ORIGINAL ARTICLE

Estimation of the dynamic variables of irrigation scheduling in common bean crop (*Phaseolus vulgaris* L.)

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Estimación de las variables dinámicas de programación del riego en frijol común (*Phaseolus vulgaris* L.)

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ABSTRACT: The research was carried out between the months of November 2020 and March 2021 and aimed to estimate the crop coefficient, root depth and abatement factor, depending on thermal time. The research area belongs to the UBPC Grito de Yara, Granma, Cuba, which is located at 200 25' 02" N Latitude and 760 53' 27" O Longitude. The estimation of the crop coefficient, root growth and exhaustion fraction was carried out using curvilinear models as a function of degree days. The estimation of root growth in the bean crop, using the three models evaluated, depending on the degree days, is reliable and is a very useful indicator for irrigation programming, since it facilitates the timely estimation of the sheet of water from the depth of the root. Growing degree days explain the allowable depletion levels of soil water for bean cultivation; In this regard, it was confirmed that the curvilinear model is accurate, which allows irrigation management, using information on degree days, to avoid water stress.

Keywords: Degree Days, Root, Depletion Fraction.

RESUMEN: La investigación se desarrolló entre los meses de noviembre de 2020 a marzo de 2021 y tuvo como objetivo estimar el coeficiente del cultivo, la profundidad radicular y el factor de abatimiento, en función del tiempo térmico. El área de la investigación pertenece a la UBPC Grito de Yara, Granma, Cuba, la cual se encuentra ubicada a los 20^0 25' 02" de Latitud N y a los 76^0 53' 27" de Longitud O. La estimación del coeficiente del cultivo, crecimiento radicular y fracción de agotamiento, se realizó mediante modelos curvilíneos en función de los grados día. La estimación del crecimiento radicular en el cultivo de frijol, mediante los tres modelos evaluados, en función de los grados día, es confiable y, es un indicador de suma utilidad para la programación del riego, ya que facilita la estimación oportuna de la lámina de agua a partir de la profundidad de la raíz. Los grados día de crecimiento explican los niveles de agotamiento permisibles de agua en el suelo para el cultivo de frijol; al respecto, se corroboró que el modelo curvilíneo es exacto, lo cual permite el manejo del riego, utilizando la información de los grados día, para evitar estrés hídrico.

Palabras clave: grados día, raíz, fracción de agotamiento.

INTRODUCTION

To program irrigation scientifically, it is necessary to know the three dynamic scheduling variables throughout the crop's phenological cycle according to Servín-Palestina *et al.* (2017) ,which define the evapotranspirative capacity of the crop, the extractive zone of the root and the Stress sensitivity: crop coefficient (Kc), root depth (Pr) and depletion fraction (*f*). In sustainable agricultural production systems, where consistent and uniform management of crops and irrigation water is applied, it is possible to establish a precise relationship between *Kc*, *f*, *Pr* and degree days (°D) (Olivera *et al.*, 2018). In this way, it is possible to determine the degree of water stress of the crop based on the °D, in order to establish irrigation schedules. The estimation of degree days, a concept also known as thermal time (TT) according to Aguilar-Rodríguez *et al.* (2020), is a determining factor in the soil-climate-plant interaction, which is related to the stages of crop development according to

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Servin-Palestina *et al.*, (2018); Bispo *et al.*, (2022) and, extremely useful for making estimates based on crop development and root depth (Achinas *et al.*, 2020).

From this perspective, the coefficients or parameters are adjusted to the prevailing meteorological conditions at the site under study, to obtain normalized curves of the coefficients based on °D. Kc values are of limited use according to Chavarría-Párraga *et al.*, (2020) when defined based on days after emergence or another unit of time. Its use is restricted to localities with a climate similar to that of the site where the curves were obtained, since it does not take into account the effects of temporal climate variability on the growth and development of crops.

Traditionally, a value of *f* equal to 0,5 has been taken. However, the value depends on both the crop and the soil, irrigation management and environmental conditions. At the beginning of the cycle a crop can be stressed, so the value of *f* is large; To the extent that it reaches its critical periods, such as flowering or fruit formation, *f* reaches its minimum value (Covarrubias *et al*., 2019). The research was based on the hypothesis that the phenological development of the bean crop, expressed in degree days, it allows to know the dynamic variables of irrigation scheduling that define the evapotranspirative capacity, the root extractive zone and the sensitivity to stress and, had as objective to estimate the crop coefficient, root depth and depletion fraction, as a function of thermal time.

METHODS

Location of the experimental trial

The research was carried out between the months of November 2020 to March 2021. The research area belongs to the UBPC Grito de Yara, belonging to the Paquito Rosales Agricultural Company of Granma, Cuba, which is located at 20° 25 ' 02" of Latitude N and at 76° 53' 27" of Longitude W, with a height of 6 m.a.s.l.

