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USO DO SOFTWARE AQUACROP PARA SIMULAR A RESPOSTA DO FEIJÃO À DIFERENTES REGIMES DE IRRIGAÇÃO

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1 RESUMO

Os softwares de simulação de crescimento e desenvolvimento das culturas no campo têm tido bastante aplicação, visto o objetivo de técnicos e pesquisadores em evitar perdas no campo e almejar melhorias a cada cultivo. O feijão é bastante cultivado e consumido no Brasil, o que atrai atenção para o ajuste do software *AquaCrop* à cultura nas condições edafoclimáticas brasileiras. O objetivo deste trabalho foi analisar a resposta do software *AquaCrop* quando ajustado para condições de ambiente e irrigação em que o feijoeiro foi cultivado. Observou-se dados simulados semelhantes e em concordância estatística com o observado, com maiores diferenças no acúmulo de biomassa e balanço hídrico ao longo do ciclo da cultura. A semelhança entre os dados simulados e observados na cobertura do dossel ao longo do ciclo da cultura traduzem uma boa resposta da equação utilizada para converter o índice de área foliar em cobertura do dossel para a cultura do feijão. Conclui-se com o estudo, que o software *AquaCrop* é confiável para a simulação do crescimento e desenvolvimento do feijão, pois os dados obtidos em campo são semelhantes aos simulados pelo modelo.

Palavras-chave: manejo, eficiência do uso da água, função de produção.

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USE OF AQUACROP SOFTWARE TO SIMULATE BEAN CROP RESPONSE TO DIFFERENT IRRIGATION REGIMES

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2 ABSTRACT

The simulation software's of crop growth and development in the field has had many applications, since the aim of technicians and research in avoiding losses on the field and to target for improvements in each crop. The crop bean is highly cultivated and consumed in Brazil, what draws attention to the adjustment ~~of~~ the AquaCrop software for this crop under Brazilian edaphoclimatic conditions. This study aimed to analyze the response of the AquaCrop when adjusted for irrigation and greenhouse conditions in which the crop bean was cultivated. It was observed simulated data were similar and in statistical accordance with the observance in the field, to higher differences in biomass accumulation and water balance throughout the crop cycle. The similarity between the simulated and observed data for canopy coverage throughout the crop cycle translates a good answer of the equation used to convert the leaf area index canopy coverage for crop bean. We concluded with this study, that AquaCrop software is reliably simulating the growth and development of the crop bean because the data obtained on the field are similar to those simulated by the model.

Keywords: management, water use efficiency, production function.

3 INTRODUCTION

Grain cultivation is traditional for Brazilian farmers, particularly beans, which are a staple of the population's diet. Brazil is the world's largest bean producer, with the states of Paraná and Minas Gerais accounting for approximately 36.7% of the country's bean production, according to the National Supply Company (Conab, 2020). The country is also one of the largest consumers and producers of this food (COÊLHO, 2018).

Beans, which are short-cycle crops of approximately 90 days, can be grown more than once a year if there are no limiting conditions. Beans are cultivated in virtually all regions of Brazil, allowing for up to three harvests per year (Conab, 2020).

The bean crop is sensitive to water stress and high temperatures and is nutrient demanding (SANT'ANA; SANTOS; SILVEIRA, 2011; SANTOS *et al*., 2015). It is quite vulnerable to changes in water availability, responding immediately to any water stress it may suffer. However, its greater tolerance to this type of stress stands out at the V3 and V4 stages, and from the R8 stage onward, water restriction becomes beneficial because at this stage, the pods already have full grains, beginning the maturation and drying period (SANTOS *et al*., 2015).

Red beans are widely consumed in the state of Minas Gerais and are widely cultivated by local producers. This cultivar is resistant to pathogens that cause anthracnose, angular leaf spot, and rust, has an indeterminate growth type, and has a semierect habit (SANTOS *et al*., 2015). According to Conab (2020), the national bean production in the country in the 2019/2020 harvest was 3.07 million tons, approximately 1.9% higher than the production observed in the previous harvest.

Climate variability and inadequate management have affected bean production in the main growing regions, particularly the increasingly severe scarcity of water resources (VIEIRA *et al*., 2020). This requires plants to increasingly produce higher yields with less water. Therefore, tools such as irrigation systems and their proper management have become important factors in increasing crop productivity (SOUZA *et al*., 2017).

