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Water and energy flux measurements in rainfed cowpea cultivated in Northeast Brazil

José R. de S. Lima[1], Antonio C. D. Antonino[2], Claude Hammecker[3],
Carlos A. B. de O. Lira[2] & Eduardo S. de Souza[2]

[1] Universidade Federal Rural de Pernambuco, Unidade Acadêmica de Garanhuns, Av. Bom Pastor, s/n, Boa Vista, CEP 55296-901, Garanhuns-PE, Brasil. E-mail: romualdo_solo@yahoo.com.br
[2] Universidade Federal de Pernambuco, Centro de Tecnologia, Departamento de Energia Nuclear, Av. Prof. Luiz Freire, 1000, Cidade Universitária, CEP 50740-540, Recife-PE, Brasil. E-mail: acda@ufpe.br; cabol@ufpe.br
[3] Institut de Recherche pour le Développement – IRD, 29, Thanon Sathorn Tai, Bangkok 10120, Thailande. E-mail: claude.hammecker@ird.fr
[4] Universidade Federal Rural de Pernambuco, Unidade Acadêmica de Serra Talhada, Fazenda Saco, s/n, CEP 56900-000, Serra Talhada-PE, Brasil. E-mail: eduardosouza@uast.ufrpe.br

ABSTRACT

In the areas of rainfed agriculture it is very important to be able to quantify losses of water by evapotranspiration (ET). The water (WB) and energy (EB) balance methods are commonly used for measuring ET due to their simplicity, robustness and low cost. Therefore, the objective of this study was to assess the WB and EB components in the soil cultivated with cowpea in an area of 4 ha in the municipality of Areia, PB (6º 58’ 12” S e 35º 42’ 15” W, 620 m), besides comparing the methods used to determine the cowpea ET. To determine the EB, the area was instrumented with a rain gauge, a pyranometer, a net radiometer and sensors for measuring air temperature and relative humidity at two levels. To determine the WB, three experimental plots, equipped with a one-meter access tube for neutron probe measurements, and 8 mercury manometer tensiometers were installed. The mean value of the net radiation was 76% of the global solar radiation, in which 73% appeared as latent heat flux, 18% as sensible heat flux and 9% as soil heat flux. This study showed that both EB and WB methods could be used to determine the ET. The mean value for actual evapotranspiration, obtained by using the WB and EB methods, was 4.20 and 4.28 mm day^{-1}, respectively.

Key words: Bowen ratio, Beerkan method, drainage, evapotranspiration

Fluxos de água e de energia em feijão-caupi em condições de sequeiro, no Nordeste Brasileiro

RESUMO

Em áreas de agricultura de sequeiro a quantificação das perdas de água por meio da evapotranspiração (ET), assume grande importância. Os métodos dos balanços de água (BH) e de energia (BE) vêm sendo muito utilizados devido à sua simplicidade, robustez e menor custo. O presente trabalho objetivou avaliar os componentes do BH e do BE em solo cultivado com feijão caupi além de se fazer comparações entre os métodos de determinação da ET; para tal foram realizados experimentos numa área de 4 ha em Areia, PB (6º 58’ S, 35º 41’ W); para determinação do BE a área foi instrumentada com um pluviógrafo, um piranômetro, um radiômetro e sensores para medidas da temperatura e da umidade relativa do ar em dois níveis. Com vista à determinação do BH, foram instalados três sítios tensio-neutrônicos, contendo um tubo de acesso para sonda de nêutrons e oito tensiômetros. O valor médio da razão Rn/Rg foi de 76% sendo utilizado, em média, como 73% no fluxo de calor latente, 18% como fluxo de calor sensível e 9% como fluxo de calor no solo. Verificou-se que o BH e o BE podem ser usados para determinação da ET. Os valores médios da ET foram de 4,20 e 4,28 mm dia^{-1}, determinados pelos métodos BH e BE, respectivamente.

Palavras-chave: razão de Bowen, método Beerkan, drenagem, evapotranspiração

Introduction

Quantification of the major components of the water and energy budget is essential when planning for the development of water resources of an arid area, estimating water-supply, and understanding the ecological effects of development (Bidlake et al., 1996), is also important for planning crop irrigation, understanding and modeling process of mass and energy transfer in the soil-plant-atmosphere continuum, besides the possible connection link between these processes and the changes happened in the global climate.

