. Due to the ineffective land management during the last decades, the irrigated farms concentrated at specific areas and, therefore, conflicts over water use already took place in western Bahia (Lima, 2011). At the same time, management practices applied by farmers are not sustainable in terms of fertilizer and water usage, especially due to the lack of scientific studies that support their decisions (Bruno et al., 2011).

Numerical modeling applied to agriculture is a useful tool to simulate biophysical processes and can be used to obtain short-term results and future predictions under defined scenarios. The information generated is helpful for establishing a more sustainable agriculture as well as supporting strategies for the mitigation of pollution, named by Strauch et al. (2013) as the "Best Management Practices". The hydrological model SWAP (Soil, Water, Atmosphere and Plant) is one of the existing algorithms used worldwide for a variety of soils, crops and climatic conditions (Chirico et al., 2013; Crescimanno et al., 2012; Eitzinger et al., 2004; Kamble et al., 2013; Ma et al., 2011; Noory et al., 2011). The model has shown consistent results when applied to maize crops in sub-tropical climates (Pinheiro et al., 2013) and to soybeans and common beans in tropical climates (Scorza Junior et al., 2010; Durigon et al., 2012). SWAP was successfully validated already under several climatic and environmental conditions as cited Ines et al. (2006). More recent studies

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http://dx.doi.org/10.1016/j.agwat.2014.09.029

with this model found close agreement between measured and simulated values (Mishra et al., 2013; Singh et al., 2010; Utset et al., 2007; Vazifedoust et al., 2008; Verma et al., 2012).

This study aimed to use SWAP to evaluate the deep drainage of a savanna coffee plantation and analyze irrigation scenarios in view of water productivity and conservation, minimizing environmental impacts. Values of SWAP input parameters were acquired from a one-year experimental database coming from a study performed on a mature coffee crop growing in central Brazil (Bortolotto et al., 2011, 2012; Bruno et al., 2011). The computer simulations focused on improving water usage and understanding of water dynamics in a sandy soil typical of the Brazilian savanna, an area that is recently intensively used to grow perennial crops. We studied several scenarios of irrigation to improve water productivity for the chosen area.

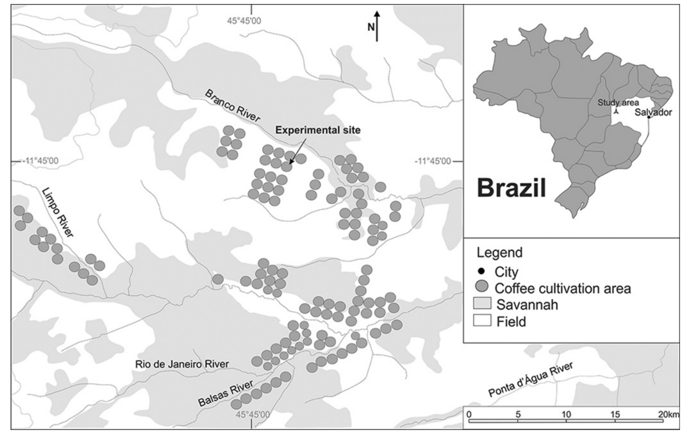

Fig. 1. Experimental site localization, showing central pivot circles in 2013.

2. Materials and methods

2.1. The Soil, Water, Atmosphere and Plant model (SWAP)

The model SWAP was developed more than 40 years ago and was gradually upgraded reaching its last version SWAP 3.2 (Kroes et al., 2008). This last version of the model had the source code restructured, numerical stability improved, macropore process integrated, and simplification of precipitation and evapotranspiration inputs included (van Dam et al., 2008).

SWAP makes use of Richards' equation in one dimension added by the sink terms (S) to calculate the water movement in the soil matrix, as follows:

$$\frac{\partial\theta}{\partial t} = \frac{\partial\left[K(h)\left(\left(\partial h/hz\right)+1\right)\right]}{\partial z} - S(h) \quad (1)$$

where θ (cm^3 cm^{-3}) is the volumetric soil water content, t (d) time, S (cm^3 cm^{-3} d^{-1}) the soil extraction rate by plant roots, K (cm d^{-1}) the soil hydraulic conductivity, h (cm) the soil water pressure head and z (cm) the vertical coordinate taken positively upwards. SWAP uses Richards' equation for describing water flux in the unsaturated and saturated zones of the soil and solves Eq. (1) numerically, using the relations between θ, h and K, with the Mualem–van Genuchten relations $\theta(h)$ and $K(h)$ (Mualem, 1976; van Genuchten, 1980).

The upper-boundary conditions in SWAP are determined according to the rates of potential evapotranspiration ET_p (mm), irrigation I (mm) and precipitation P (mm) of the area under study. Daily ET_p is calculated with the Penman–Monteith equation (Monteith, 1965, 1981) using meteorological data of air temperature T_{air} (°C), solar radiation RAD (kJ m^{-2}), wind speed S_w (m s^{-1}) and air humidity H_a (kPa).

The water balance is determined as in the following equation:

$$\pm\Delta W_s = P + I - ET_a \pm RO - P_i \pm Q \quad (2)$$

where W_s (mm) is the soil water storage in a defined elemental soil volume, ET_a (mm) the actual evapotranspiration, RO (mm) the run-off and run-on, P_i (mm) the canopy water interception and Q (mm) the soil water drained at the lower boundary, equal to $-Q_d$ or $+Q_{cr}$. The percolation Q_d is downwards and Q_{cr} the upwards, when capillary rise is present. Q_d can still be subdivided into the components Q_{dI}, due to irrigation, and Q_{dP}, due to the rainfall. Actual evapotranspiration is calculated considering the reduction of root water uptake when there is water or salinity stress, and the reduction of soil water content due to the soil surface drying. The actual transpiration T_a (mm) is obtained as follows:

$$T_a = \int_{-R_d}^{0} S_a(z)\mathrm{d}z \quad (3)$$

where the lower integration limit R_d is rooting depth and S_a the root water flux, which is related to the potential transpiration T_p (mm). During water stress, $S_a(z)$ is described in SWAP as proposed by Feddes et al. (1978). In this function, the root water uptake is regulated by the critical pressure head values h_1 (point where water extraction begins due to anoxia), h_2 (begin of constant maximum root extraction), h_3 (end of constant maximum root extraction), h_4 (wilting point, where root extraction ends). The actual evaporation is determined by Darcy's relation and empirically either according to Black et al. (1969) or to Boesten and Stroosnijder (1986), to be selected by the SWAP user. The bottom-boundary condition is adjusted by the user and can be, for example, prescribed with pressure head values of the bottom soil compartment, calculated as a function of the groundwater level, or the boundary condition can be the free drainage of the soil profile.

SWAP contains simple and detailed crop growth modules, which should be selected by the user according to the available plant data. In the simple model the user provides the leaf area index (LAI), crop factor (K_c) and rooting depth as a function of the crop development stage (DS). These data are used to calculate the canopy interception P_i, potential transpiration T_p and potential evaporation E_p.

2.2. Experimental site and field experiment

An experimental test used to calibrate and compare the results of the SWAP model was performed between August 1st, 2008 and July 31st, 2009, at a private farm near the city of Barreiras (11°46′00″S, 45°43′32″W), in Bahia, northeast Brazil (Fig. 1). The soil is classified as a Typic Hapludox according to the USDA Soil Taxonomy (Soil Survey Staff, 2010), with low natural fertility and is located in a savanna region. The precipitation is very variable, ranging from 800 to 1800 mm per year, with most events occurring from October to April. Meteorological data, acquired from the National Institute of Meteorology (INMET, Brazil), were collected at the meteorological station of the municipality of Barreiras, 90 km far from the experimental site. The input variables farmer irrigation depths and precipitation along the experimental year used for SWAP simulations are shown in Fig. 2. It is important to observe that irrigation is not discontinued during the rainy season, due to the fertilizer application that is carried out year round.

