



WATER BALANCE ESTIMATE OF BEANS USING A DYNAMIC SYSTEMS MODEL BASED ON CROP COEFFICIENT (Kc) VARIATION

Alisson Lopes Rodrigues¹ , Pedro Manuel Villa*²  & Lineu Neiva Rodrigues³ 

1 - Federal University of Viçosa, Department of Agricultural Engineering, Viçosa, Minas Gerais, Brazil

2 - Federal University of Viçosa, Department of Forestry Engineering, Viçosa, Minas Gerais, Brazil

3 - Brazilian Agricultural Research Agency (EMBRAPA – Cerrados), Planaltina, DF, Brazil

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ABSTRACT

The crop coefficient (Kc) is one of the most important parameters for studying the water balance, which aims to assess the relationship between growth and production dynamics and the management of water resources in irrigation systems. Thus, in this study, the effect of Kc variation on the water balance was evaluated throughout the bean crop cycle in Northeast Brazil, using a dynamic systems model. The effect of Kc variation scenarios on the water balance in the bean crop in Northeastern Brazil was simulated using the Vensim program. The soil water storage was used as state variable, input flow variable and outflow of water in the soil, and auxiliary variables that influence system flows were also considered. Thus, four simulation scenarios were performed changing values of the bean crop coefficient (Kc = 0.62; Kc = 0.72; Kc = 0.82; Kc = 0.92). The variation in soil water storage showed negative values in most phenological phases, showing significant differences between Kc conditions, depending mainly on the precipitation dynamics.

Palavras-chave:

Phaseolus vulgaris
Déficit hídrico
Evapotranspiração
Fluxos de água
Modelo hidrológico

ESTIMATIVA DO BALANÇO HÍDRICO DO FEIJÃO BASEADO EM MODELO DE SISTEMAS DINÂMICOS EM FUNÇÃO DA VARIAÇÃO DO COEFICIENTE DA CULTURA (Kc)

RESUMO

O coeficiente da cultura (Kc) é um dos parâmetros mais importantes para o estudo do balanço hídrico das culturas agrícolas, que tem como finalidade avaliar a relação da dinâmica de crescimento e produção com o manejo de recursos hídricos em sistemas de irrigação. Assim, neste trabalho avaliou-se o efeito da variação do Kc sobre o balanço hídrico ao longo do ciclo da cultura do feijão do Nordeste do Brasil, por meio de um modelo de sistemas dinâmicos. Para simular o efeito de cenários de variação do Kc sobre o balanço hídrico na cultura do feijão no Nordeste do Brasil, utilizou-se o programa Vensim usando como variável de estado o armazenamento de água no solo, variáveis de fluxo de entrada e saída de água no solo, e variáveis auxiliares que influem nos fluxos do sistema. Assim quatro cenários de simulações foram realizados alterando valores do coeficiente da cultura do feijão (Kc = 0,62; Kc = 0,72; Kc = 0,82; Kc = 0,92). A variação no armazenamento de água no solo apresentou valores negativos na maior parte das fases fenológicas da cultura, mostrando diferenças significativas entre condições de Kc, dependendo principalmente da dinâmica da precipitação.

INTRODUCTION

The soil water storage is one of the most important components for the study of the water balance of agricultural crops. This water storage allows to assess the dynamics of growth and production; as well as the planning and management of irrigation systems (NOVAK; HAVRILA, 2006; JERSZURKI *et al.*, 2018). The water balance includes all the processes of entry, storage in the soil, and outflow of water in the soil-plant-atmosphere system; beyond being one of the main methods for determining evapotranspiration (LIBARDI, 2005; SOUZA *et al.*, 2015). However, in many agricultural systems in the world, especially in tropical regions, there are many technical limitations to adjust the use of water resources according to the demands of the crops and the variability of the climate (GÉRARDEAUX *et al.*, 2016; TORQUEBIAU *et al.*, 2016). However, valuable tools for studying and understanding dynamic systems, such as water balance modeling, are available and can be used to calibrate and adjust the availability of water in agricultural systems (KHAN *et al.*, 2009; and LUO *et al.*, 2009; XI; POH, 2013).