In order to improve the understanding of mass and energy transfer processes in the soil-plant-atmosphere system, extensive research has been conducted in various parts of the world with different objectives. These studies focused on different topics like the quantification of (i) evaporation, (ii) transpiration and evapotranspiration, (iii) modeling of the processes of heat and mass transfer in the soil-plant-atmosphere system, (iv) comparison of methods to estimate the evapotranspiration, (v) long term monitoring of the climatic changes. In these papers the components of the water and/or energy balance were quantified in temperate (Takagi et al., 2009), semi-arid (Shen et al., 2004; Antonino et al., 2005; Azevedo et al., 2007; Zhang et al., 2007; Silva et al., 2009) or tropical climate areas (Cruz et al., 2005; Brito et al., 2009), in bare or cultivated soils.

In spite of this extensive literature, still little work is found on the joint measurement of the components of the water and energy balances in cropped soil (Zhou & Zhou, 2009), and this lack of information is even more accentuated for regions of tropical climate, and especially for the northeast of Brazil (Azevedo et al., 2003; Teixeira et al., 2008). In this region, cowpea (*Vigna unguiculata* (L.) Walp.) is widely cultivated as it represents the basic element in the food of the poor population. Therefore, besides playing a fundamental role in the composition of the Brazilian agricultural production, this crop also has an important social function for the supply of the nutritive needs.

Despite the major importance of cowpea, little research has yet been accomplished, to study the components of the water (Lima et al., 2006; Bastos et al., 2008) and energy balance (San José et al., 2003; Neves et al., 2008; Lima et al., 2011) of this crop, whereas most of the work already done in the quantification of these components, refers to the *Phaseolus vulgaris*.

Evapotranspiration (ET), linking the cycles of water and energy is one of the major components of the water balance for terrestrial ecosystems and food crops. The accurate estimation of water loss by ET is very important for assessing water availability and requirements of terrestrial ecosystems and making proper water resources planning (Zhou & Zhou, 2009).

The methods used for measuring evapotranspiration vary from direct measurement techniques, using lysimeters, to measurements of the water and energy balance. Precision lysimeters are very costly experimental devices, being only used for research purposes. Therefore water and energy balance methods have been very useful due to their simplicity, robustness and lower cost (Lima, 2004).

The objective of this study was to assess the water and energy balance components in a soil cultivated with cowpea in the Northeast of Brazil, as well as comparing the two methods used to determine the evapotranspiration of cowpea.

Material and Methods

Characteristics of the experimental site, climate and soil and study period

The experiment was conducted in the experimental station “Chã do Jardim” of the Centro de Ciências Agrárias, UFPB, in the municipality of Areia, Paraiba State (6º 58’ S, 35º 41’ W, 620 m), in the Northeast, Brazil. According to Köppen classification, the regional climate is of type As’ (i.e., hot and humid with summer rains). The mean annual rainfall at the experimental area is around of 1,400 mm, the daily mean air temperature is 24.5 ºC, while the daily mean relative humidity is 80%. The rainy season period is constituted by the months of April, May, June and July, which represents 62% of the annual precipitation (Oliveira et al., 2009). The soil of the field site is classified as Yellow Latossol (Oxisoil) (Embrapa, 2006). The physical and chemical properties of the soil are presented in Lima et al. (2011).

Measurements were made in a cowpea field of approximately 200 m long and 200 m wide (4 ha), at the experimental station. Cowpea was planted on March 11, 2003, spaced at 1.0 m between rows and 0.5 m between the plants. The harvest occurred on May 30, 2003.

Two hand weeding were performed during the cropping cycle of the bean. No pests or disease occurrence was observed during this cycle. Fertilization was performed at planting, which consisted of 100 kg ha^{-1} of ammonium sulfate, 200 kg ha^{-1} of potassium chloride and 178 kg ha^{-1} of triple superphosphate.

Measurements and instrumentation used

A micro-meteorological tower was set up in the center of the experimental field, for installing sensors to take measurements of energy fluxes in the interface between cowpea/soil system and the atmosphere during experimental period (11^{th} March to 30^{th} May 2003). The location of this tower provided a fetch of 100-140 m in all direction.

The net radiation (Rn) was measured by a net radiometer (Q7, Campbell Scientific Inc., USA) installed at 1.5 m above the vegetation canopy. Soil heat flux (G) was measured by two soil heat flux plates (HFT3, Campbell Scientific Inc., USA) inserted at 0.05 m underneath the soil surface, as well as two temperature sensors (108L, Campbell Scientific Inc., USA) located at 0.02 and 0.08 m below the soil surface to calculate the surface ground heat flux. Dry and wet bulb temperatures were measured using two integrated temperature-humidity probes (HMP45C, Vaisala, Helsinki, Finland) at two levels. Wind speed (u) was monitored with cup anemometers (014A, Campbell Scientific Inc., USA) at two levels. The heights of the two fixed measurements were 0.35 m and 1.05 m above the top of the canopy. The solar global radiation (Rs) was measured by a pyranometer (LI-200X, LI-COR Inc., Lincoln, NE, USA). Total rainfall was measured with a tipping bucket rain gauge (TE 525WS-L, Texas Eletronics). Signals from all the sensors mentioned above were recorded by a data logger

(CR10X, Campbell Scientific Inc., USA) every 60 s and 1800 s mean/sum of data were logged as well. Measurements were made continuously during the experimental period.