The coffee species was *Coffea Arabica* L., variety *Catuaí Vermelho*. Plants were seven years old at the beginning of the experiment and were planted at a spacing of 3.8 m between lines and 0.5 m between plants in a circular arrangement for central pivot irrigation with a total area of 80 ha, adapted for fertigation. Irrigation was applied homogeneously over the planted area, and the experimental site consisted of the pivot circle number 4, starting from

Table 1
Physical characteristics of the experimental site soil as a function of depth.

Soil depth (cm)	Number of samples for K_s test	K_s (cm d^{-1})	S.D. (cm d^{-1}).	D_b (g cm^{-3})	Sand[a] (%)	Clay[a] (%)	Silt[a] (%)
0–10	15	184	130	1.79	78	16	6
10–20	6	349	106	1.79	78	19	3
20–40	4	354	51	1.57	73	22	4
40–60	3	454	155	1.53	71	23	6
60–80	3	268	135	1.52	70	24	6
80–100	3	267	15	1.50	69	25	6

Note: K_s, saturated hydraulic conductivity; S.D., standard deviation of K_s; D_b, bulk density.
[a] Texture values are from three replicates.

Table 2
Parameters of van Genuchten obtained for the 1 m soil profile.

van Genuchten parameters	5% lower	Mean	5% upper
θ_s (cm^3 cm^{-3})	0.367	0.387	0.407
θ_r (cm^3 cm^{-3})	0.076	0.097	0.117
n	1.379	1.636	1.893
α (cm^{-1})	0.009	0.016	0.025

Note: Upper and lower values for van Genuchten parameters represent upper and lower limits in the interval of 95% of confidence.

the center of the coffee plantation (Bruno et al., 2011). Irrigation was performed by LEPA-type emitters, which distribute the water according to the circular coffee lines, avoiding the application of water in the interrow. The pivot operation was continuous during the year and stopped only during harvest (May–June), according to farmer's practice.

For the saturated hydraulic conductivity K_s (cm d^{-1}), soil bulk density D_b (g cm^{-3}) and soil particle size analyzes, soil samples were extracted from soil layers 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm (Table 1) in the coffee field. In the laboratory, the constant head method (Reynolds et al., 2002) was employed for obtaining K_s. Soil water retention curves were constructed using sieved soil samples (2 mm sieve), assuming that for sandy soils the structure of the samples is of little importance. Samples of each soil layer were submitted to the pressures of 100, 200, 330, 500, 1,000, 3,000, 5,000, 10,000, 15,000 cm of water in the laboratory, using the Richards pressure plate extractors. A soil water retention curve was established by fitting the van Genuchten (VG) model to all water retention data for the 1 m soil profile, using the RETC program (van Genuchten et al., 1991). The saturated and residual water contents (θ_s and θ_r, cm^3 cm^{-3}), the shape parameters n and α (cm^{-1}) needed for SWAP simulations were obtained together with their 5% upper and lower limits (Table 2). The upper limits of VG parameters were represented by θ_s^+, θ_r^+, n^+ and α^+, and the lower limits by θ_s^-, θ_r^-, n^- and α^-.

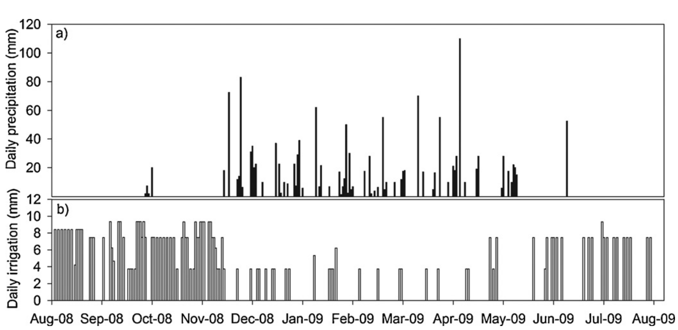

Fig. 2. Daily precipitation (a) and irrigation (b) during the experimental year (August, 2008 to July, 2009).

2.3. Climatologic water balance

Previous studies were performed in this coffee plantation as mentioned before, and the hydrological evaluation of this area was achieved by Bortolotto et al. (2012). In their study the climatologic water balances (CWB) were calculated for the pivot area with time intervals of 5 days, during the entire one-year coffee producing cycle, using a sequential method proposed by Rolim et al. (1998). Due to the characteristics of the plantation, flat and well drained with a deep water table located several meters below soil surface, the *RO* was considered to be zero, as well as Q_{cr}. Bortolotto et al. (2012) estimated ET_p by the Thornthwaite (1948) and Monteith (1965) models. They considered the coffee crop factor (K_c) as equal to 1.0, based on studies that showed values in the range of 0.6 to 1.4 (Pereira et al., 2002, 2008; Santinato et al., 1996). The sequential CWB in Bortolotto et al. (2012) assumes $P_i = 0$ and calculates a component called water excess (*EXC*), which includes *RO* and *Q*. As *RO* and Q_{cr} are considered zero, it is assumed that the $EXC = Q = Q_d$, and that *Q* is only the downward drainage which is lost from the crop below the 1 m depth.

2.4. Parameter estimation

Information about soil hydrology, plant and meteorological data are the SWAP input requirements to run it. The model works with a collection of input files: main file, crop file, irrigation file and meteorological files for each year of the simulation. The irrigation file requires dates and amounts of water applied by irrigation and the meteorological file requires daily variables: air temperature T_{air} (°C), solar radiation *RAD* (kJ m^{-2}), wind speed S_w (m s^{-1}), air vapor pressure H_a (kPa), and *P* (mm).

The water balance components were simulated for each month during the one-year period of study. The moment of crop emergence was set on August 1st, 2008 and the crop harvest was on July 31st, 2009, the period of the coffee cycle (Bruno et al., 2011). The amount of water applied by irrigation was scheduled as shown in Fig. 2.

The initial pressure head distribution in the soil was unknown and necessary for the water balance simulation, so the pressure head distribution in the soil profile at the end of one year of the first simulation with SWAP was used thereafter as the initial condition. The soil profile (0–1 m) was divided into three sub-layers with thicknesses of 10, 40 and 50 cm, each sub-layer containing 10, 8 and 5 layers with 1, 5 and 10 cm width, respectively. This possibility of soil profile discrimination in SWAP allows us to analyze in details the evolution of predicted θ and h in the time frame. The bottom-boundary condition of free drainage of the soil profile was selected in SWAP because the water table is located several meters below the soil surface. In this case, the bottom flux of the SWAP soil profile is equal to the hydraulic conductivity in the last soil compartment, as the gradient of water potential in soils under drainage can be assumed to be unity (Kroes et al., 2008).

The empirical parameter of pore connectivity λ, proposed by Mualem (1976), is difficult to be evaluated directly. According to

Table 3
Standard values used in SWAP simulations.