Climatological variables directly affect crop development, and precipitation stands out as one of the limiting factors (VIEIRA *et al*., 2020) since the irregularity in rainfall distribution throughout the year restricts cultivation to the period of greatest water supply, making cultivation unfeasible at other times. Even though the crop has great climatic adaptability, it has critical periods in which the lack of water causes a significant reduction in yield, such as in the reproductive phase, which is a period that requires greater water demand (FERNANDES *et al*., 2015).

One alternative to assist in crop management and yield prediction is the use of productivity simulation models. Mathematical models are fundamental for studying plant responses to different conditions and involve the visualization of scenarios that can help researchers search for more resilient production strategies to ensure food security, develop effective crop planning and management, and assess the risk of yield losses in cases of nutritional stress or pest and disease attacks, among other conditions (HOLZWORTH *et al*., 2015). In this sense, testing and adaptations are necessary, as productivity variability depends largely on climatic conditions, which can be particularly affected by climate change (LECERF *et al*., 2019), different scenarios, and the genetic characteristics of the crop used (PICHENY *et al*., 2017; YIN, VAN DER LINDEN, STRUIK, 2018). Importantly, the calibration and validation ~~of~~ models that simulate crop productivity are essential for evaluating, with a certain margin of safety, their performance in different scenarios (HE *et al*., 2017).

AquaCrop is a widely used crop growth and productivity simulation software (RAES *et al*., 2012). It was developed by the *Food and Agriculture Organization (FAO) of the United Nations* and is a robust program that uses several parameters and coefficients to calculate crop management and represents the field as closely as possible to reality.

Numerous studies have been conducted using *AquaCrop* with agricultural management data for various crops in different countries. However, calibration and validation studies of the model for Brazilian soil and climate conditions, particularly for bean crops, are still scarce. Given the above, the objective of this study was to perform an initial adjustment of the *AquaCrop management software* for bean crops, analyze the coefficients obtained from this adjustment and compare the simulated crop performance with that observed in the field.

4 MATERIALS AND METHODS

The work was carried out between July and October at the Coimbra Experimental Station, MG, a dependency of the Federal University of Viçosa, located in the Zona da Mata of Minas Gerais, at coordinates 20° 45' S latitude and 42° 5' W longitude and at an altitude of 698 m.

The soil type was classified as Dystrophic Red–Yellow Argisol, terrace phase, with a clayey texture (ANDRADE *et al*., 2005). The field capacity moisture content per unit volume was 43.5%, the wilting point was 22.8%, and the hydraulic conductivity was 236.1 mm day $^{-1}$. In the simulations, the 0–20 cm and 20–40 cm soil layers were considered, as was the allowable RAW (Readily Available Water) depletion of 12 mm. The soil and water used did not present salinity problems since the soil electrical conductivity was 0.058 dS m $^{-1}$.

At sowing, fertilization management followed the recommendations of Chagas *et al.* (1999) and was carried out mechanically using 14 seeds per meter. Fertilization was carried out at planting with NPK 8--28--16 at a dosage of 348 kg ha^{-1}. Topdressing was performed with urea at a dosage of 200 kg ha^{-1}.

The growing season was typical of winter, transitioning into spring, with low temperatures during the germination/emergence and vegetative phases and relatively high temperatures during the flowering and maturation phases. This period was characterized by low rainfall in the region. Therefore, frequent irrigation was needed, with intervals varying from 2--3 days throughout the bean growing season.

Rainfall was also recorded during the winter period, but this was an isolated case, as rains occurred more frequently after the harvest period.

Tests were carried out at four different irrigation depths: L1 = 239 mm; L2 = 310 mm; L3 = 322 mm; and L4 = 386 mm. Irrigation was carried out via a conventional central pivot system with a tower, with the capacity to irrigate an area of 2 ha, with an application intensity of 2 mm h^{-1} and without the observation of surface runoff.

Irrigation management was initiated on the basis of plant development. Water depths were differentiated from the end of the bean vegetative development stage.

The beans were grown via a no-till system. Irrigation was carried out by calculating crop evapotranspiration and applying the deficit corresponding to the period during which the crop received no irrigation or rainfall.

Crop water requirements were monitored via climate data, along with the equations for determining reference evapotranspiration presented by Allen *et al.* (1998) and crop evapotranspiration presented by Bernardo *et al.* (2006). The soil water availability was monitored by determining the soil moisture. Climate data were obtained from an automatic weather station located near the crop, which provided daily data on maximum, average, and minimum air temperatures (°C), solar radiation (W m^{-2}), average relative humidity (%), average wind speed (ms $^{-1}$), and precipitation (mm). Soil moisture sampling was carried out weekly, and then sample analysis was conducted according to the standard greenhouse method.