To determine the water balance, three plots were selected in the field and equipped with one access tube for neutron probe measurements, and 8 mercury manometer tensiometers. Soil water content measurements were made at three sites of the experimental field using a neutron probe (Troxler, model 4300). These measurements were recorded daily at 08:00 h in 0.1 m intervals, with a maximum soil depth of 1.20 m. Matric potential was also measured daily in the depths 0.1, 0.2, 0.3, 0.4, 0.6, 0.8; 1.0 and 1.20 m with mercury tensiometers.

Infiltration tests were performed in the surface soil and in the depths of 0.2, 0.4, 0.6 and 0.8 m in order to estimate the soil hydraulic conductivity. Infiltration tests consisted recording the time necessary for a fixed volume of water (100 mL), poured into the cylinder slightly driven into the soil surface to infiltrate completely. This test provides the three-dimensional infiltration in function of the time I_3 (t). Initially a soil sample was collected to determine its initial gravimetric water content (ws). Another sample of known volume was collected to determine its bulk density (ρ). At the end of the experiment, the saturated soil is sampled to determine the gravimetric water content of saturated soil and thus the saturated volumetric water content (θs) from the bulk density and the gravimetric water content, considering that water density as 1 kg dm^{-3}: θs = ws ρ.

The lower extremity of the cylinder presents a bevel cut facilitating its' introduction into the soil surface. This introduction should be accomplished with minimum effort in order to guarantee the structural integrity of the soil surface. Then, the cylinder is positioned at the soil surface and inserted to a depth of about 0.01 m to avoid lateral loss of the ponded water at the soil surface. A single ring infiltrometer (0.15 m diameter) similar to those described by Beerkan methodology (Souza et al., 2008) was used for the infiltration measurements.

In order to measure the height and the percentage of ground cover, 10 plants were selected in the experimental plot. These measurements were performed weekly from the plant establishment until the harvest of the crop.

Bowen ratio energy balance method

The Bowen ratio energy balance (BREB) is a very popular micrometeorological method used to estimate the latent heat flux and to derive the evapotranspiration. The energy balance equation can be expressed as:

$$Rn = G + H + LE \qquad (1)$$

where Rn (W m^{-2}) is the net radiation, LE (W m^{-2}) is the latent heat flux, H (W m^{-2}) is the sensible heat flux and G (W m^{-2}) is the soil heat flux.

The partition of energy between sensible (H) and latent (LE) heat flux is usually obtained by the BREB method (Lima et al., 2005) by means of the Bowen ratio:

$$\beta = \frac{H}{LE} = \gamma \frac{\Delta T}{\Delta e} \qquad (2)$$

where ΔT and Δe are the temperature and vapor pressure difference between the two measurement levels; γ is the psychometric constant (0,066 kPa $^{o}C^{-1}$).

In Equation (2), it is assumed that eddy diffusivities of heat and water vapor are equal, and that ΔT and Δe are measured over the same height intervals. The Bowen ratio (β) is calculated from the differences in air temperature and vapor pressure measured at two heights above the crop canopy.

Using Equations (1) and (2), it is possible to calculate the latent and sensible heat flux as:

$$LE = \frac{(Rn - G)}{1 + \beta} \qquad (3)$$

$$H = \frac{\beta}{1 + \beta}(Rn - G) \qquad (4)$$

LE was related to ET by:

$$ET\_EB = \frac{LE}{L} \qquad (5)$$

where ET_EB is actual evapotranspiration (mm day^{-1}) obtained by BERB method, L is the heat of water vaporization, considered as constant (2,45 MJ kg^{-1}). The calculation of ET_EB at a daily time scale was obtained by summation of every 1800 s values for 24 h periods.

The convention used for the signs of the energy fluxes is Rn positive downward and G positive when it is conducted downward from the surface. Sensible and latent heat fluxes are positive upward, with a direction opposite to that of the gradients.

Soil water balance method

Soil water balance is an indirect method for estimating evapotranspiration and it is based on the principle of conservation of mass (Lima et al., 2006):

$$\Delta S = P + I + Cr - D \pm R - ET\_WB \qquad (6)$$

where P is the rainfall (mm), I is the irrigation (mm), Cr is capillary rise (mm), D is the deep drainage (mm), R is surface runoff (mm), ET_WB is the actual evapotranspiration (mm), and ΔS is the change in soil water storage (mm) and can be calculated as:

$$\Delta S = S_{t2} - S_{t1} \qquad (7)$$

with S_{t2} and S_{t1} are the soil water storage at the final and initial time, respectively.