Description	Parameter symbol	Value	Unit
Soil			
Saturated volumetric water content	θ_s	0.3874	$cm^3\ cm^{-3}$
Residual volumetric water content	θ_r	0.0969	$cm^3\ cm^{-3}$
Shape parameter of the retention curve	n	1.636	–[a]
Shape parameter of the retention curve	α	0.017	cm^{-1}
Shape parameter of hydraulic conductivity curve	λ	0.5	–
Saturated hydraulic conductivity	K_s	266	$cm\ d^{-1}$
Plant			
Light extinction coefficient for diffuse visible light	K_{dif}	0.9	–
Light extinction coefficient for direct visible light	K_{dir}	0.86	–
Leaf area index at the beginning of simulation	LAI_0	8.8	$ha\ ha^{-1}$
Leaf area index for 50% of the simulation period	$LAI_{50\%}$	10.3	$ha\ ha^{-1}$
Leaf area index for 75% of the simulation period	$LAI_{75\%}$	12.0	$ha\ ha^{-1}$
Leaf area index at the final of simulation	$LAI_{100\%}$	7.7	$ha\ ha^{-1}$
Crop coefficient	K_c	1.1	-
Interception coefficient of Von Hoyningen-Hune and Braden	a	0.025	-
Rooting depth during the experimental period	R_d	1.00	m
Relative root density in soil surface ($RR_d = 0$)	R_{y0}	1.00	m
Relative root density for $RR_d = 0.6$	$R_{y0.6}$	1.00	m
Relative root density at $RR_d = 1.0$	$R_{y1.0}$	0	m
Critical pressure heads for root extraction	h_1	−1	cm
	h_2	−25	cm
	h_{3h}	−500	cm
	h_{3l}	−800	cm
	h_4	−15,000	cm

Note: RR_d, relative root depth.
[a] "–" refers to non-dimensional parameter.

data compiled by De Jong van Lier et al. (2009), values of λ commonly vary between 6 and −6, whereas values of 0.5 or 0 are more often used. Therefore, several values of λ were used in the sensitivity analysis to show the influence of this parameter in our simulations. An average K_s-value (from Table 1) representative of the 1 m soil layer was used in the simulations.

The SWAP simple crop module requires information of the leaf area index, crop factor, maximum rooting depth as a function of the development stage, as well as the light extinction coefficient and the critical pressure head values of the Feddes et al. (1978) distribution. The model is recommended for annual crops with short growing cycles, up to one year maximum. Nonetheless, a small number of studies applied SWAP to perennial plants, including wine grapes (Ben-Asher et al., 2006; Rallo et al., 2012) and citrus (Martínez-Ferri et al., 2013). Because not all the data needed about the coffee plant was available in the database of Bruno et al. (2011) and Bortolotto et al. (2012), the simple crop module was our choice to represent the coffee plantation.

Coffee leaf area index (*LAI*) was estimated from leaf dry matter (available in Bruno et al., 2011), the measured specific leaf area, *SLA* ($18\ m^2\ kg^{-1}$), per plant soil cover, *SCA* ($1.9\ m^2$). A variety of coffee leaf sizes was collected from the same experimental plants in 2013 to determine the average *SLA*. The obtained values of *LAI* for different stages (LAI_0, $LAI_{50\%}$, $LAI_{75\%}$ and $LAI_{100\%}$) along the experimental cycle are shown in Table 3.

For the characterization of the coffee crop in SWAP, we assumed a constant crop coefficient K_c for the entire year, equal to 1.1 (Allen et al., 1998). The coffee rooting depth R_d, as measured by Bortolotto et al. (2012) and Bruno et al. (2011), reaches the maximum depth of 1 m and was considered constant during the experimental year. Additional information about the root density (R_y) distribution along the soil profile was obtained for the crop based on visual observations of Bruno et al. (2011). Four times during the experimental year they collected an entire plant and measured dry matter of leaves, branches, and roots, as well as root depth and distribution in the soil profile. According to these authors, the relative root density is abundant from the surface down to the 0.6 m depth, decreasing linearly from there until zero at 1 m.

The coefficient k_{gr} is the product of the extinction diffuse light coefficient for visible light (k_{dif}) and the extinction coefficient for direct visible light (k_{dir}). The parameter k_{gr} was analyzed using values between 0.2 and 2.2 (Kroes et al., 2008) in the analysis of sensitivity. Measurements of the extinction coefficient of coffee are rare in the literature. Field measurements with a five-year old coffee plantation of the São Paulo region showed an extinction coefficient of 0.53 for an average *LAI* equal to 3.8 (Angelocci et al., 2008). The interception coefficient of Von Hoyningen-Hune and Braden (a) was selected for the present study from Kroes et al. (2008), for ordinary crops.

The information regarding the limiting pressure head for soil water extraction by plant roots is described in the SWAP crop file. Between h_1 and h_2 water extraction by roots is assumed to increase linearly towards low values of h. The optimal root water uptake occurs between h_2 and h_{3h} (at high potential transpiration) or h_{3l} (at low potential transpiration). The wilting point was selected to be $h_4 = -15{,}000$ cm. The values h_3 are those recommended for deciduous fruit plants shown in Taylor and Ashcroft (1972), which is the kind of plant that better adjusts to the characteristics of the coffee crops. The parameter values established in the soil and crop files for SWAP simulations in this study (Table 3) were called standard values.

2.5. Model evaluation

In the analysis of sensitivity regarding the standard values of the parameters presented in Table 3, the Root Mean Square Error (*RMSE*) (Smith et al., 1997) was used and calculated using Eq. (5). SWAP Q_i simulations obtained with those standard values were compared with SWAP Q_i' simulations obtained when varying one of them and maintaining all other constant. The lower the value of *RMSE*, the smaller the sensitivity of the model to the varied parameter.

$$RMSE = \sqrt{\frac{1}{k}\sum_{i=1}^{k}(Q_i - Q'_i)^2} \quad (5)$$

SWAP simulations were also compared to Bortolotto's CWBs, using the following equation:

$$RMSE = \sqrt{\frac{1}{k}\sum_{i=1}^{k}(F_i - B_i)^2} \tag{5a}$$

where B_i are monthly values of Q or ET_a from Bortolotto et al. (2012), F_i the corresponding SWAP forecasted values, and k the number of observations. In this case, the lower the value of *RMSE*, the closer the proximity of the predicted F_i values to the B_i values.

In order to estimate Q and ET_a errors for SWAP simulations, meteorological data were generated advancing and retarding the variables one and two days in relation to the real meteorological data presented in Fig. 2. This approach resulted in five sets of monthly values of Q and ET_a for which the averages and standards deviation were obtained, showed by bars in Fig. 6.

2.6. Parameter sensitivity

The sensitivity of the SWAP model in relation to the crop (K_c, LAI, K_{dif}, K_{dir}, R_d, h_{3h} and h_{3l}) and hydrological soil parameters (θ_s, θ_r, n, α and λ) was performed before and after establishing the standard values (Table 3) of the parameters for the simulation. Before the establishment of standard values a visual analysis was carried out by trial and error to detect the most sensitive plant and soil parameters. Afterward, a second analysis of sensitivity for soil parameters was made using several combinations of VG parameters. *RMSE* values were obtained replacing the standard combination of parameters by upper ($\theta_s{}^+$, $\theta_r{}^+$, n^+, α^+) and lower ($\theta_s{}^-$, $\theta_r{}^-$, n^-, α^-) values, according to Table 2. Each parameter was substituted once and the simulation with SWAP was performed. In the case of crop parameters, they were changed by 10% and 50% of the standard combination (Table 3) to obtain *RMSE* values.

2.7. Irrigation scenarios and water productivity

Different scenarios of irrigation were analyzed with the model, aiming to determine more efficient water managements in relation to deep drainage losses and water use efficiency at the farm under study. The irrigation scenarios were classified according to irrigation frequencies (*IF*), choosing intervals of 3 (IF_3), 5 (IF_5), 10 (IF_{10}) and 15 (IF_{15}) days between applications. For each IF_i, the amount of water applied was obtained based on the net irrigation depth (*ID*) between 1 and 50 mm (discounting P from I within each period), and when precipitation was higher than or equal to *ID*, irrigation was not applied. The scenarios with no irrigation and farmer irrigation management (IF_{Farmer}) were also evaluated, totalizing 34 setups (Table 4). The criterion for the irrigation scenarios was that I should not be too low (i.e. <40 mm) or too high (i.e. >900 mm) during the year, ensuring the comparison between the scenarios for the several *IF*.