Additionally, periodic monitoring of the crop leaf area index and dry biomass was carried out. Equation (1), proposed by Hsiao *et al.* (2009), was used to obtain an estimate of canopy cover through observed leaf area data.

$$CC = 1{,}005[1 - \exp(-0{,}6LAI)]^{1{,}2} \qquad (1)$$

where:
CC is the canopy cover, %; and
LAI: Leaf area index.

AquaCrop software (Version 4.0) from June 2012 was used for the simulation. Climate data from the common bean growing season were entered into *AquaCrop* via ETo *Calculator software*. The management and crop treatment data included soil cover with organic matter in 90% of the experimental area. The crop data adopted a minimum root depth of 0.10 m and a maximum of 0.40 m; a basal temperature of 10 °C and a maximum of 30 °C; a Kc_{TR} (crop coefficient when canopy cover is complete and the crop is in a stage prior to senescence) of 1.10; the effect of high temperature on pollination was considered, with a maximum tolerance limit of 32 °C; and no salinity problems in the experimental plots. Initially, no adjustments were made to crop productivity indices or growth patterns.

The unknown conservative parameters of the beans were obtained in the simulation through the trial and error method, which uses data observed in the field on biomass, canopy cover and productivity.

This study also evaluated the water productivity index (WP – *water productivity*), which represents the relationship between grain productivity and the total amount of water applied; IWP (*irrigation water productivity*), which represents the relationship between grain productivity and water applied only through irrigation, thus eliminating the amount of rainfall that occurred; and EWP (*evapotranspiration water productivity*), which is the relationship between productivity and crop evapotranspiration (ALI; TALUKDER, 2008).

To evaluate the results of the simulations, an efficiency model – Ef (Equation 2) of the measured data in relation to those observed in the field, root mean square error – RMSE (Equation 3) according to Loague and Green (1991), and a concordance index – d (Equation 4) proposed by Willmott (1982) were used.

$$Ef = \frac{\sum_{i=1}^{n}(O_i - MO)^2 - \sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - MO)^2} \qquad (2)$$

where:
Ef is the efficiency;
Hi: these are the observed values;
Si: the simulated values; and
MO is the average of the observed values.

$$RMSE = \left[\sum_{i=1}^{n}\frac{(P_i - O_i)^2}{n}\right]^{0,5} \cdot \frac{100}{M} \qquad (3)$$

where:
RMSE: the root mean square error, %;
Pi: the simulated values;
Hi: these are the observed values;
n: the number of observations; and
M is the average of the observed values.

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P'_i| + |O'_i|)^2}\right] \qquad (4)$$

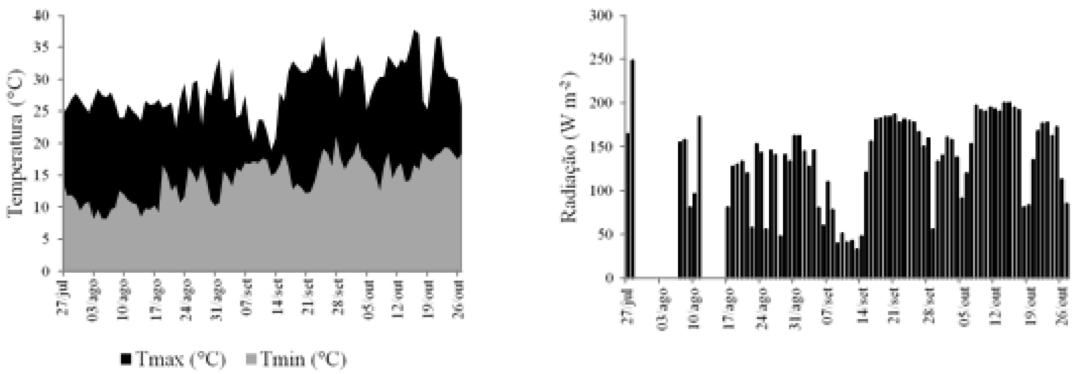
where:
d: is the concordance index;
P'i = Pi – M, where M is the average of the observed values
O'i = Hi – M.