Considering that the soil water content was obtained for constant soil layers from the surface (z = 0) down to the bottom of the measured soil depth (z = L), the storage soil moisture (S) was determined as:

$$S_L = \int_0^L \theta(z)\,dz = \left[0,50\theta(z_0) + \sum_{i=1}^{n-1}\theta(z_i) + 0,50\theta(z_n)\right]\Delta z \qquad (8)$$

where θ is the mean soil layer moisture, in $m^3\ m^{-3}$ and Δz the thickness of soil layer, in m.

In this study, the surface runoff (R) and irrigation (I) were neglected as the experimental site was flat and no irrigation was performed.

The flux (q) of water crossing the bottom of the soil layer (deep drainage, D, or capillary rise, Cr) was obtained as follows:

$$q = -K(\theta)\nabla\psi_t \qquad (9)$$

where K(θ) is the soil hydraulic conductivity, $\nabla\psi_t$ the vertical gradient of hydraulic potential, ψ_t the total soil water potential obtained by the tensiometric measurements and z is the soil depth.

The van Genuchten (1980) parametric functions were used to obtain soil water retention function as:

$$\theta(\psi_m) = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1+(\alpha\psi_m)^n\right]^m} \qquad (10)$$

where θ_r and θ_s are residual and saturation soil water contents, respectively in $m^3\ m^{-3}$, ψ_m the soil matrix potential in cm of water, α, n and m are empirical constants. The constant "m" was obtained according to Burdine (1953):

$$m = 1 - \frac{2}{n} \qquad (11)$$

The parameters of the water retention curves were obtained by fitting Eq. 10 to experimental field and laboratory data. In order to simplify the fitting procedure θr was set to 0 according to the method described by Antonino et al. (2005).

The hydraulic conductivity of unsaturated soil, K (θ), was determined as:

$$K(\theta) = K_s S_e^2\left[1-\left(1-S_e^{1/m}\right)^m\right] \qquad (12)$$

where K_S is the saturated soil hydraulic conductivity, S_e is the effective soil water content, obtained as:

$$S_e = \frac{(\theta-\theta_r)}{(\theta_s-\theta_r)} \qquad (13)$$

An analytical equation for the three-dimensional transitory infiltration was used to obtain the saturated hydraulic conductivity, K_s [LT^{-1}] of an unsaturated soil (Haverkamp et al., 1994). The expression of the cumulative infiltration for large-times is given by (Haverkamp et al., 1994):

$$I(t) = \left[K_s + \frac{\gamma_o S^2}{r_d(\theta_{fin}-\theta_{init})}\right]t + \frac{S^2}{2(K_s-K_0)(1-\beta_o)}\ln\left[\frac{1}{\beta_o}\right] \qquad (14)$$

and the steady-state infiltration rate q_∞ [$L\ T^{-1}$]:

$$q_\infty = K_s + \frac{\gamma_o S^2}{r_d(\theta_{fin}-\theta_{init})}t \qquad (15)$$

where rd is the radius of the cylinder [L], S is the soil sorptivity, K_0 is the corresponding hydraulic conductivity at the volumetric water content initial [$L\ T^{-1}$] θ_{init} [$L^3\ L^{-3}$], Ks is the corresponding saturated hydraulic conductivity at the volumetric water content final θ_{fin} [$L^3\ L^{-3}$], β_o is a constant ($0<\beta_o<1$) and mean value is 0,6 (Haverkamp et al., 1994), and γ_o is a proportionality constant ($0.6<\gamma_o<0.8$) to take into account for the gravity effect at the water profile edges and considering a mean value for $\gamma_o = 0.75$.

Table 1 shows the parameters of the van Genuchten-Burdine model for the water retention and saturated hydraulic conductivity characteristics.

Table 1. Parameter values of the soil water retention θ(h) and K_S, van Genuchten (1980) and Burdine (1953) equations, for the field site at Areia-PB, Brazil

Depth m	θ_s $m^3\ m^{-3}$	α cm^{-1}	n	K_s mm day^{-1}
0.40	0.4653	0.8238	2.0932	468.10
0.60	0.4588	0.2282	2.1150	527.89
0.80	0.4574	1.0914	2.0778	481.24

The soil water balance Equation (6) can be simplified as:

$$ET\_WB = P + Cr - D - \Delta S \qquad (16)$$

Evapotranspiration can be calculated from Equation (16) once rainfall, soil water flux and soil moisture are known.