For each irrigation scenario, the water productivity WP_{I+P} (kg m^{-3}), which relates crop yield to water use, and the actual yield Y_a (t ha^{-1}), were calculated by Eqs. (6) and (7), respectively, for the interpretation of the effects of the scenarios during a year of coffee production.

$$WP_{I+P} = \frac{T_a}{T_p}\left(\frac{Y_p}{P+I}\right) \tag{6}$$

$$Y_a = \frac{T_a}{T_p}Y_p \tag{7}$$

where Y_p (t ha^{-1}) is the biological productivity of coffee, corresponding to the dry matter yield. Y_p was calculated based on the coffee fruit productivity for 2008/2009 (3060 kg ha^{-1} y^{-1}) and the coffee harvest index of 0.012 (Nair, 1993).

Table 4
Scenarios of irrigation generated for SWAP application.

Irrigation depth (mm)	I (mm y^{-1})			
	IF_3	IF_5	IF_{10}	IF_{15}
1	83	46	–[a]	–
3	251	137	56	–
5	421	228	94	55
8	688	365	151	89
11	900	511	209	122
14	–	668	269	155
17	–	826	329	189
20	–	–	389	222
25	–	–	490	278
30	–	–	595	394
40	–	–	823	460
50	–	–	–	594

Note: IF_3, irrigation (I) applied each 3 days; IF_5, irrigation applied each 5 days; IF_{10}, irrigation applied each 10 days; IF_{15}, irrigation applied each 15 days.
[a] "–" represents not evaluated scenarios.

As water is available in large quantities from rainfall and irrigation during the entire year, water stress conditions were not expected to take place. Coffee fruit productivity used here is the potential one. Calculated *WP* is a relative number because it is affected only by the irrigation scenarios and meteorological data. The *WP* relation is a new way to characterize water productivity, and it is described in details by Vazifedoust et al. (2008).

3. Results and discussion

An application of the SWAP model is presented for a perennial crop during one experimental year. SWAP input parameters and their influence on the simulations of the components of the water balance Q and ET_a were evaluated. For plant characterization, experimental data and information from studies found in the literature were used, and a simple coffee plant model was established for one year in 2008/2009. Water balances simulated by SWAP were then compared to a study developed in the same savanna area. After the model calibration, scenarios of irrigation were appraised looking for the best management that would benefit water and coffee productivity when compared to the farmer's actual practices.

Table 5
Sensitivity of the SWAP model for deep drainage Q prediction evaluated through the root mean square error (Q-*RMSE*), in relation to variations of the van Genuchten and Mualem parameters, for chosen values of pore connectivity.

λ	Q-*RMSE* (mm)								
	STD[b]	n^-	n^+	α^-	α^+	$\theta_s{}^-$	$\theta_s{}^+$	$\theta_r{}^-$	$\theta_r{}^+$
6	13.1	15.9	12	13	13.1	14.7	11.9	11.9	14.9
5	11.6	14.6	10.5	11.4	11.7	13.3	10.3	10.3	13.5
3	7.5	11.1	6.9	7.1	7.9	9.6	6.1	6.1	9.9
1	1.6	6.5	3.8	1.6	2.3	4.6	2.5	2.5	4.8
0.5	0	5.3	4.2	1.1	1.2	3.3	3.7	3.8	3.5
0	1.5	2.7	5.3	1.9	1.9	2.7	4.2	4.2	2.9
−1	5.7	2.7	10.1	6.3	4.9	5.7	6.8	6.8	5.8
−3	29.5	10	–[a]	40.5	25	30.5	28.5	28.5	30.6
−6	–	–	–	–	–	–	–	–	–

Note: λ, pore connectivity parameter of Mualem (1976); n^- and α^-, shape parameter values of the lower limit of 5% interval; n^+ and α^+ shape parameter values of the upper limit of 5% interval; $\theta_s{}^-$ and $\theta_s{}^+$, lower and upper values of saturated volumetric soil water content of the 5% interval; $\theta_r{}^-$ and $\theta_r{}^+$, lower and upper values of residual volumetric soil water content of the 5% interval.
[a] Non-convergence of Richard's equation in SWAP.
[b] STD, standard values of van Genuchten parameters.

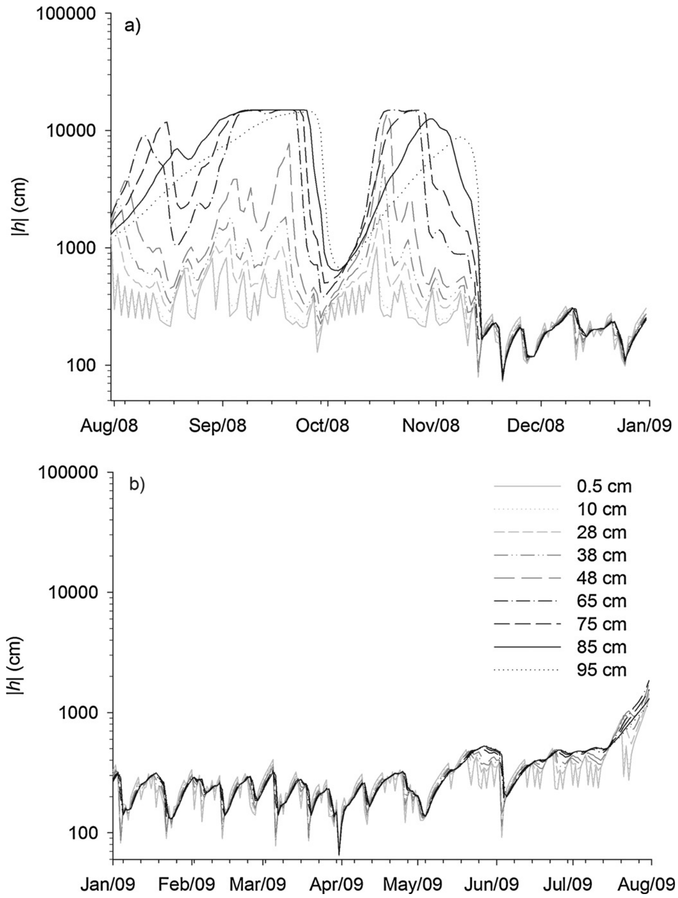

Fig. 3. Daily values of soil water pressure head h (cm) of the soil profile predicted by SWAP at depths 0.5 to 95 cm, (a) from July 31st to December 31st, 2008 and (b) from January 1st to July 31st, 2009.

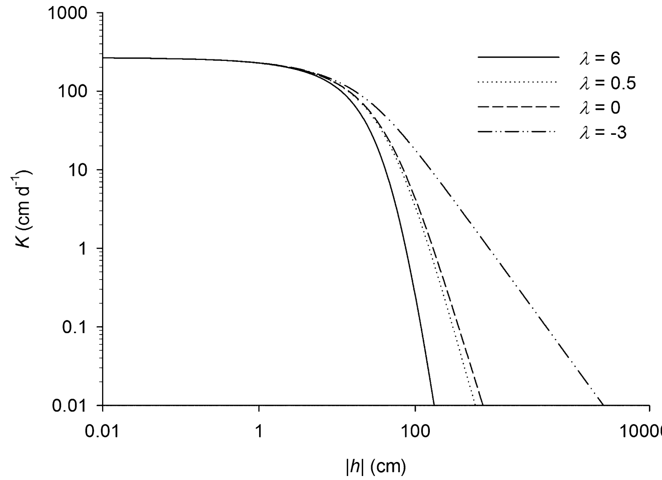

Fig. 4. Hydraulic conductivity K (cm d^{-1}) versus soil water pressure head h (cm) for different values of the pore connectivity parameter λ.

Table 6
Sensitivity of the SWAP model for deep drainage Q prediction evaluated through the root mean square error (Q-$RMSE$), in relation to variations in 10% and 50% of plant standard parameters.