5 RESULTS AND DISCUSSION

The average maximum temperatures for the months of August, September and October 2015 were 26.4, 28.3 and 31.4 °C, respectively; the average minimum temperatures, following the same order, were 11.5, 15.8 and 17.1 °C; and the average radiation rates for this period were 120.3, 126.2 and 157.8 W m $^{-2}$, respectively (Figure 1). The radiation values in the first two months of cultivation are less than the ideal values for common beans. According to Heinemann, Stone and Silva (2009), this range varies between 150 and 250 W m $^{-2}$. Low radiation values, accompanied by low temperatures, provide a heat range for the development of this bean cultivar, which has a basal temperature of 10 °C, an optimum temperature of 21 °C, and a maximum temperature of 30 °C.

Figure 1. Variation in the maximum and minimum air temperatures (A) and solar radiation (B) from July 27 to October 27, 2015. Viçosa, MG.

A. B.



In the final flowering phase, maximum temperatures above 35 °C were recorded, which may have caused the abortion of some flowers that were still open to pollination and some newly formed pods, thus harming part of the plant's grain production. Heinemann, Stone and Silva (2009) reported that maximum air temperatures above 35 °C and minimum temperatures above 25 °C cause the abscission of flowers and small pods.

Crop evapotranspiration (ETc) during this period, according to the methodology of Allen *et al.* (1998), presented average values for the months of August, September and October of 2.28, 2.68 and 3.65 mm day $^{-1, \text{respectively}}$. According to Heinemann, Stone and Silva (2009), water consumption for beans in the state of Minas Gerais varies between 3.20 mm day $^{-1}$ in the southern region and 5.00 mm day $^{-1}$ in the northern region.

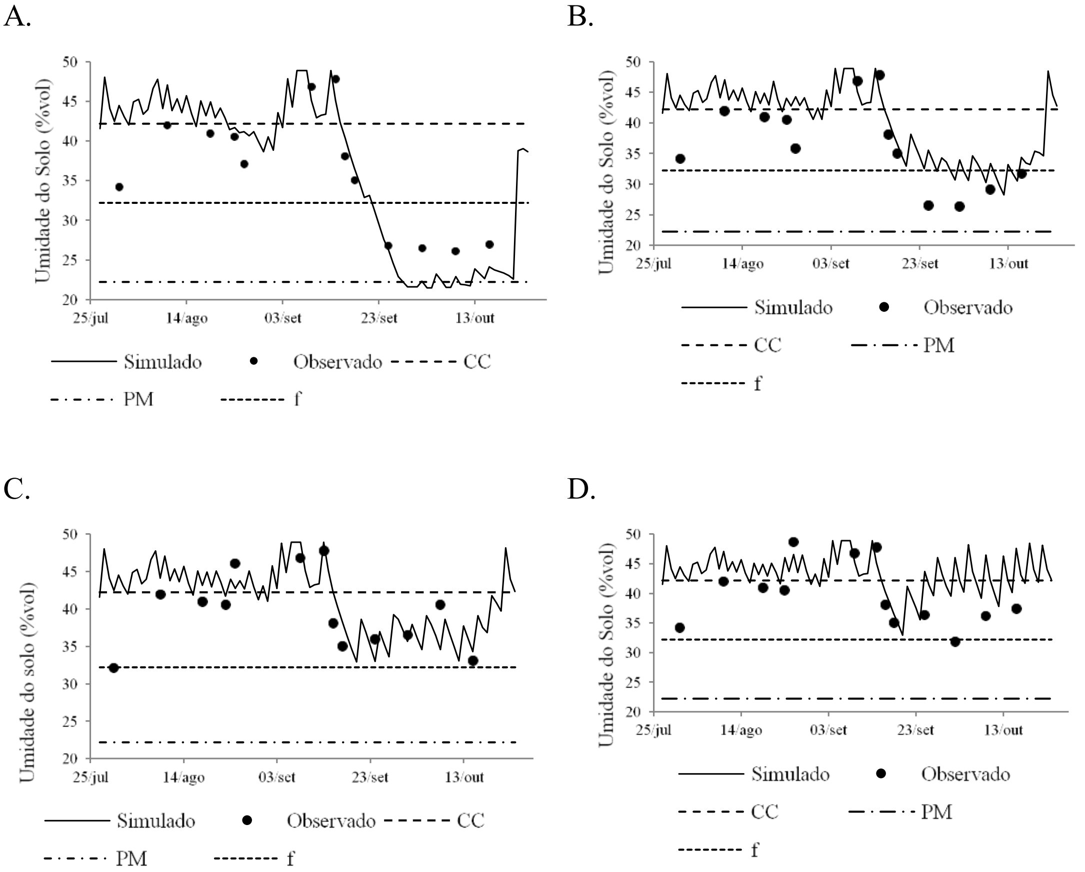
Table 1 shows the amount of water applied to each treatment, along with the amount of rainfall and actual precipitation. The applied depth values vary within the crop's required limits, which are 300 to 500 mm (DOORENBOS; KASSAM, 1979). There was greater actual precipitation in the deficit plot because of the drier soil. Therefore, most of the precipitated water was retained in the root water extraction profile.