Most models for simulating the water balance of agricultural crops have focused on analyzing the main flows of entering and leaving water in the systems, such as precipitation, evapotranspiration, runoff (LIBARDI, 2005; JERSZURKI *et al.*, 2018). However, studies that evaluate the effects of the variation of parameters that influence these flows, and consequently on the storage of soil water, are limited. For instance, the evapotranspiration of a crop will be different from the reference crop (ET_o), as its soil coverage characteristics, vegetation properties and aerodynamic resistance differ (ALLEN *et al.*, 1998; NOVAK; HAVRILA, 2006).

The models of hydrological simulation to estimate the water balance in agricultural cultures generally have been based on constant values of K_c throughout the different phenological phases of the crops (ALLEN *et al.*, 1998). Irrigation must be planned according to the water conditions of the soil and the water consumption by the plant throughout its development in order to calculate

the water demand necessary to guarantee the growth and productivity of agricultural crops (LIBARDI, 2005; JERSZURKI *et al.*, 2018). Thus, the calculation of evapotranspiration and soil water storage is based on climatic conditions. However, it also depends on the method of estimating the crop coefficient (K_c), which can determine the level of precision of the calculation (ALLEN *et al.*, 1998).

An alternative to explain the relevance of K_c on the water balance, can be simulating different conditions of K_c with probable values estimated in the field, consequently expecting a variation in soil water storage. This simulation is important to understand the K_c sensitivity when it remains constant throughout the phenology of each crop. In this context, beans (*Phaseolus vulgaris*) can be cited as one of the most important crops in Brazil, especially in the Northeast, where there is a strong limitation of water resources (GUIMARÃES *et al.*, 2016). The bean crop is an agricultural product extremely appreciated by Brazilians, is considered staple food and one of the main sources of protein in the population's diet (CUNHA *et al.*, 2013). However, beans are classified as sensitive plants, both to water deficiency and to water excess in the soil. Therefore, the requirement for water by the crop varies with its stage of development (NÓBREGA *et al.*, 2001).

Studies on the analysis of dynamic systems to assess water balance in different cultures in the region (eg, simulation models), as an alternative for management and conservation of water resource, are still limited. Thus, the aim of this study was to evaluate the effect of the K_c variation on the water balance throughout the bean crop cycle in Northeast Brazil, using a dynamic systems model. Therefore, researching the dynamics of the water balance of this important crop is necessary to improve the water resource management.

MATERIAL AND METHODS

The estimation of the water balance was based on data from 12 climatological stations (INMET, 2020, Figure 1) considering only the regions where the model's input data were obtained (Table 1). Thus, the values of the different input, auxiliary, and output variables of the water balance dynamic

model (Figure 2) related to environmental variables were obtained from the results of research performed in the northeastern region of Brazil (ANTONINO *et al.*, 2000; LIMA *et al.*, 2006; CUNHA *et al.*, 2013; SOUZA *et al.*, 2015). The phenological stages of the bean crop were defined for a cycle of 92 days after sowing in the July-October period (RIBEIRO; PELOSO, 2009; CUNHA *et al.*, 2013).

The effect of Kc variation scenarios on the water balance in the bean crop in Northeastern Brazil was simulated using the Vensim program, version 3.0. The dynamic system model was adapted from the approach proposed by Khan *et al.* (2009) and Luo *et al.* (2009). This model presents three types of variables: state variable is the soil water storage (A), flow variable is represented by differential equations (P, E, C, Q), and auxiliary variables are those that influence system flows (Figure 2). Thus, four simulation scenarios were performed changing values of the bean crop coefficient (Kc = 0.62; Kc = 0.72; Kc = 0.82; Kc = 0.92). The optimization of the known values of the input variables was performed to generate the corresponding results in the state variables (A). Validation was performed to verify that the provided results coincide with those that were actually measured. Considering the effective root zone (0-20 cm deep) as a single layer, the soil water balance at the field level can be expressed in terms of storage, according to Equation 1, according to Allen *et al.* (1998) and Libardi (2005):

$$\Delta A_i = P_i + C_i - ET - Q_i - ES_i \quad (1)$$

Where: ΔA_i corresponds to the variation of soil water storage on day i, P_i is precipitation; C_i is the capillarity from the water available in the depth of the soil; ET is evapotranspiration; Q_i is percolation; e ES is surface runoff. Irrigation input was not considered, as soon as the water inputs came exclusively from precipitation. In unsaturated conditions, the actual evapotranspiration (ET) is calculated using Equation 2:

$$ET = Kc * Ks * ET_o \quad (2)$$

Where: Ks is a dimensionless factor that

expresses the effects of limiting soil moisture conditions on crop evapotranspiration; and Kc is the crop coefficient (ALLEN *et al.*, 1998). Crop coefficients (Kc) were determined according to Allen *et al.* (1998), through the possession of the values of evapotranspiration of the crop (ETc) without water restriction and reference evapotranspiration (ETo). Therefore, the soil moisture coefficient used in Equation 3 is calculated by:

$$Ks = \int_{TAW-RAW}^{TAW-D} \frac{D \leq RAW \text{ ou } RAW \leq D \leq TAW}{TAW-RAW} \quad (3)$$