Plant parameters	Q-RMSE (mm)				
	50%	10%	STD[b]	−10%	−50%
K_{dif}	0.003	0	0	0.004	0.08
K_{dir}	0.003	0.003	0	0.004	0.08
R_d	1.90	1.00	0	0.80	1.50
K_c	33.00	13.00	0	7.00	43.00
a	0.10	0.04	0	0.04	0.11
LAI	–[a]	–	0	0.027	0.135

Note: K_{dif}, extinction coefficient for diffuse light; K_{dir}, extinction coefficient for direct light; R_d, rooting length; K_c, crop factor; a, interception coefficient of Von Hoyningen-Hune and Braden; LAI, leaf area index.

[a] Not evaluated.

[b] Standard values of van Genuchten parameters.

3.1. Sensitivity analysis and model calibration

Table 5 shows results of the *RMSE* for the estimations of Q for the several values of λ and combinations of VG parameters. Soil hydrological parameters assumed either the upper or lower value of a given VG parameter, delimiting the 95% confidence interval. When one parameter had its value changed from the standard value, the others remained in the standard combination. It can be observed that the *RMSE* in relation to Q estimation is more sensitive to variations in λ. In this analysis, we varied λ between 6 and −6, but for values of λ equal to −6 and one value for −3 the simulations with SWAP resulted in the non-convergence of Richards' equation. Changes in VG parameters only affect the simulations of *RMSE* for Q slightly, and the shape parameter n had the greatest influence. The *RMSE*-value equal to zero corresponds to the standard combination of VG and Mualem parameters (Table 3).

We also studied the influence of K_s on model results of the water balance. For the component Q, the *RMSE* did not show great differences when K_s varies from 26 to 455 cm d^{-1}.

The component Q is highly affected by Mualem's λ as it can be seen in Table 5 for all VG parameters. The effect that the pore connectivity produces on the results of water balance components may be clarified by the behavior of the hydraulic conductivity function for different values of λ, shown in Fig. 4. Almost all the h-values occurring during the experimental year remain in the range −60 to −15,000 cm, where the K function can take several shapes depending on λ. It is important to emphasize that an appropriate value of λ for the sandy soil should be determined to obtain a more precise evaluation of the soil–plant system under study. Similar results of λ effects on the hydraulic conductivity function can be found in Sakai et al. (2009)

SWAP results in Fig. 3 show that the soil pressure head values between −1 and −25 cm are not reached in this study, and therefore h_1 does not affect the simulated results. Pressure head h remains in the range of −100 and −15,000 during the dry period and the range of −60 and −1000 cm during the rest of the year (wet period). In relation to soil evaporation, no difference was found in the annual result when applying the procedures of Black et al. (1969) or Boesten and Stroosnijder (1986). The explanation may be the fact that the soil evaporation simulated with SWAP is almost insignificant (lower than 1 mm y^{-1}), and consequently no effect would be expected to happen when changing the method of calculation.

Table 6 shows the results of SWAP sensitivity analysis in relation to selected plant input parameters. As shown the results of Q-$RMSE$ in this study, variations in the coffee light extinction coefficients (k_{dif} and k_{dir}), R_d, a and LAI in the SWAP crop file did not affect Q-values significantly. The parameters k_{dif} *and* k_{dir} are used in the calculation of soil evaporation, which in the conditions of the present study were very low, explaining the low influence of these parameters on the WB values. The *LAI* values estimated from leaf dry matter data were relatively high (Table 3) as compared to literature values, however they can be acceptable when comparing to measurements performed in 2–4 years old coffee plants in the literature (Gutiérrez and Meinzer, 1994). The analysis of sensitivity of *LAI* was not possible for +10% and +50% of the standard value because the results were higher than the maximum value allowable

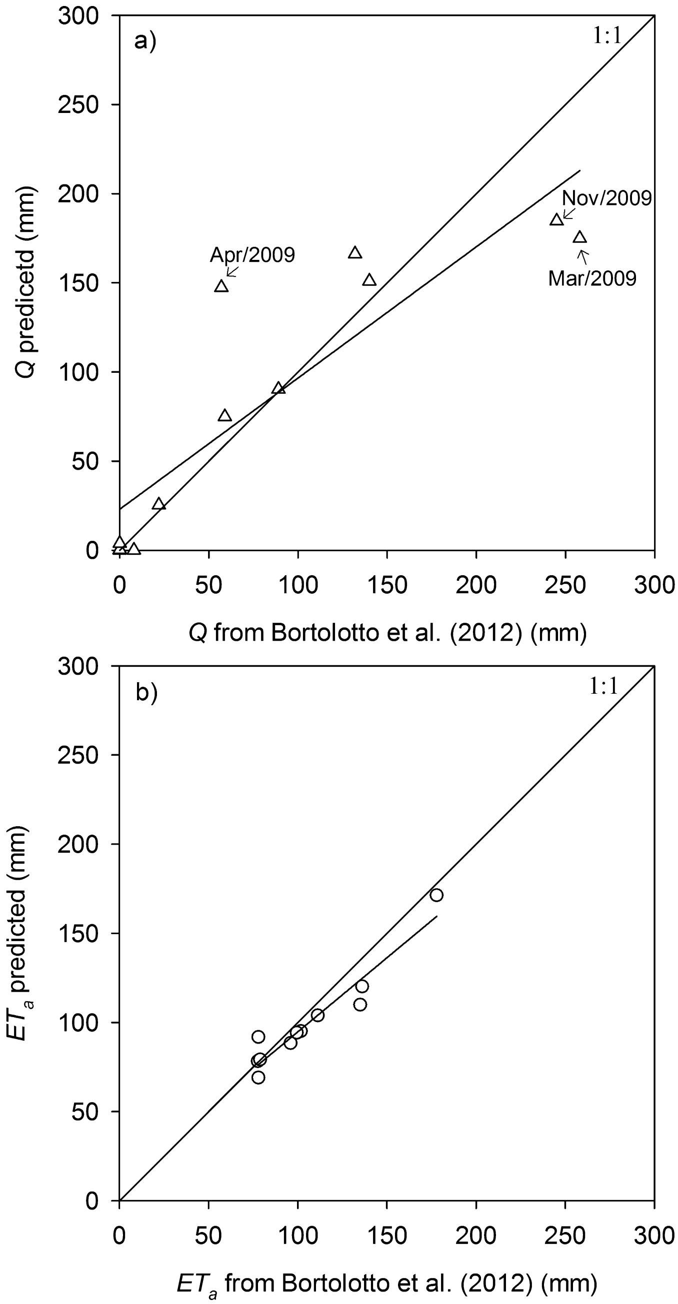

Fig. 5. Linear regression between Bortolotto et al. (2012) data and predicted (SWAP) monthly values of (a) drainage Q (mm) and (b) actual evapotranspiration ET_a (mm).