Table 1. Amount of applied blades and effective and ineffective precipitation according to each treatment.

Treatments	Applied irrigation blade	Noneffective precipitation	Effective precipitation	Total water applied
L1	175.8	83.7	63.2	322.7
L2	256.0	93.5	53.4	402.9
L3	272.3	97.3	49.6	419.2
L4	345.9	106.9	40.0	492.8

The soil moisture content of each slide was compared to that estimated by *AquaCrop*, as shown in Figure 2.

Figure 2. Soil moisture measured and simulated by AquaCrop in the irrigation determination methods of treatments L1 (A), L2 (B), L3 (C) and L4 (D).



Treatment L1 had the highest efficiency and agreement index, and L3 had the lowest error with the simulated data, similar to that estimated by the program and in agreement with that proposed in *AquaCrop*, which uses the same method proposed by Allen *et al.* (1998) to calculate the ETo demand and soil water balance. L4 showed the greatest difference between the simulated and measured data, as it exceeded the amount of water applied (Table 2).

Table 2. Efficiency (Ef), root mean square error (RMSE) and agreement index (d) of the simulated and measured soil moisture values.

Treatments	Eph	RMSE	d
L1	0.688	18,337	0.937
L2	0.514	24,854	0.790
L3	0.503	16,325	0.830
L4	0.899	29,021	0.532

The “d” values presented here agree with those presented by Coorevits (2010), who studied the *AquaCrop parameterization* for beans in the climate conditions of Belgium.

The adjustment of local cultivation conditions and each irrigation event carried out in *AquaCrop* resulted in the indices presented in Table 3. These values differed from the values observed for crop productivity and yield, given that there was an isolated response for each water regime.

Table 3. Indices used in *AquaCrop* to adjust the simulation of bean growth and productivity for cultivation and irrigation conditions.

Parameters evaluated	L1		L2		L3		L4	
	Med*	Est**	Med*	Est**	Med*	Est**	Med*	Est**
Biomass (kg ha $^{-1}$)	4976	4968	5033	5062	6620	6641	6699	6687
Potential biomass		6413		5879		7712		8284
Productivity (kg ha $^{-1}$)	2160	2137	2437	2427	3355	3340	3421	3454
GD (°C) [1]		980.2		980.2		980.2		980.2
Evaporation (mm day $^{-1}$)		38.3		45		38.3		38.3
Perspiration (mm day $^{-1}$)		116.8		141.3		150.5		141.7
Infiltrated blade (mm)		312.6		383.6		401.6		464.6
Drained blade (mm)		167.6		196.2		210.1		276.5
EWP (kg m $^{-3}$) [2]		1.38		1.4		1.77		1.93
WP (gm $^{-2}$) [3]		11.0		9.9		12.0		12.8
HI (%) [4]		43.0		48.4		50.3		51.7
CCo (%) [5]		1.32		1.21		1.25		1.29
CGC (% day $^{-1}$) [6]		15.2		15.4		15.0		15.3
CDC (% day $^{-1}$) [7]		20.3		17.9		12.0		12.2

[1] GD: degree days; [2] EWP: evapotranspired water productivity index in production; [3] WP: water productivity index of water applied during cultivation (rainfall plus irrigation); [4] HI: harvest index; [5] CCo: initial canopy growth rate considering 90% emergence; [6] CGC: exponential vegetative growth rate of the crop; [7] CDC: rate of decline in crop development after reaching maturity and initiating senescence. Med* – Measured, Est** - Estimated

The ratio of potential biomass to actual biomass ranged from 86% to 77%. The productivity and biomass corresponded to the applied water depth. Degree days and evaporation were the same for all the treatments, as the same bean cultivar was used for the treatments, and the irrigation system was also a central pivot. This meant that the percentage of wetted area was the same, and the plant cover used on the soil was consistent across all plots.

The degree-day (DG) value observed for common beans was 980 °C throughout the cycle (Table 3), as mild temperatures predominated in two of the three growing months. Renato (2013) reported a degree-day value for common beans of 1,300 °C in a 100-day cycle with predominantly high temperatures. Lopes (2006), in a bean crop in which the maximum temperature during the cycle was approximately 29 °C, reported results of approximately 1,000 degree days.