Where: D is the depletion of the root zone; RAW is soil water readily available in the root zone; TAW is the total available water from the soil in the root zone (NOVAK; HAVRILA, 2006). According to the dynamic model (Figure 2), the Equation 4 was considered:

$$Ks = \int_{\theta_{\text{threshold}} - \theta_{\text{wp}}}^{\theta_{\text{limit}} - \theta_{\text{wp}}} \theta \geq \theta_{\text{limit}} \text{ or } \theta_{\text{wp}} \leq \theta \leq \theta_{\text{limit}} \quad (4)$$

Where: θ is the volumetric water content; θ_{wp} is the water content at the fluctuation point; and the θ_{limit} is the limit point of water content when water stress occurs. Thus, the water content limit was calculated according to Equation 5:

$$\theta_{\text{limit}} = (1 - p) * \theta_{fc} + p * \theta_{wp} \quad (5)$$

Where: p is the fraction of total available water that a crop can extract from the root zone, and θ_{fc} is the water content in the field capacity.

Under unsaturated conditions, the well-established soil water retention empirical function proposed by Brooks and Corey (1964) is used (Equation 6):

$$h(\theta) = \frac{hb}{\left[\frac{\theta - \theta_r}{\theta_s - \theta_r} \right]^{1/\lambda}} \quad (6)$$

Where: h (θ) is the main negative pressure; hb is the main air inlet pressure; θ is the volumetric water content of the soil; θ_r is the residual water content; θ_s water content at saturation; and λ is the soil pore size index (LUO *et al.*, 2009).

Unsaturated hydraulic conductivity is calculated by Equation 7:

$$K(\theta) = K * e^{-\frac{\alpha}{h(\theta)}} \quad (7)$$

Where: K is the saturated vertical hydraulic conductivity; and α is the texture-specific empirical constant, which is 1.0 for clay soil (TINDALL *et al.*, 1999). Soil with higher clay content has greater cohesion between soil particles, and for greater agricultural productivity the soil must have a porosity close to $0.50 \text{ m}^3 \text{ m}^{-3}$ and a percentage distribution of 34% for macropores and 66% for micropores (KIEHL, 1979; SÁ; SANTOS JÚNIOR, 2005).

Thus, Darcy's Law was used to calculate the percolation of water from soil to groundwater (KHAN *et al.*, 2009), as indicated in Equation 8:

$$Q = \frac{(h(\theta) - h) * K(\theta)}{T} \quad (8)$$

Where: h is the groundwater head; and T is the thickness of the soil between the rooting zone and the underground layer (LUO *et al.*, 2009).

The upward capillary flows of groundwater are normally assessed using empirical formulas that involve some parameters related to the soil and

consider the depth of the water table below the root zone (LUO *et al.*, 2009).

The capillary increase is assessed using the following exponential relationship (LI; DONG, 1998); according to Equation 9:

$$C = ET * e^{-\sigma * d} \quad (9)$$

Where: C is the capillary increase; ET is the crop evapotranspiration; σ is a parameter that relates to the soil's ability to transmit capillary flows; and d is the depth of the water table below the zone of the considered root system (LUO *et al.*, 2009). Assuming that throughout the crop growing season there was no standing water, when the soil becomes saturated after precipitation, the redundant water is discharged as surface runoff (LUO *et al.*, 2009). The surface runoff of the field is given in Equation 10:

$$Es = \begin{cases} 0 & \theta \leq \theta_s \\ \Delta A - (\theta_s * Dr) & \theta \geq \theta_s \end{cases} \quad (10)$$

Where: θ_s is the saturated water content; θ the volumetric water content of the soil; Dr is the depth of the root and ΔA corresponds to the soil water storage (LUO *et al.*, 2009).

The soil water potential is calculated by Equation 11, derived from the van Genuchten model (VAN GENUCHTEN, 1980).