Field methodology

The experiment was carried out on a Fluvisol soil Hernández *et al.* (2015) , with an organic matter content of less than 2%. The main hydrophysical properties of the soil are the following: clay loam texture, apparent density of 1,36 $g\ cm^{-3}$, field capacity (CC) and permanent wilting point (PMP) of 0,38 and 0,22 $cm^{3}\ cm^{-3}$, respectively, for 0 at 30 *cm*. The Buenaventura common bean variety was studied, which has a potential yield of 2,99 $t\ ha^{-1}$, the growth habit is determined (Type II), the cycle is 79 *d* and its planting date is recommended from September to January. A planting frame of 0,05 *m* between plants and 0,45 *m* between rows was used. The area was irrigated with a Bayatusa 2000 center pivot machine, with a length of 350 m.

Irrigation scheduling was carried out using the soil water potential method (tensiometers), for which four tensiometers were installed in the selected quadrant (I), grouped in two measurement stations, which ensured the validity of the readings. Root length measurements were performed weekly, at four sampling points selected from the central groove of quadrant number I of the center pivot machine. At each sampling point, 5 plants were selected. The emergence time of 90% of the plants was observed by counting the germinated plants at the four sampling points. The minimum, maximum and average temperature data were provided by the Veguitas Agrometeorological Station, belonging to the network of stations of the Ministry of Science, Technology and Environment (CITMA), which is located at a distance of less than 2 *km* from the plot experimental.

Calculation of dynamic variables

Crop coefficient.

The crop coefficient was determined based on degree days, according to Ojeda-Bustamante *et al.* (2004) **:**

$$K_c = K_{máx} \quad erfc\left(\left(\frac{x - x_{Kmáx}}{\propto_1}\right)^2\right) \qquad (1)$$

Si $K_c < K_1$ then $K_c = K_1$

where: *Kmax* is the maximum value of *Kc* during the crop cycle; *erfc* is the complementary error function; *x* expresses the degree days of accumulated growth (ΣºD) normalized with respect to the total *ºD* required to complete its normal phenological cycle; *xKmax* is the value of the degree days of accumulated growth where the value of *Kmax* is presented; $\propto_1$ is the regression parameter obtained by fitting experimental data to the model; K_1 is the crop coefficient for the first phenological stage that depends mainly on soil evaporation. Growth degree days were calculated according to the procedure described by McMaster & Wilhelm (1997) The value of the base temperature of the culture, 9*°C* and maximum temperature, 30 *°C*, were taken from Raes *et al.* (2022).

Root depth calculation

The root depth was estimated using empirical models, which were compared with each other, to propose the most appropriate model for simulation in the study area:

$$P_r = P_{mín} + (P_{máx} - P_{mín})\, t/t_{máx}$$ Fereres *et al.* (1981)

$$P_r = P_{máx},\ t > t_{máx} \qquad (2)$$

$$P_r = P_{máx}, \quad t > t_{máx}$$

$$P_r = P_{mín} + (P_{máx} - P_{mín})\frac{K_c(t)}{K_{máx}} \quad \text{para} \quad t \le t_{máx}$$

Ojeda-Bustamante & Flores-Velázquez (2015)

$$P_r = P_{máx}, \quad \text{para} \quad t \ge t_{máx} \quad (3)$$

$$P_r = P_{mín} + (P_{máx} - P_{mín})\sqrt[n]{\frac{\left(t - \frac{t_o}{2}\right)}{t_{máx} - \frac{t_o}{2}}}$$

Raes *et al.* (2022) (4)

where: *Pr* is the estimated root depth, *m*; *Pmin* is the minimum or planting root depth, m; Pmax is the maximum root depth, m; t is the time after sowing, °D; t_{max} is the time to reach the maximum root depth, *°D*; *Kc(t)* is the value of the cultivation coefficient at a time t and *Kcmax* is the maximum value of the cultivation coefficient; *n* shape factor, determined by fitting between observed and simulated data; time to reach the 90% of emergence of the seedlings, *°D*.

Evaluation of the models

The evaluation of the accuracy of the models that predict root depth was carried out through graphic analysis and the use of three statistical indices: The coefficient of determination (R^2): represents the percentage of the variability of the observed values that has been explained by the fitted regression model. Values greater than 0,50 were considered acceptable and values greater than 0,80 were classified as good.

$$R^2 = \frac{Scr}{Sct} \times 100 \quad (5)$$

where: R^2 is the coefficient of determination, %; *Scr* the sum of squares due to regression; *Sct* the total sum of squares.