Transpiration differed between the treatments because of differences in the amount of water available. Despite receiving the most water, the L4 treatment resulted in lower transpiration than did the L3 treatment, as the L4 treatment resulted in maximum transpiration tolerance relative to irrigation. The average daily transpiration value was consistent with the range reported by Ogindo and Walker (2004) when the authors evaluated transpiration efficiency in a common bean plant.

In relation to the infiltrated and drained water depths, there was greater water retention in the soil profile in the L4 treatment, which directly reflected the data of the irrigated water productivity indices. When only the irrigation depth (IWP) was considered and irrigation plus rainfall (WP) was considered (Table 4), the observed productivity was balanced with the amount of water used, indicating that excess water sometimes does not necessarily result in high productivity because when it exceeds the soil retention capacity in the studied profile and is beyond the crop's needs, it may not be used, which is not desirable when efficient and adequate irrigation management is carried out.

Table 4. Productivity indices of the amount of water applied through irrigation (IWP) and accounting for irrigation plus rainfall (WP).

Treatments	IWP (kg ha $^{-1}$ mm $^{-1}$)	WP (kg ha $^{-1}$ mm $^{-1}$)
L1	13.03	6.90
L2	13.56	9.90
L3	14.58	8.89
L4	12.33	8.05

The EWP (Table 3) was proportional to the amount of water applied, as water availability favors both transpiration and evaporation. However, the relationship is not linear, as can be observed. When the plant reaches its maximum productivity, the amount of extra water applied becomes excessive and is not well utilized by the plant. Furthermore, it favors vegetative growth, resulting in high biomass production but low grain productivity (ALI; TALUKDER, 2008).

The L3 treatment resulted in the highest yield of water application converted into productivity, as this depth better met the crop's water needs (Table 3). The behavior of the indices calculated for L1 was likely due to the stress experienced by the plant, as there was low water availability. This performance agrees with that presented by Hegab *et al.* (2014), who also reported high productivity index values in water deficit plots.

When applied at the appropriate time, beans respond positively to water stress in terms of productivity. With respect to the mode of application, a plant can respond positively when it is applied gradually or negatively when it is applied suddenly (ALI; TALUKDER, 2008). Therefore, despite not achieving high productivity in the deficit plot compared with the other plots, the plants that experienced water stress presented comparable water use performance.

The grain yield (WP) was lower in L1 than in L1 because of the moment at which the water deficit phase began, immediately after the vegetative phase. There was an increase in WP in L2 due to the greater water supply (Table 3).

The reproductive phase of common beans requires good water availability for effective production, which directly impacts the final grain yield. However, if this stress had occurred during the vegetative phase, around the V3 and V4 stages, the response could have been positive in terms of plant structure and utilization of applied water, as it is at these stages that the plant's performance does not decline owing to low soil water availability (SANTOS *et al.*, 2015).

L4 also has a low rate, despite

considerable productivity. This may imply a low cost/benefit ratio, where the cost of irrigation and the entire system operation are not advantageous compared with the resulting productivity.

The WP obtained in this work was lower than that reported by Yuan *et al.* (2013), who cultivated beans and other C3 species in a semiarid climate. This difference occurred because of differences in climatic characteristics between the regions of the compared works.