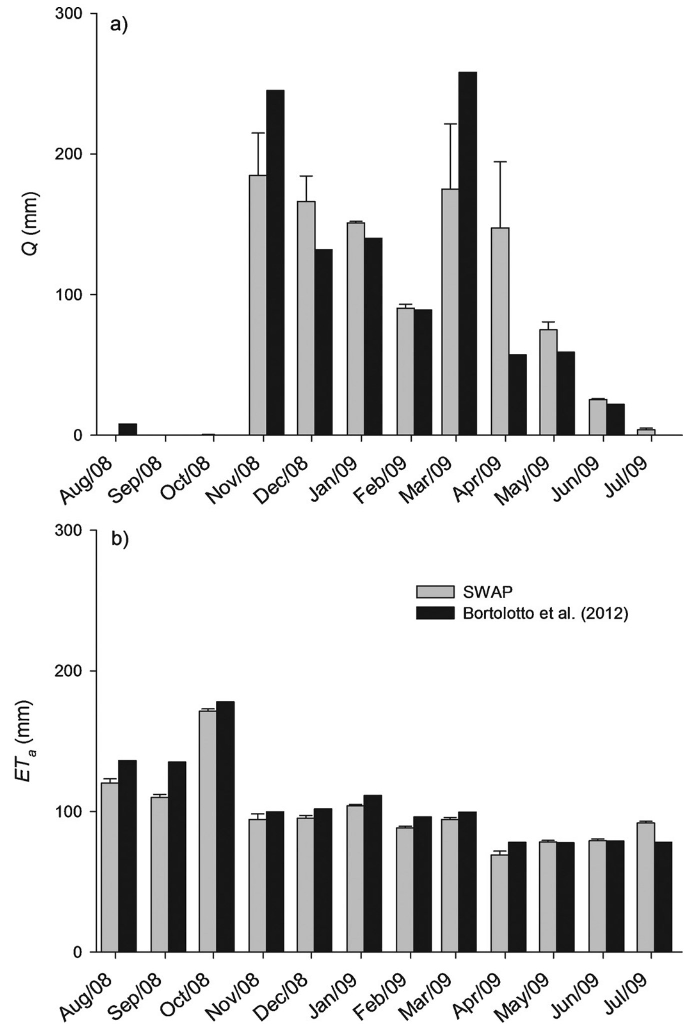

Fig. 6. Bortolotto et al. (2012) data and predicted (SWAP) monthly values of (a) drainage Q (mm) and (b) actual evapotranspiration ET_a (mm).

by SWAP. The critical soil water pressure head parameters were also evaluated in the sensitivity analysis and did almost not influence Q simulations with SWAP. The parameter K_c effected SWAP simulations for Q considerably, as Q-*RMSE* variations related to changes in this parameter were high.

3.2. Model comparison

The comparison between SWAP predictions and Bortolotto's values of Q and ET_a is shown in Figs. 5 and 6. In this study, no actual measurements of ET_a and Q were available, so that we relied on the quality of this comparison. As it can be appreciated, the results of Q satisfactorily agreed with calculations of Bortolotto et al. (2012) presenting a linear relationship with $R^2 = 0.77$ (Fig. 5a). Fig. 5a shows specific months, those with the highest Q found during the year, responsible for the deviation of the tendency line. On the other hand, most of the results follow the 1:1 line. The resulted *RMSE* for Q is around 43 mm, possibly a response to the predicted values in November and December of 2008, and March and April of 2009 (Fig. 6). On these dates, a similar behavior of SWAP predictions for Q in relation to results of Bortolotto et al. (2012) can be observed: the first month (November or March) had Q underestimated and the next month (December or April) overestimated by SWAP. In the course of simulations, the water saved in one month is delivered to the next two months, the behavior of Q becoming closer to the 1:1 line in the third month of the sequence (Figs. 5a and 6a). This behavior of retaining and distributing water during the following months is confirmed when comparing the ET_a curves simulated in SWAP with those obtained by Bortolotto et al. (2012). These curves had similar results. Considering that there are only two ways to lose the water from this system (by evapotranspiration and drainage), the water transported by drainage Q in the simulations with SWAP is just distributed differently from Bortolotto's during the year.

During the dry period of the experimental year, from July to November of 2008 (Fig. 3a), soil pressure head at depths 65, 75, 85 and 95 cm assumed values equal to or very close to −15,000 cm. However, h did not remain at these low values for a long time, a maximum of 23 days for the 85 cm depth in September and 12 days for the 65 cm depth in October. The behavior of h in the

Table 7
Components of the annual water balance simulated by SWAP and calculated by CWB of Bortolotto et al. (2012).

Water balance components (mm)	SWAP	CWB
P	1535	1535
I	697	697
P_i	18	–[a]
ET_a	1194 ± 6	1270
RO	0	–
Q	1019 ± 6	1010

Note: CWB, climatologic water balance; P, precipitation; I, irrigation; P_i, canopy interception; ET_a, actual evapotranspiration; RO, run-off; Q, bottom flux.
[a] Not available.

65–95 cm soil layer during the dry period can initially (from August to September) be understood by the infiltration of water from irrigation and later due to the rain events of September (P = 31 mm in four days) and the beginning of November (P = 90.5 mm in two days). Irrigation water did not reach layers deeper than 95 cm during August and most of September, since h in this region decreases almost linearly and stabilizes at −15,000 cm, increasing only due to the large rain event in late September. The rain events of November make the pressure head increase and become almost uniform along the soil profile. The simulated Q is, therefore, nearly zero from August to October of 2008 (Fig. 6a), confirming that there is no drainage due to irrigation during the dry period of the year. The water delivered by irrigation and rainfall during the dry period is retained in the 1 m of the soil profile and is kept available to plants or deep drainage in the wet period.

The results of ET_a showed to be well in agreement to the observations of Bortolotto et al. (2012) since the linear regression between them was obtained with R^2 = 0.9. However, the model tended to underestimate the results since most of the points remain under the calculated values in Fig. 5b. SWAP takes into consideration plant characteristics as already mentioned for the estimation of E_a and T_a. Since the ET_a calculation in Bortolotto et al. (2012) is based only on the K_c for coffee, we should not expect an exact agreement between Bortolotto's data and SWAP simulations. Nonetheless, the *RMSE* for monthly ET_a was around 11 mm.

The uncertainties of SWAP modeling for Q and ET_a due to the meteorological input data are shown in Fig. 6a and b (see Section 2.5). Based on the results of Fig. 6a, we verified that Q is highly influenced by the meteorological values and that it can vary more in the wet months. During the dry period of the year the uncertainties are smaller, which lead to the conclusion that Q is mainly governed by the precipitation. Differently from these results, Fig. 6b shows that ET_a did not appear to be affected by the employed meteorological scenarios since the error bar for each month is too small.

Table 7 presents the components of the annual water balance obtained by SWAP and the estimated results of Bortolotto et al. (2012). Even with the monthly differences shown in Fig. 6, the annual results of the components Q and ET_a ended up very close. As shown by the simulations of SWAP, only a small portion of the water entering the system during the year is converted into P_i. However, this component is much higher than the annual E_a that was 0.6 mm. These results could be consequences of the high density of leaves in the plantation since the coffee plants are at full maturity. Conclusively, all the water assigned as ET_a in Table 7 represents plant transpiration. However, for annual values of ET_a and Q there is little difference by changing the dates of the meteorological data position (Section 2.5) as the errors found in the predictions are very low compared to their means.

The proximity between our predictions of the water balance components by SWAP for this savanna soil with coffee and the estimative of Bortolotto et al. (2012) indicates that SWAP can be used to simulate more environment friendly fertilizer and water management systems. Being a more robust and versatile model than the CWB, SWAP could be used with advantage for a variety of soil physical conditions, crop architectures and climates. Another advantage over the CWB is that SWAP admits, for example, to be tested for soil water flow processes considering hysteresis, and for a variety of surface and bottom boundary conditions. SWAP gives also detailed spatial distribution data of soil water flow, soil water content, or pressure head in the soil profile, and all these output results can be obtained promptly.