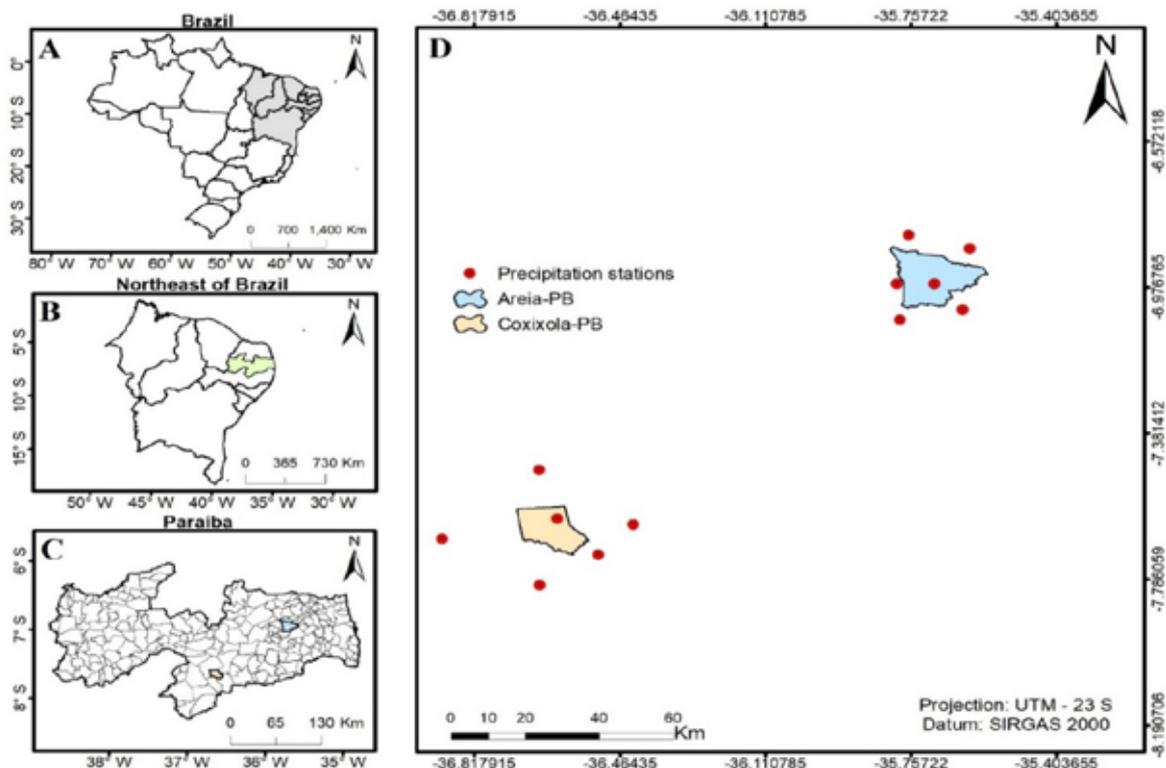


Figure 1. Geographic location of 12 weather stations selected to obtain model input data

$$Ph = \frac{\left[\frac{[\theta_s - \theta_r]^{1/m} - 1}{\theta - \theta_r} \right]^{1/n}}{a} \quad (11)$$

Where: Ph is the soil water potential in Kpa; a, m, and n are dimensionless coefficients; and the others are the same parameters indicated above.

Finally, the Shapiro-Wilk test was performed to assess the normality of water storage in the decoy as a state variable. Then, the Kruskal-Wallis test followed by a post hoc Dunn test for data not normally distributed were used to compare the

variation of soil water storage between different Kc conditions established as simulation scenarios (Kc = 0.62; Kc = 0.72; Kc = 0.82; Kc = 0.92). These statistical analyses were performed using the car and dunn.test packages (DINNO, 2017) in the R software (R DEVELOPMENT CORE TEAM, 2018).

The values of the variation of soil water storage (ΔA), precipitation (Pp), and evapotranspiration (ETc), surface runoff (ES) are presented. Q is the flow of water in the soil, where negative values indicate drainage and negative values of ascension by capillary.