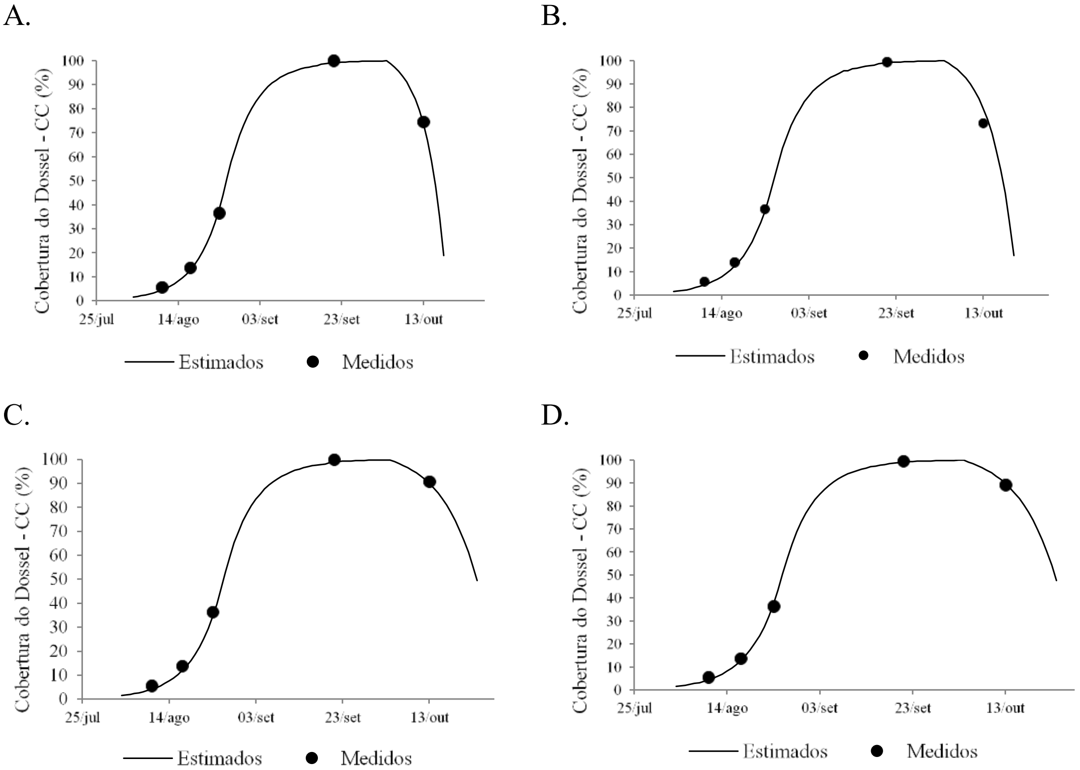
The CCo and CGC were similar between the treatments because the same amount of water was applied at the beginning of cultivation until the appearance of the first trifoliate to form a good *stand* of plants and because of the occurrence of considerable rainfall in this phase, which standardized the initial growth.

According to the CDC, in the plots with better water availability, such as L1 and L2, the crop decline was slower, with the crop nearly completing its full phenological cycle. The faster senescence is attributed to a short cycle due to water restriction, in this case. This can result in lower productivity or lower-quality grains.

The GCA values were higher than those reported by Yuan *et al.* (2013), since grain production was lower than that reported by these authors and biomass production was slightly greater. The CDC value was also lower than the simulated value; therefore, the bean cultivated by the aforementioned authors had a longer maturity and senescence than the one studied here.

It was possible to compare crop development through simulated and measured canopy cover data for each irrigation regime, as presented in Figure 3.

Figure 3. Simulated and observed canopy cover on slides L1 (A), L2 (B), L3 (C), and L4 (D).



L1 – 175.8 mm, L2 – 256 mm, L3 – 272 mm and L4 – 345.9 mm.

With the adjustment, reliable values were obtained between the simulated and observed values, verifying efficiency and agreement values between the data of 0.99 and errors varying between 1% and 6%, which, according to Jamieson, Porter and Wilson (1991), is considered an excellent simulation (Table 5).