Results and Discussion

Canopy height and ground cover data, as a function of days after sowing (DAS), are shown in the Figure 1. The mean canopy height was of 9.2 ±1.03 cm at 12 DAS, and reached 14.4 ±1.18 cm, with a mean rate of growth of 0.75 cm day^{-1} at 19 DAS. At 33 DAS the canopy height was at 23.2 ±2.37

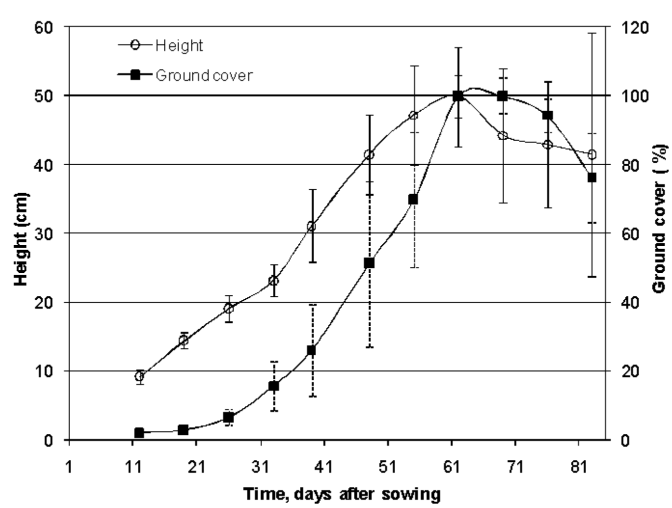

Figure 1. Seasonal trend of canopy height and ground cover for cowpea during the period from 12 to 81 days after sowing - DAS (24/03 to 02/06/2003) at Areia, PB. Error bars represent standard deviation

cm, with a mean rate of growth of 0.58 cm day^{-1}. The average canopy height at 55 DAS reached 47.2 ±7.22 cm, with an average growth rate of 1.01 cm day^{-1}, while the maximum height of the canopy was attained at 62 DAS, with a mean value of 49.9 ±7.28 cm. Afterwards, as the crop reached physiologic maturity and senescence approached, a decline in canopy height occurred.

The evolution of ground cover was concomitant to the canopy height evolution as expected since the largest growth occur with a larger ground cover. Maximum ground cover happened at 62 DAS, when the canopy was at its highest stage. Similarly, the decline of ground cover occurred in the same way as physiologic maturity and senescence approach.

Figure 2 shows the daily rainfall for the period of March 11 to May 30, 2003 with a total amount of 341.4 mm rainfall. The rainfall distribution is homogeneous for the whole period, except for 74 to 84 days after sowing (DAS) when no rainfall occurred. During the 84 days of the study, 40 days had no rainfall; 33 days had 10 mm rainfall and 11 days with higher rainfall including a heavy storm with 34.4 mm at 42 DAS.

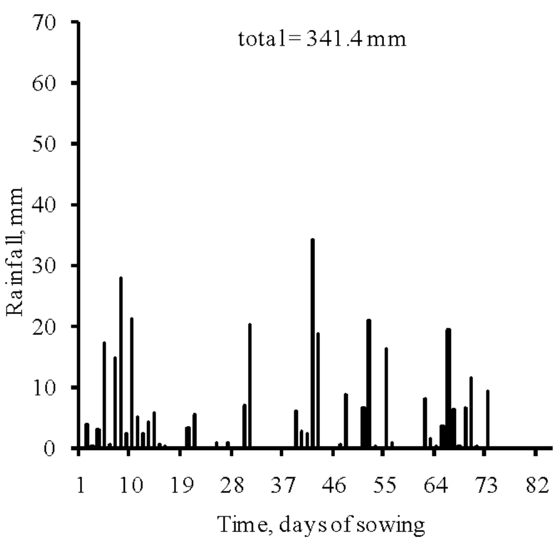

Figure 2. The daily rainfall measured at Areia-PB, Brazil in the period from 01 to 81 days after sowing - DAS (March 11 to May 30, 2003)

The daily variation of the ratio of net (Rn) to global radiation (Rg), together with ratios of latent heat flux (LE), sensible heat flux (H) and soil heat flux (G) to net radiation, over cowpea crop growing during the period of March 11 to May 30, 2003 are shown in Figure 3.

The proportion of net radiation in relation to the global radiation (Rn/Rg) presented a regular distribution with a mean value of 0.76 ± 0.04. The maximum value of 0.85 occurred at 7 and 13 DAS, while minimum values (0.70-0.73) were observed at 26 to 29 DAS and 34 to 38 DAS.