Table 1. Water balance of the Northeast region corresponding to the reference study areas selected to obtain input data from the model

Month	ΔA	Pp	ES	ETc	Q
January	33,92	62,23	14,86	24,84	11,39
February	-17,80	31,49	4,80	16,52	-27,97
March	-0,66	29,23	3,27	17,50	-9,12
April	32,17	78,74	23,67	34,52	11,62
May	-14,28	100,08	16,89	38,60	-58,87
June	-15,92	13,97	0,52	21,50	-7,88
July	2,13	54,11	13,77	24,98	-13,23
August	-8,77	4,57	0,46	12,65	-0,23
September	-4,44	0,0	0,0	1,15	-3,29
October	2,02	8,38	0,0	4,70	-1,66
November	-2,89	3,56	0,0	4,36	-2,08
December	44,23	141,22	45,29	27,71	23,99
Total	49,71	527,58	123,53	229,03	-125,30

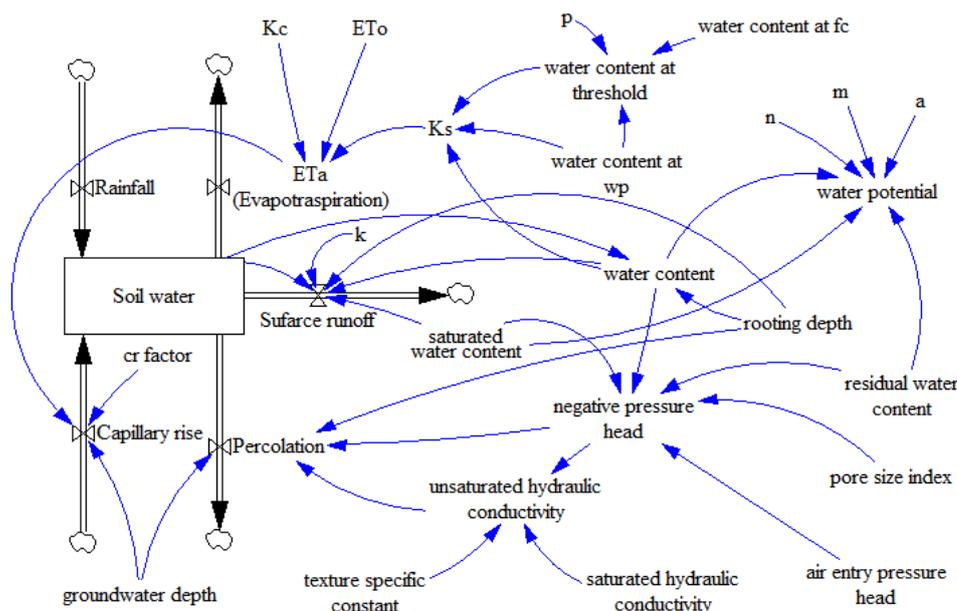


Figure 2. Model of dynamic systems for water balance. Adapted from Khan *et al.* (2009) and Luo *et al.* (2009)

RESULTS AND DISCUSSION

The soil water storage reduces over time, presenting negative values in most of the phenological phases of the crop (Figure 3A). The soil water storage showed marginally significant differences between Kc-62 and Kc-92 according to the Kruskal- Wallis test ($\chi^2 = 4.11$, $df = 3$, $p < 0.05$) (Figure 3B). These results show that there are variations in the soil water storage due to changes in Kc of the bean crop, even maintaining

different soil parameters and water parameters. Thus, some researchers have observed a high dependence on irrigation in the bean crop in the Northeast region due to the low precipitation in the region (ANTONINO *et al.*, 2000; LIMA *et al.*, 2006; CUNHA *et al.*, 2013). For instance, bean evapotranspiration has been higher in periods of greater water availability, with an average value of 4.12 mm d⁻¹, with the highest water consumption occurring in the reproductive phase (LIMA *et al.*, 2006).