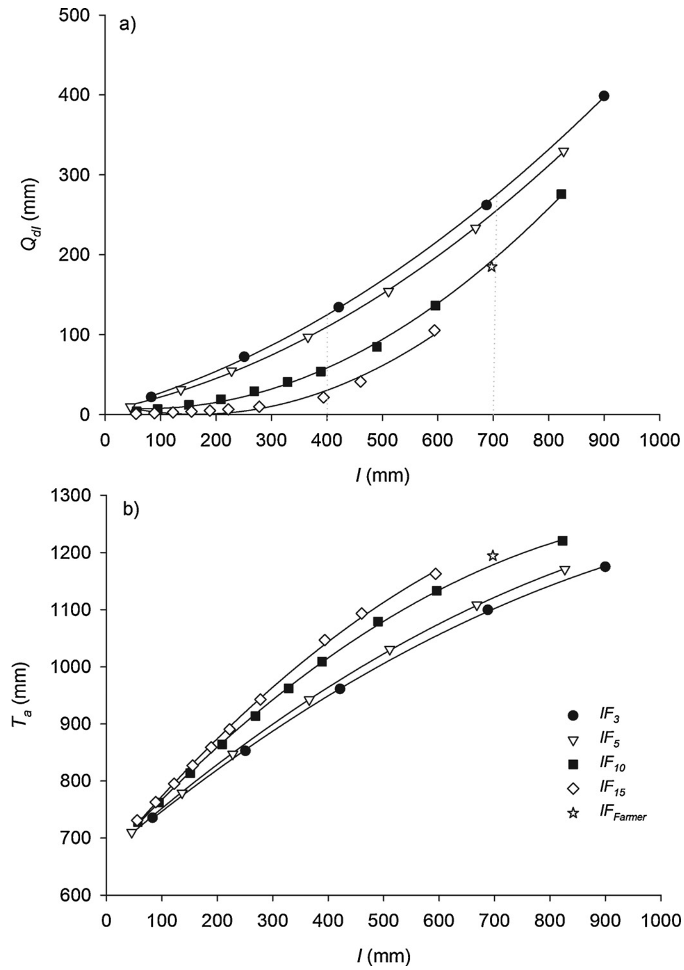

Fig. 7. (a) Annual drainage due to irrigation only Q_{dI} (mm) and (b) annual plant transpiration T_a (mm) for different irrigation frequencies (IF) as a function of the amount of water applied I (mm) throughout the experimental year.

3.3. Scenarios of irrigation

In order to generate new information on water management for coffee cultivation in the west of the state of Bahia, several scenarios of irrigation were simulated with SWAP (Figs. 7 and 8). With this information we planned to demonstrate the influence of I on Q, and also to analyze different possibilities of management, in contraposition to the choice of the farmer. Usually irrigation water is applied in several volumes distributed during the year by the farmers, and this routine is necessary because they fertigate the crop year round. Alternatively, this information would also serve to lead farmers to adopt more sustainable practices of water management in this agricultural region.

SWAP simulation with no irrigation yielded the value of Q_{dP}, the drainage only due to rainfall (833.4 mm), which is very high, showing that rainfall is the main factor responsible for Q in the

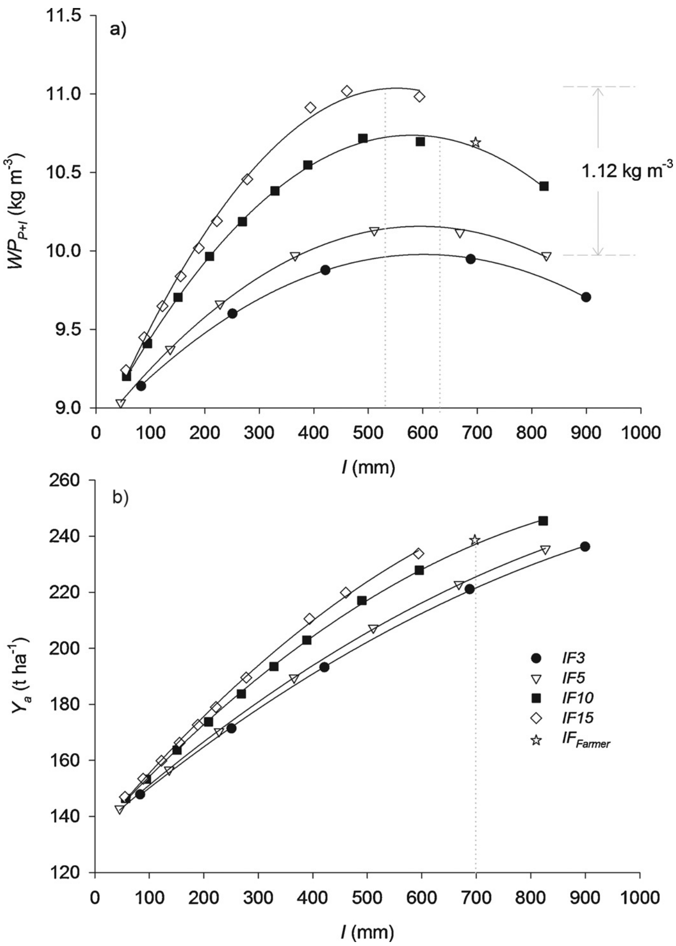

Fig. 8. (a) Water productivity WP_{P+I} (kg m^{-3}) and (b) actual yield Y_a for different irrigation frequencies (*IF*) and amount of water applied *I* (mm) throughout the experimental year.

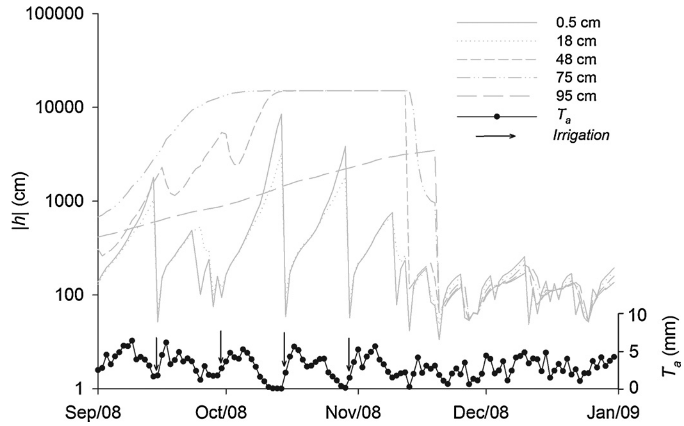

Fig. 9. Daily values of actual transpiration T_a (mm) and soil water pressure head *h* (cm) predicted by SWAP during the year at soil depths of 0.5, 18, 48, 75 and 95 cm, for the irrigation scenario *I* equal to 460.5 mm and *IF* of 15 days.

annual balance. This value was subtracted from the total *Q* to obtain Q_{dI}, the drainage due to irrigation only. For all simulations of Fig. 7a we present Q_{dI} maintaining the actual rainfall (2008/2009).

Each of the four curves in Fig. 7a was fitted to a 2nd order polynomial model to appreciate their behavior better. Results indicate that Q_{dI} values tend to be lower when the frequency of irrigation is high (IF_3), which can be verified comparing the results for a fixed *I*. As an example, for 400 mm, the values of Q_{dI} from the respective regression curves are 24 mm for IF_{15}, 63 mm for IF_{10}, 109 mm for IF_5, and 129 mm for IF_3. In this case, Q_{dI} increases 39 mm from IF_{15} to IF_{10}, 46 mm from IF_{10} to IF_5, and 20 mm from IF_5 to IF_3, showing that there is a considerable rise in Q_{dI} when reducing the irrigation frequency. Taking the amount of water applied by farmers (*I* = 697 mm), the correspondent Q_{dI} is 134 mm (IF_{15}), 205 mm (IF_{10}), 248 mm (IF_5), and 282 (IF_3). As it can be observed, farmer's irrigation management (IF_{Farmer}) practically encloses the IF_{10} curve. The IF_{10} and IF_{15} scenarios are characterized by having several days between applications of water and consequently in these scenarios there is no irrigation during the wet period of the year.

Plant response to irrigation scenarios is presented in Fig. 7b. For fixed values of *I*, T_a increases as the frequency of irrigation (*IF*) decreases. Larger intervals of irrigation might induce a drier microclimate in the canopy, therefore, increasing T_a. Both results of T_a and *Q* show that there is less loss of water by drainage (more loss by transpiration) when the irrigation is applied with greater time intervals. For all the scenarios there is a tendency of Q_{dI} and T_a to increase with the amount of water used yearly by the irrigation.