The normalized root mean square error (*NRMSE*): is a statistical parameter that allows a simulation to be considered excellent when a value less than 10% is reached; good if it is between 10 and 20%; adequate if it is between 20 and 30% and poor if it is greater than 30% Raes *et al*. (2022).

$$NRMSE = \frac{1}{\bar{M}}\sqrt{\frac{\sum_{i=1}^{N}(M_i - S_i)^2}{N}} \quad (6)$$

where: $\bar{M}$ is the average of the measured values, *m*; *Mi* the measured values, *m*; *Si* the simulated values; N the number of observations.

The acceptance rate (d): is a measure of the relative error in the model estimates. It is a dimensionless number that varies between 0 and 1; high values were considered when it was greater than 0,65.

$$d = 1 - \frac{\sum_{i=1}^{N}(S_i - M_i)^2}{\sum_{i=1}^{N}(|S_i - \bar{M}| + |M_i - \bar{M}|)} \quad (7)$$

Calculation of the depletion fraction

The linear model, proposed by Ojeda-Bustamante *et al*. (2004) ,estimates the depletion fraction (*f*) from the crop coefficient (*Kc*) with the following relationship:

$$f = \propto_3 - \propto_4 K_c \quad (8)$$

where: $\propto_3$ is the intercept at the origin, its value is associated with the irrigation system, for central pivot it is 0,45 (Ojeda *et al*., 2004); $\propto_4$ the slope of the line is related to the sensitivity of the crop to water stress, 0,1 is assumed.

RESULTS AND DISCUSSION

Analysis of degree days and crop coefficients by stages

The crop changes phenological stage when the thermal time reaches the value required for it. For example, the stage of the first trifoliate leaf (V3) lasted 4 days and was reached when the crop accumulated 123 *°D* (Table 1). The longest stage (R8) lasted 17 days and was reached when the culture accumulated 632 *°D*. The crop cycle requires a total of 1005 *°D*. The incorporation of the degree day concept to schedule irrigation has proven to be an excellent tool that can be applied both in plots and in large irrigation areas, even in variable climate and water availability conditions.

TABLE 1. Crop coefficient by phenological stage as a function of *°D*

Stages	Code	Duration (d)	GD (°D)	GDA (∑°D)	Kc
Germination	V0	4	55,2	55,2	0.1
Emergency	V1	2	27,3	82,5	0,1
Primary leaves	V2	3	40,5	123	0,15
First trifoliate leaf	V3	4	54	177	0,23
Third trifoliate leaf	V4	6	80	257	0,51
Pre-flowering	R5	8	108	365	0,92
Bloom	R6	13	175	540	1,1
Pod formation	R7	7	92	632	1,1
Pod filling	R8	17	214	846	0,9
Maturation	R9	13	159	1005	0,34

Kc has a distinguishable variation according to the phenological stage (Table 1). During stages *Vo* and *V1* the value of *Kc* is low (0,1). The crop begins to consume water until it emerges. However, since sowing, the *Kc* value is greater than zero since it considers soil evaporation. For the following stages (*V2-R5*), the *Kc* value (0,15-0,92) reflects the physiology of the crop and its leaf area. When the crop reaches maximum coverage *R6* and *R7*, the *Kc* value is maximum (1,1) since the crop is capturing the maximum amount of solar radiation. In the final stage (*R8* and *R9*) the crop's water consumption begins to gradually decrease until harvesting.

Rodríguez (2023) determined the *Kc* values of the bean crop, based on the moisture balance relationship, and reported values of 0,45 for the first stages, 1 for the intermediate stages and 0,38 for the final stages. The *Kc* of the first stages (0,45) differs from that found in this research (0,1); However, there is similarity between the rest of the *Kc*. Zamora & Duarte (2022) reported *Kc* values higher than those found in this research for all stages of the crop.

Analysis of root depth estimation

The extraction of water by the roots is critical for the development of a crop. The curve that describes the root depth presented a very high slope up to 0,15 m depth and 270 °*D* (Figure 1), which is expressed by a straight segment with an inclination that tends to the vertical, which confirms the growth cultivation accelerated in this period. The maximum root depth (0,22 m) was reached when the culture accumulated 645 °*D*. The graphic adjustment demonstrated that the models simulated the observed root depth values reasonably well; However, the models Fereres *et al.* (1981) y Raes *et al.* (2022), presented the lowest deviations for the entire crop cycle.

In the case of the Ojeda-Bustamante *et al.* (2004) model, a greater range of dispersion was found compared to previous models, although the graphic fit was satisfactory for greater depths. All three models tend to underestimate root depth, especially between 257 °D and 365 °D. In this interval are stages R4 and R5, which is where the crop has the growth flare, and the model algorithms do not consider it.