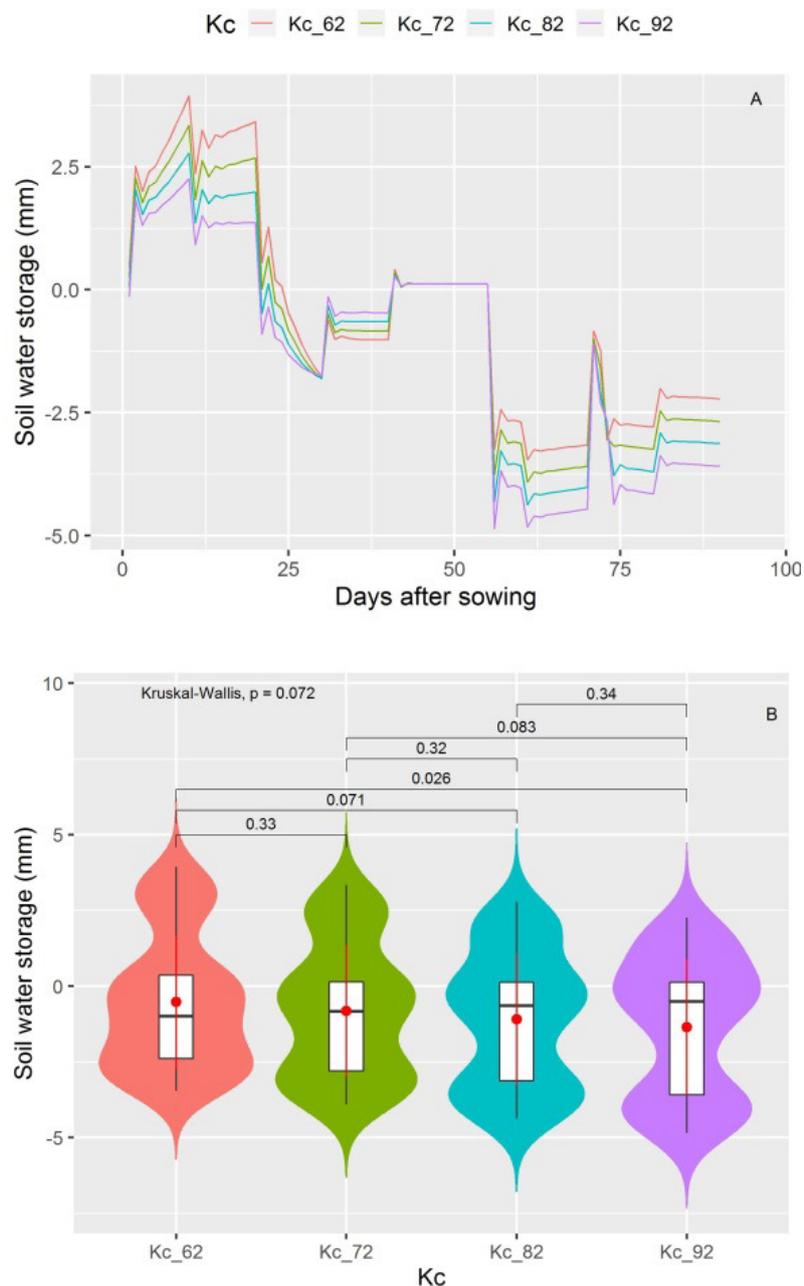


Figure 3. Soil water storage in the different treatments of variation of the crop coefficient (Kc) throughout the crop cycle (A), and differences in water storage between Kc treatments (B)

The simulations of the water balance in the bean crop, estimated from the four scenarios of variation of the crop coefficient ($K_c = 0.62$; $K_c = 0.72$; $K_c = 0.82$; $K_c = 0.92$), presented contrasting negatives values in the soil water storage capacity in most phenological phases (Table 2). In other studies in the Northeast region, it has also been observed that the variation of water storage in the soil follows variations from precipitation. Furthermore, soils without vegetation coverage or low coverage have large water losses (ANTONINO *et al.*, 2000; LIMA *et al.*, 2006), which can be corrected with planned irrigation, with frequency and hydraulic accounting (CUNHA *et al.*, 2013).

On the other hand, Souza *et al.* (2011), discuss how the type of crop management and monitoring of variations in soil water storage and flows within the dynamic system, allow estimating the components of the water balance, such as the effective evapotranspiration of the crop, and later, the cultivation coefficients. Thus, these researchers found higher K_c values in the condition of direct planting of peppers. This fact is associated with the absorption of water by the sorghum and crotalaria straw, making, initially, a larger irrigation blade necessary to increase the soil water content until the humidity corresponding to the field capacity.

The results of the research demonstrate the relevance of K_c in the estimates of the water balance in the bean crop, which could probably be influenced by the phenological changes of the crop and microclimate variations within the agricultural systems (SOUZA *et al.*, 2011, CUNHA *et al.*, 2013; JERSZURKI *et al.*, 2018). Therefore, we can highlight that the knowledge of the water balance

from a local scale to a planting scale can be decisive to increase efficiency in the productivity of crops in the Northeast region. This knowledge is important to adapt the use of water for irrigation and establish an adequate space-time zoning of crops according to their phenology. Thus, although the differences in water storage were not so contrasting, this study highlights the importance of analyzing K_c in the different stages of bean development, which can be decisive in real estimates of water balance. In addition, the study allowed us to exemplify that the use of dynamic systems models could be applied to estimate possible deficits in the water balance and assist in the exploration of soil parameters to improve the water resources management.