The effect of irrigation scenarios on the soil–plant system is interpreted in a different perspective when looking at water productivity (*WP*) outcomes. These results show that there is a limit for the amount of water used during the year, which is confirmed by the peak values in each curve of Fig. 8a. For the same amount of irrigation, the difference between *WP* for the several *IF*-curves in Fig. 8a does not pass 1.12 kg m^{-3} (1.12 kg of dry matter per ha, per mm of water). This relative low influence of *I* on the results of WP_{P+I} can be attributed to the dominant rainfall in this coffee cultivation region. In any case, when analyzing the efficiency of the irrigation scenarios, not only *WP* should be considered, but also the respective *Q*.

The maximum values of WP_{I+P} obtained from the regression curves in Fig. 8a occurred when *I* was between 530 and 630 mm. When water was applied in intervals of 15 days (IF_{15}) during the year, the *WP* had the highest values. The best management practice, however, would bring benefits not just to water conservation, but also to coffee productivity. From Fig. 8b, it can be noted that the actual coffee yield Y_a increases according to *I* increments. Any irrigation scenario with *I* between 650 and 750 mm and water application intervals of 15 days (IF_{15}) (Table 8), would result in higher Y_a values and also of *WP* in relation to the farmer's management scenario (IF_{Farmer}). The scenario IF_{Farmer} resulted in Y_a equal to 238 t ha^{-1} and WP_{I+P} equal to 10.70 kg m^{-3} (10.70 kg ha^{-1} mm^{-1}), which is not so different from the most efficient irrigation management (WP_{I+P} that is around 11.06 kg m^{-3}, Fig. 8a). In comparison, when *I* is extrapolated to 700 mm, with IF_{15}, Y_a would result in 248 t ha^{-1}, WP_{I+P} in 10.90 kg m^{-3}, and the corresponding Q_I reduced by 49 mm in comparison to the farmer's irrigation scenario. Considering that the time scale of coffee cultivation can reach up to 18 years, a yearly reduction of Q_{dI} and the increase of Y_a presented above, although relatively small, would greatly benefit water conservation and groundwater pollution, as well as coffee productivity.

It should be mentioned that a low-frequency irrigation scenario could lead to a too dry soil condition in some periods of the year, considering that the annual rainfall distribution in the area defines wet and dry periods. Evaluating the *h*-values in the soil profile for the scenario IF_{15} (*I* = 460.5 mm), as an example, it can be verified that soil water depletion from depths 48 to 95 cm (Fig. 9) occurs during the months of September and October. When analyzing monthly data, these low values of *h* apparently have a potential effect on plant transpiration. From SWAP simulation outcomes, plant transpiration in September is T_a = 107 mm (T_p = 145 mm) and in October is T_a = 85 mm (T_p = 197 mm). Daily *h*-values in this soil layer reveal that the soil remains close to wilting conditions for about 45 days and T_a tends to decrease and reaches almost zero

Table 8
Values of water productivity (*WP*), plant productivity (Y_a), and bottom flux due to irrigation (Q_{dI}) for selected scenarios of irrigation (*I*) obtained from SWAP simulations.

I (mm y^{-1})	WP (kg m^{-3})		Y_a (t ha^{-1})		Q_{dI} (mm)		ΔQ_{dI}[a] (mm)	
	IF_{15}	IF_{10}	IF_{15}	IF_{10}	IF_{15}	IF_{10}	$IF_{Farmer} - IF_{15}$	$IF_{Farmer} - IF_{10}$
600	11.05	10.72	238	228	88	149	96	36
650	10.99	10.69	243	233	111	176	74	8
700	10.90	10.64	248	237	136	207	49	−22
750	10.78	10.56	253	241	163	240	22	−55
800	10.61	10.45	257	244	193	275	−8	−90

Note: IF_{15} and IF_{10}, scenarios of irrigation with water application each 15 and 10 days, respectively; IF_{Farmer}, farmers' scenario of irrigation; ΔQ_{dI}, difference between bottom flux due to irrigation only, using values obtained from IF_{Farmer} (Q_{dI} = 185 mm), IF_{15} and IF_{10} scenarios.
[a] Negative values mean that bottom flux due to irrigation IF_{Farmer} is lower than the amount in the considered scenario.

three times. An excessive depletion of the available water can convey irreversible consequences in coffee productivity and development, and this situation could occur for the scenarios with low amounts of water applied in the IF_{15} or IF_{10} choices. On the other hand, the coffee plant stress by a lack of water during a certain period of the year could bring benefits for production, as presented in the technical report of Guerra et al. (2005).

We analyzed a year in which rainfall was considerably high (1535 mm), and this is an important detail to be considered for a complete search of the best management practice. As cited before, rainfall averages range from 800 to 1800 mm and, therefore, in a dry year, the results of the irrigation scenarios could be driven to distinct results of water use efficiency. The stochastic employment of meteorological data or exclusively of the rainfall applied in SWAP would be highly recommended for a complete evaluation of the behavior of the irrigation scenarios and also for the analysis of climate effects. Bennett et al. (2013) introduced a stochastic approach with SWAP to quantify time and space uncertainties in deep drainage due to rainfall, land management and soil hydraulic properties in Australia. Rainfall was found to be the most important factor and a source of uncertainty to be considered for the drainage predictions, and precise rainfall data is required in such kind of study. Another point to be concerned with is that the studied coffee plants were fully mature, and these predictions should be re-evaluated for young coffee crops.

This application of SWAP tried to find the best adjustment of the model to a perennial crop and showed ways of using it to evaluate the possibility for improvements in irrigation management. Some concerns exist nevertheless in respect to our evaluations, since the outcomes are restricted to the one-year of available experimental data, and a proper validation of model simulations was not possible. It should be taken into consideration that our conclusions from the presented evaluations and scenarios with SWAP are subject to such limitations.

4. Conclusions

This study showed the potential of the SWAP model for studying a perennial crop in a savanna ecosystem in Brazil and for generating irrigation scenarios. SWAP's most sensitive input parameters were determined experimentally and other less sensitive were obtained from the literature to establish the calibration. Model simulations for monthly drainage when compared to the climatological water balance CWB data generated a determination coefficient R^2 of 0.77. The estimated annual deep drainage by SWAP was within 99% of the value determined by the climatologic water balance. Therefore, we assumed that SWAP is already a validated model that has been widely tested and proven to be efficient in different parts of the world. For that reason we could predict scenarios of irrigation for our region of coffee cultivation.

Irrigation scenarios simulated with SWAP for the experimental year showed to be efficient in water use and coffee productivity when longer intervals of irrigation were used. According to this analysis, adopting an irrigation interval of 15 days and yearly water amount between 650 and 750 mm could be an option for better management compared to the farmer's scenario. The results of water productivity, plant productivity, and deep drainage indicate that the farmer's management practices could be improved, minimizing loss of water by drainage and at the same time increasing coffee production. The information presented here should support farmers to improve their water irrigation management practices and alert them to environmental losses that might occur in these heavily fertilized coffee plantations in western Bahia, Brazil.

Some concerns still exist, however, with respect to the performed simulations: (1) there was limited experimental data for the simulations (a one-year period); this could be improved with a new study with information about the coffee plant and the SWAP plant module being structured year by year; (2) the absence of model validation with proper data; (3) the deterministic approach here used could be replaced by a new stochastic evaluation applied to meteorological and soil hydrological data, to solve spatial and temporal limitations of the simulations.

Acknowledgements

This research was financed by the São Paulo Research Foundation (FAPESP/Grant #:2011/22320-1). We would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES/Grant #:8313-12-1) and the National Council for Scientific and Technological Development (CNPq/Grant #:302261/2011-7) for the scholarships. Herman Burema and Wesley Vieira (Fazenda Morena) for field support.

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