The results displayed in Figure 3 show that the largest portion of the Rn was used as LE, with a mean value of 0.73 ± 0.10. The lowest values of LE/Rn (0.50-0.66) were found while the soil was still bare and at 16 to the 19 DAS (0.54-0.58) (Figure 1), when soil water content was low, as it corresponded to a less rainy period (Figure 2). The mean value of H/Rn ratio was 0.18 ± 0.07, with maximum values ranging from 0.25 to 0.40 in the initial stage of crop development and at 16 to 20 DAS, during the less rainy period. The H/Rn ratio remained stable (0.18) from 40 to the 79 DAS, presumably because of the higher ground cover in these phases and finally increased during the senescence phase because of the low ground cover (Figure 1). The mean G/Rn ratio value was 0.09 ± 0.04, with maximum values of 0.14 to 0.18 occurring in the initial stage, when the ground cover was still low, and in periods when soil water content was small (Figure 2).

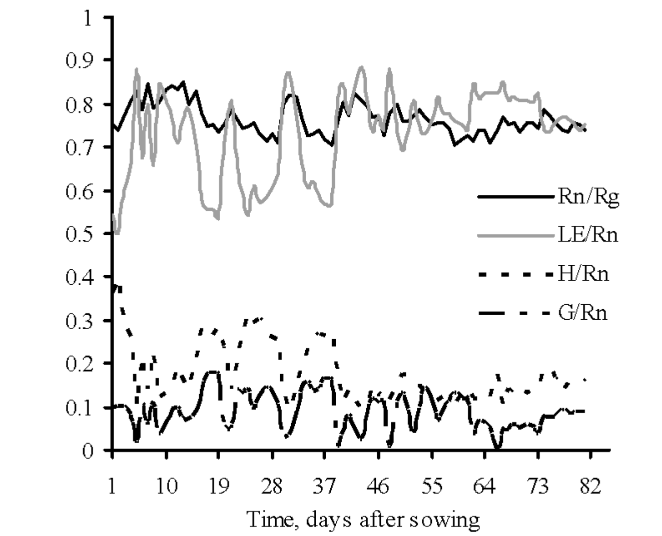

Figure 3. Daily change of the ratios between net radiation (Rn) and global radiation (Rg) and between the latent heat (LE), sensible heat (H) and soil heat (G) fluxes and net radiation (Rn) in cowpea, during the period from 01 to 81 days after sowing - DAS (11/03/2003 to 30/05/2003), in the municipality of Areia-PB, Brazil

In Venezuela, San José et al. (2003) studied the simultaneous mass and energy transfer over two contrasting cowpeas (*Vigna unguiculata* (L.) Walp cvs. TC-9-6 and M-28-6-6), and they found a mean value of 0.72 for latent heat flux to net radiation ratio (LE/Rn). Lima et al. (2005), under the same conditions of this research, found an average value of 0.71 for LE/Rn, while Lima et al. (2011) found a mean value of 0.65, due to occurance of low rainfall.

The daily variation of the energy balance components and of the global radiation over cowpea crop growing during the period from March 11 to May 30, 2003 are displayed in Figure 4. It can be seen that the variations of the latent heat flux (LE) follow net radiation (Rn), which follows the variations of the global radiation (Rg).

The maximum and minimum values of Rg were, respectively, 24.59 and 4.66 MJ m^{-2} per day, with a mean value of 17.10 ±4.49 MJ m^{-2} day$^{-1.}$ The maximum, minimum and average values of Rn were 18.90, 3.88 and 12.84 ± 3.33 MJ m^{-2} day^{-1}, whereas the values of LE were 13.40, 3.34 and 9.32 ± 2.07 MJ m^{-2} day^{-1}. In the Venezuelan Savanna conditions, San José et al. (2003), found very similar values for a cultivar of cowpea (TC-9-6), namely average values of RN and LE of 12.00 and 8.45 MJ m^{-2} day^{-1}, respectively.

The maximum, minimum and mean values of sensible heat flux (H) were respectively 6.76, 0.61 and 2.47 ±1.38 MJ m^{-2} day^{-1}. The maximal values (5.53-6.76 MJ m^{-2} day^{-1}) were found at the initial stage, in 1-3 days after sowing, as well