The statistical indices used in the evaluation of the accuracy of the models (Table 2) allow to corroborate that the simulated data adjusted excellently to the observed data, which is evidenced by the coefficient of determination with high values of 0,98, 0,87 and 0,96, for the models respectively. The NRMSE demonstrated that simulations with the models of Fereres et al. (1981); Raes et al. (2022); Ojeda-Bustamante et al. (2004), respectivamente, respectivamente. were excellent, having values of 9,9 and 7,1%, respectively. The simulation with the

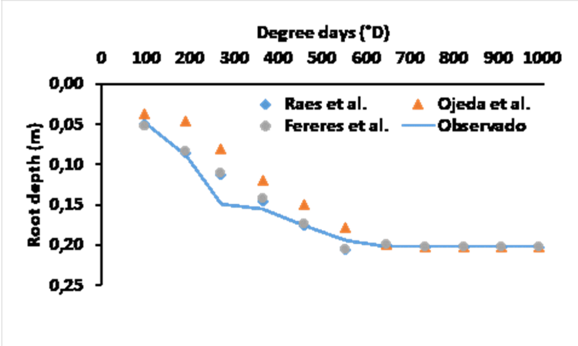

FIGURE 1. Behavior of the observed and simulated root depth.

Ojeda et al. model. It turned out to be good, presenting a value of 17%.

TABLE 2. Values of the statistical indices of the simulation

Model	*R2*	*NRMSE (%)*	*d*
Fereres et al. (1981)	0,98	9,9	0,98
Ojeda-Bustamante et al. (2004)	0,87	17	0,94
Raes et al. (2022)	0,96	7,1	0,98

The acceptance index presented high values (>0,65) for the three models. These values demonstrated that the three models were capable of adequately simulating root depth, which corresponds to the results reported by Fereres et al. (1981); Raes et al. (2022); Ojeda-Bustamante et al. (2004)

In general, the models used adequately represented the behavior of the root as a function of climatic variation, a characteristic of curvilinear models (Servín *et al.*, 2017). The models allow irrigation up to Pr=0,20 m and avoid percolation, thereby achieving greater efficiency in water use, since the total irrigation sheet applied is reduced.

Analysis of the depletion fraction and its relationship with *Kc*

The models of *f* and *Kc* vs. °*D*, reflect a curvilinear response (Figure 2), since they represent the response of the crop as a living being, which is affected by the climate the line (Servin *et al.*, 2018). The above is related to the fact that, the greater the water requirement of the crop, the more sensitive it is to water stress.

The f value decreases with increasing *Kc* up to 735 °*D*, which suggests the need for more frequent irrigation to promote crop growth and is within the range of 0,34 to 0,44. Inversely, *f* increases with the decrease in *Kc* from 821 °*D* to 907 °*D*, which suggests a reduction in irrigation frequency and is in the range of 0,36 to 0,45. The values reported for f by USDA (1991),wering - pod formation (0,4), pod filling - ripening (0,5).

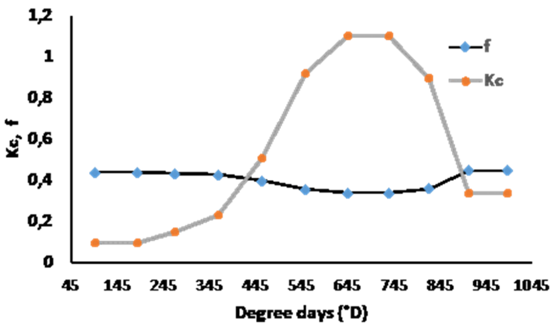

FIGURE 2. Relationship between *Kc* and *P* with accumulated degree days.

On the other hand, according to Allen *et al.* (1998) report values of 0,45 for evapotranspiration conditions of 5 *mm d* $^{-1}$ and reductions of between 5 and 10%, for soils similar to those of this research. The value of f normally varies between 0,30 for plants with shallow roots, at high rates of ETc (> *8 mm d* $^{-1}$), to 0,70 for plants with deep roots and low rates of ETc (< 3 *mm d* $^{-1}$). The f value for high frequency irrigation (drip irrigation) generally varies between 0,2 and 0,6, while for low frequency irrigation (gravity irrigation) it varies between 0,4 and 0,8.

CONCLUSIONS

The estimation of root growth in the bean crop, using the three models evaluated, depending on the degree days, is reliable and is a very useful indicator for irrigation programming, since it facilitates the timely estimation of the sheet of water from the depth of the root.

Growing degree days explain the allowable depletion levels of soil water for bean cultivation; In this regard, it was confirmed that the curvilinear model is accurate during the development of the crop, which is sensitive to water deficit, so the precision of irrigation water management, using information on degree days, is essential to avoid water stress.

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