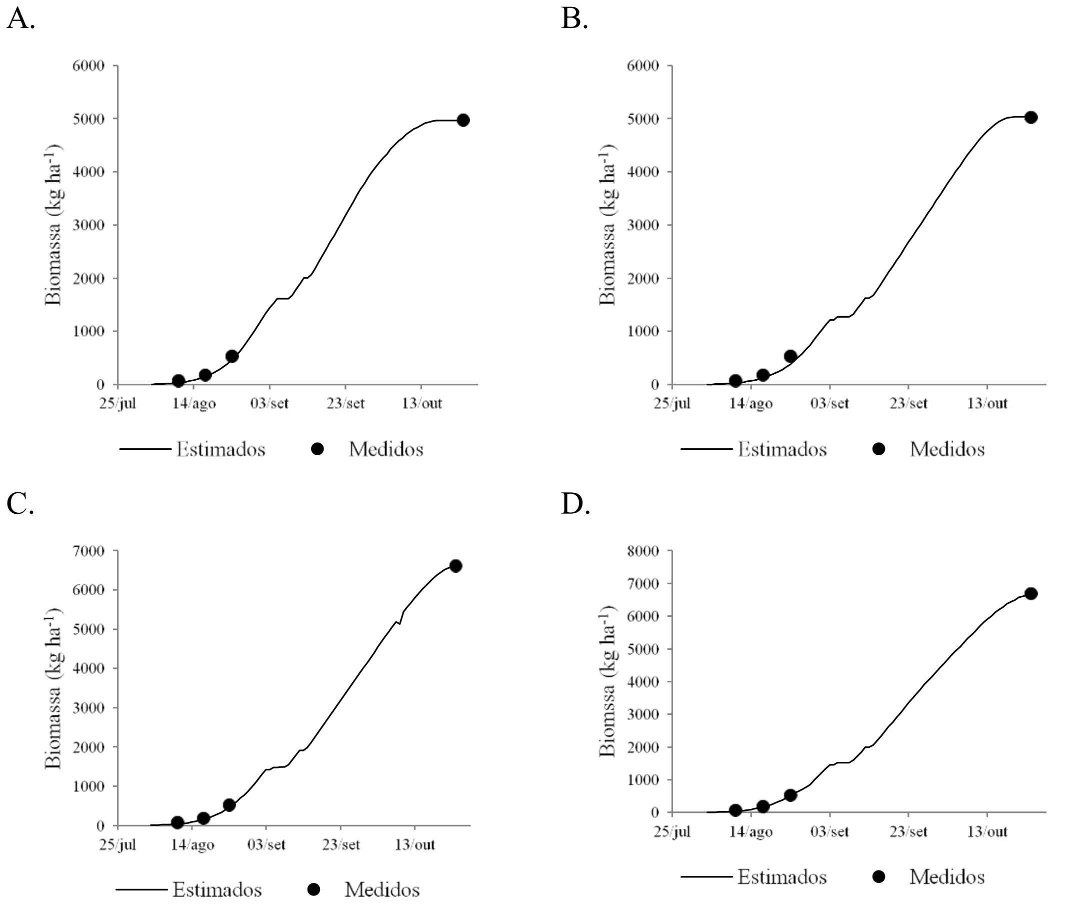
Table 5. Efficiency (Ef) of the simulated values compared with the measured data, the root mean square error (RMSE) and the agreement index (d) of the canopy cover.

Treatments	Eph	RMSE (%)	d
L1	0.999	2,146	0.999
L2	0.992	4,738	0.998
L3	0.998	3,496	0.999
L4	0.999	1,771	0.999

The observed biomass presented a different behavior from the simulated biomass, since the program considers the accumulation of dry mass as continuous and increasing, whereas in reality, there is a decrease in the value at the end of the cycle due to the bean plant losing mass in the period in which the pod with the grains dries and these reach the point of adequate humidity for harvesting.

Figure 4 shows that the crop cycle was shorter in the L1 and L2 treatments. There was a sudden accumulation of biomass, followed by a gradual decrease, likely due to the applied water stress. Moreover, in treatments L3 and L4, the accumulation slower, reaching peak biomass later.

Figure 4. Differences in behavior between the biomass measured in the field and that estimated by *AquaCrop* in the treatments irrigated at depths of L1 (A), L2 (B), L3 (C) and L4 (D).



L1 – 175.8 mm, L2 – 256 mm, L3 – 272 mm and L4 – 345.9 mm.

Treatments L3 and L4 performed more closely to those estimated by the program, suggesting that the greater the amount of water applied was, the more the plant was able to fully complete its phenological stages, and the crop growth results observed in the field were closer to those modeled by the program. Those that received less water experienced faster and more pronounced growth, with a greater drop in biomass in the final production stage, thus presenting greater variation from the simulated value, as shown in Table 6.

Table 6. Efficiency (Ef) of the simulated values compared with the measured values, root mean square error (RMSE) and agreement index (d) for biomass.

Treatments	Eph	RMSE (%)	d
L1	0.638	66,906	0.862
L2	0.613	70,858	0.836
L3	0.819	53,703	0.935
L4	0.885	38,958	0.963

The L1 treatment resulted in a lower efficiency and higher RMSE because of the greater deviation of the simulated points from those measured at the flowering stage until maturation.

In the work of Hsiao *et al.* (2009), which was carried out with a corn crop, there was greater agreement between the obtained and simulated data in terms of biomass gains since the biomass accumulation curve of this crop follows the one estimated by the program. The data presented by Coorevits (2010) for bean crops are close to what was observed in this adjustment.

6 CONCLUSION

The growth and development of bean crops can be monitored with the *AquaCrop software*, depending on the application of appropriate indices.

Canopy cover was the parameter that best fit the model proposed by *AquaCrop*. The same was not observed for the biomass gain parameter.

The soil moisture estimated through *AquaCrop* was closer to that observed in the field when the moisture was close to field capacity.

It is necessary to develop other studies for Brazilian conditions and adapt the models proposed by the program to data observed in the field.

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