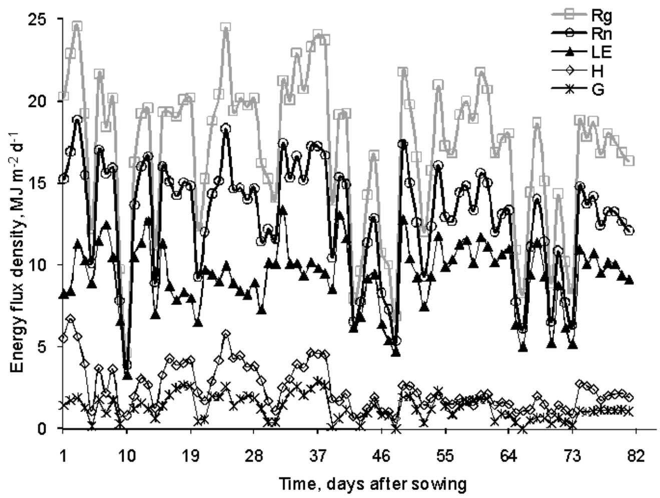

Figure 4. The time course of global radiation (Rg), net radiation (Rn), latent heat flux (LE), sensible heat flux (H) and soil heat flux (G), over cowpea crop growing during the period from 01 to 81 days after sowing - DAS (11/03/2003 to 30/05/2003), in the municipality of Areia-PB, Brazil

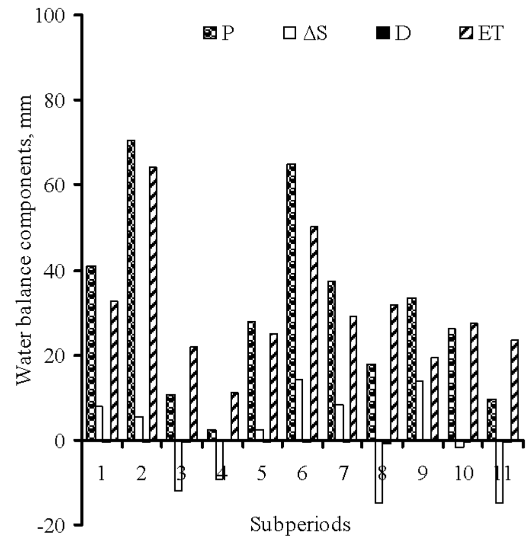

Figure 5. Water balance components during the period of 11/03/2003 to 30/05/2003 in a soil cultivated with cowpea, at Areia-PB, Brazil

as at 23-26 DAS (4.20-5.81 MJ m^{-2} day^{-1}). The sensible heat flux decreased afterwards as the cowpea reached its maximal growth and ground cover at 37-40 DAS (Figure 1), and thus most of the Rn is used for the transpiration.

The evolution of soil heat flux (G) was similar to the development of sensible heat flux (H), with the highest values found during the initial phase, followed by a decrease corresponding to the extension the ground cover. The maximum and minimum values were of 2.89 and 0.01 MJ m^{-2} day^{-1}, respectively, with a mean value of 1.29 ± 0.74 MJ m^{-2} day^{-1}. As a comparison San José et al. (2003), found average values of 3.24 and 0.31 MJ m^{-2} day^{-1} for H and G, respectively, for cowpea cultivated in the Savanna of Venezuela.

Water balance components, in the layer 0-0.60 m, were studied during 80 days divided in 11 subperiods. As there were some gaps in the measurements of soil water content and head potential, the duration of the subperiods were not equal, namely 8 subperiods were composed of 7 days, 1 was composed of 5 days, 1 of 9 days, and 1 had 10 days.

Figure 5 presents the water balance components for the period under consideration.

It can be seen that rainfall (P) had the highest values recorded for the subperiods 1, 2 and 6 with 40.8; 70.44 and 65.00 mm, respectively, and a total rainfall of 341.4 mm during this period. Soil water storage changes (ΔS) presented the highest positive values during the subperiods 1, 6, 7 and 9, with 7.73, 14.38, 8.25 and 13.90 mm, and the lowest during the subperiods 3, 4, 8 and 11, with negative values for ΔS, of -12.18; -9.05; -15.00 and -14.77 mm, respectively. In general the soil water storage changes followed the variations in rainfall.

Actual evapotranspiration (ET) showed high values during the subperiods of higher rainfall. Despite the intense rainfall events, the combination of lower temperature of the air, higher relative humidity (Calvache et al., 1998), but also higher water availability during this period, contributes to evaporation of the superficial soil layers and larger transpiration.

The sum of evapotranspiration during the period from March 11 to May 30, 2003, was 336.4 mm representing a mean value of 4.20 mm day^{-1}. Lima et al. (2006), using soil the water balance method, found mean values of ET for cowpea of 4.12 mm day^{-1} in the humid zone of Paraíba State, Brazil. In the conditions of Piauí State, Brazil, Bastos et al. (2008) determined ET of cowpea by soil water balance method, using weighing lysimeter, and showed that the mean ET was 4.10 mm day^{-1}.

Concerning the water crossing the lower part of the soil profile it has been verified that no capillary rise occurred, but only deep drainage. The computation showed that the values were small, with a total value of -5.49 mm (Figure 4). Lima et al. (2006) in the same conditions of soil and crop of this research found values of deep drainage of -17.23 mm.