The actual values of precipitation (P_p), evapotranspiration (ET_c), surface runoff (ES) are presented. Phenological stages according to the days after sowing (DDS): V0: germination (5 DDS); V1: emergency (11 DDS); V2: cotyledonous leaves (17 DDS); V3: first fully expanded trefoil (26 DDS); V4: third expanded trefoil (42 DDS); R5: flower buds (48 DDS); R6: full bloom (55 DDS); R7: pods formation (66 DDS); R8: pods filling (86 DDS); R9: physiological maturity (92 DDS) are also presented. The effective precipitation was considered in the blades calculation.

In this context, several researchers highlight how the use of K_c in irrigated agriculture allows to determine the water demand for different growth conditions. However, the K_c variations throughout the crop production cycle are little explored (SOUZA *et al.*, 2011, CUNHA *et al.*, 2013). On the other hand, Carvalho *et al.* (2011) discuss the importance of K_c for the estimation of

Table 2. Effect of the crop coefficient (K_c) variation scenarios on the water balance flows and soil water storage (A)

EF (DDS)	Kc-62				Kc-72			Kc-82			Kc-92		
	Pp	ETc	ES	A	ETc	ES	A	ETc	ES	A	ETc	ES	A
V1 (0)	5,62	3,62	0	2	4,20	0	1,42	4,78	0	0,84	4,37	0	1,25
V2 (10)	55	18,6	32,7	3,9	21,6	30	3,4	24,6	27,6	2,8	27,6	25,1	2,3
V3 (20)	65	24,8	36,7	3,5	28,8	23,5	2,7	32,8	30,2	2	36,8	26,8	1,4
V4 (30)	32	17,3	16,4	-1,71	20,1	13,6	-1,7	22,9	10,8	-1,7	25,7	7,99	-1,69
R5 (40)	5	3,10	2,92	-1,02	3,60	2,24	-0,84	4,10	1,55	-0,65	4,60	0,87	-0,47
R6 (60)	8	3,10	7,59	-2,69	3,60	7,53	-3,13	4,10	7,48	-3,58	4,60	7,43	-4,03
R7 (70)	2	3,10	2,06	-3,16	3,60	1,99	-3,59	4,10	1,92	-4,02	4,60	1,86	-4,46
R8 (80)	2	3,10	1,69	-2,79	3,60	1,64	-3,24	4,10	1,60	-3,7	4,60	1,55	-4,15
R9 (90)	2	3,10	1,12	-2,22	3,60	1,08	-2,68	4,10	1,03	-3,13	4,60	1,99	-4,59

crop evapotranspiration (ETc), emphasizing that Kc estimation methods are fundamental for the calibration of these coefficients, which should be a priority in bean plantations in the Northeast region

Finally, in addition to calibrating the model with real Kc data throughout the crop development, it is necessary to explore different scenarios of climate change and their effects on flows within the system. The approach of dynamic models could be an alternative tool to simulate different scenarios of evapotranspiration of the bean crop with different types of planting, management and coverage.

CONCLUSION

- The variation of the crop coefficient is decisive in the water balance throughout the bean crop cycle, consequently affecting the soil water storage. The soil water storage decreases over time, showing significant differences between Kc conditions, depending mainly on the dynamics of precipitation. The simulations of the water balance in the bean crop in the Northeast of Brazil presented contrasting negative values in the soil water storage capacity in most of the phenological phases. Therefore, the study allowed to exemplify how the use of dynamic systems models could be applied to estimate possible deficits in the water balance and to assist the exploration of the crops parameters to improve the water resource management.

AUTHORSHIP CONTRIBUTION STATEMENT

RODRIGUES, A.L.; VILLA, P.M.: conception of the research, acquisition of data, analysis and interpretation of data, drafting and reviewing the work. RODRIGUES, L.N.: guidance, conception of the research and reviewing the work.

DECLARATION OF INTERESTS

The authors declare that they have no knowledge of a conflict of interest that could have appeared to influence the work reported in this paper.

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