Very high values of deep drainage were expected in this soil (Yellow Latosol), which is characterized by a high infiltration capacity, mainly for the subperiods 2 and 6, as in these sub periods high values of rainfall were monitored (70.4 and 65.0 mm, respectively).

It is reasonable to suppose that during these subperiods of high rainfall, the deep drainage was underestimated because of the gaps in the measurements of soil water content and hydraulic potential, with a direct consequence of overestimation of the evapotranspiration.

According to Reichardt et al. (1974) the major difficulty in the water balance calculation is in the estimation of drainage through the Darcy-Buckingham equation, as it is sensitive to errors made in the estimation of soil water hydraulic gradients and mainly in the choice of the value of the soil hydraulic conductivity. Besides these factors, there is still the problem of spatial variability of water balance components (soil water storage, hydraulic conductivity, total potential gradients).

In the comparison between methods for estimating ET, the values of evapotranspiration obtained by the Bowen ratio energy balance method can be considered as a reference standard, as this method presents an accuracy of 90% when compared with the measurements obtained in lysimeters (Pruegger et al., 1997).

Figure 6 shows the results for the computation of evapotranspiration of cowpea with water balance (ET_WB) and Bowen ratio energy balance (ET_EB) methods during the period from March 11 to May 30, 2003. It can be seen that for most of the subperiods the values of ET_WB and ET_EB were similar. However, in the subperiod 2 the values of ET_WB were much higher than ET_EB, whereas in the subperiods 4 and 11 they were lower.

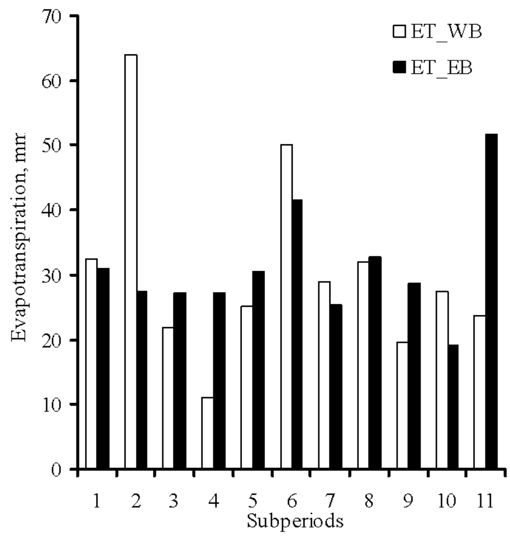

Figure 6. Evapotranspiration measured by Bowen ratio energy balance (ET_BE) and water balance (ET_WB) methods during the period of March 11 to May 30, 2003, at Areia-PB, Brazil

ET_WB was much higher than ET_EB during the subperiods with high rainfall (subperiod 2), showing that water balance method causes an overestimation of evapotranspiration during the rainy period, due, probably, as mentioned previously, to an underestimation of deep drainage (Figure 5).

The total value of evapotranspiration estimated by the soil water balance method (ET_WB) was 336.4 mm, whereas by Bowen ratio energy balance method (ET_EB) it was 342.4 mm, with a difference between them of 6.0 mm. The mean values of ET_WB and ET_EB were 4.20 and 4.28 mm day^{-1}, respectively.

Azevedo et al. (2003) studied the energy and water balance components of an irrigated mango orchard in Petrolina-PE, a semi-arid region of northeast Brazil, finding a total and mean values of evapotranspiration of 555.1 mm and 4.4 mm day^{-1}, respectively, with the water balance method whereas by the Bowen ratio energy balance method, they found 551.6 mm and 4.4 mm day^{-1}, respectively.

Results obtained in Figure 6 indicate that the water balance method was able to measure the cowpea evapotranspiration. However more accurate estimates of the components of the term deep drainage are necessary, in other words, of the gradients of total potential and of the hydraulic conductivity of the soil, mainly for the rainiest periods.

Conclusions

1. During the period from 11th March to 30th May, 2003, 76% of the global radiation was transformed into net radiation. Net radiation was used, on average, 73% in latent heat flux, 18% in the sensible heat flux and 9% in the soil heat flux.

2. As the vegetation cover increased, regardless of the soil moisture conditions, there was an increased use of net radiation and latent heat flux, i.e. a greater amount of energy was used for the process of evapotranspiration.

3. Regarding the components of water balance, it was found that the computation for the deep drainage was underestimated, considering the small amount that has been found in periods of higher water availability.

4. Except for the rainy season, this study showed a good agreement between Bowen ratio energy balance and water balance methods, to compute the values of crop evapotranspiration. The mean value of ET obtained by the water balance method was 4.20 mm day^{-1}, and 4.28 mm day^{-1} by Bowen ratio energy balance method.

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