DOI: 10.5965/223811712142022370

Revista de Ciências Agroveterinárias 21 (4): 2022
Universidade do Estado de Santa Catarina

Modelling of the growth and productivity of soy cultivars under irrigation and rainfed conditions

Modelagem do crescimento e produtividade de cultivares de soja sob condições de sequeiro e irrigação

Wemerson Saulo da Silva Barbosa[1]* (ORCID 0000-0002-4597-3215), Guilherme Bastos Lyra[2] (ORCID 0000-0002-6186-2048), Ivomberg Dourado Magalhães de Souza[2] (ORCID 0000-0003-2959-2698), José Leonaldo de Souza[2] (ORCID 0000-0002-5399-856X), Iêdo Peroba de Oliveira Teodoro[2] (ORCID 0000-0001-8581-6639), Joyce Herculano Lopes[2] (ORCID 0000-0002-1005-6812), José Wanderson Silva dos Santos[2] (ORCID 0000-0002-1894-2587)

[1]Federal University of Western Bahia, Barreiras, BA, Brazil. *Author for correspondence: agrowssb@gmail.com
[2] Federal University of Alagoas, Maceió, AL, Brazil.

Submission: 18/May/2022 | Acceptance: 11/Aug/2022

ABSTRACT

The aim of this study was to evaluate the fit of semi-empirical models for growth and productivity in soya cultivars under irrigation and rainfed conditions in the state of Alagoas. Two experiments were conducted, the first during the dry season from 14/11/18 to 03/04/19 (140 days), and the second during the rainy season from 20/06/19 to 28/10/19 (130 days) in the coastal-tableland region of Alagoas. The experimental design was of randomised blocks, with the treatments comprising six cultivars of different maturity groups and growth habits (M 6210, M 6410, BMX-Potência, AS 3730, M 8349 and BRS-9383). The following were evaluated: plant height, dry matter and leaf area index (LAI). The sigmoidal and pic log-normal logistic models showed a significant statistical fit ($p<0.05$) to the growth variables and adjusted coefficients of determination (R^2_{adj}), with a maximum of 0.994 and 0.990, respectively. The observed values and those estimated by the models showed a high association by the Pearson (r) and Willmott (d) indices, with a low Standard Error of the Estimate (SEE). The BRS-9383 cultivar had the highest observed and estimated growth rates. Under irrigation, the maximum values for plant height were 98.45 and 110.35 cm, with maximum dry matter of 65.88 and 78.70 g, and maximum LAI of 7.68 and 7.60. Under rainfed conditions, the maximum plant height was 62.91 and 72.85 cm, maximum dry matter was 40.0 and 44.91 g, and the maximum LAI was 6.34 and 6.26. The highest agricultural yields under irrigation were 6.19 and 5.90 Mg ha^{-1} for the AS 3730 and M 8349 cultivars. Under rainfed conditions, the M 6410 and M 8349 cultivars stood out with grain yields of 3.60 and 3.30 Mg ha^{-1}. Thus, growth models can be used to help analyse growth as a function of days after planting.

KEYWORDS: growth habit; empirical models; *Glycine max.* (L.) Merrill.

RESUMO

Objetivou-se com este trabalho avaliar o ajuste de modelos semiempíricos de crescimento e a produtividade de cultivares de soja submetida a condições de irrigação e sequeiro no Estado de Alagoas. Foram conduzidos dois experimentos, o primeiro durante a estação seca de 14/11/2018 a 03/04/19 (140 dias), e o segundo na estação chuvosa de 20/06/19 a 28/10/2019 (130 dias) na região dos Tabuleiros Costeiros de Alagoas. O delineamento experimental foi em blocos casualizados e os tratamentos foram seis cultivares com diferentes grupos de maturação e hábitos de crescimento (M 6210, M 6410, BMX-Potência, AS 3730, M 8349 e BRS-9383). Foram avaliadas a altura das plantas, matéria seca e índice de área foliar (LAI). Os modelos logísticos, sigmoidal e pic log normal PHresentaram ajustes estatísticos significativos ($p<0,05$) para as variáveis de crescimento e coeficientes de determinação ajustado (R^2_{ajs}) máximo de 0,994 e 0,990, respectivamente. Os valores observados e estimados pelos modelos PHresentaram alta associação pelos índices de Pearson (r), Willmott (d) e baixo Erro Padrão de Estimativa (EPE). A cultivar BRS-9383 teve as maiores taxas de crescimento observados e estimados. Em condições de irrigação, os valores de altura de plantas máxima foram 98,45 e 110,35 cm, matéria seca máxima de 65,88 e 78,70 g e o LAI máximo de 7,68 e 7,60. Em sequeiro, a altura de plantas máxima foi 62,91 e 72,85 cm, matéria seca máxima de 40,0 e 44,91 g e o LAI máximo de 6,34 e 6,26. As maiores produtividades agrícola sob irrigação, foram de 6,19 e 5,90 Mg ha^{-1} nas cultivares AS 3730 e M 8349. Em sequeiro sobressaíram-se as cultivares M 6410 e M 8349 com produtividade de grãos de 3,60 e 3,30 Mg ha^{-1}. Dessa forma, os modelos de crescimento podem ser utilizados para auxiliar a análise de crescimento em função dos dias após a semeadura.

PALAVRAS-CHAVE: hábito de crescimento; modelos empíricos; *Glycine max* (L.) Merrill.

INTRODUCTION

Cultivated in an area of approximately 127.84 million hectares, with a production of 363.0 million tons, *Glycine max* (L.) Merrill soybeans assume a relevant socioeconomic role worldwide (USDA 2022). Brazil is the largest vegetable producer, producing approximately 138.15 million tons of grain in the 2019/2020 crop, planted area of 38.50 million hectares, and average productivity of 3,525 $kg.ha^{-1}$ (CONAB 2022).

Soy culture has gained space in non-traditional regions in grain cultivation, such as the State of Alagoas, which produced 6,900 t, on 2,300 hectares with an average productivity of 3,000 $kg.ha^{-1}$ in the 2021/2022 crop (CONAB 2022). However, this productivity is still low compared to other producing regions of the Brazilian Northeast (NEB), mainly due to the lack of knowledge about adapting cultivars to the edaphoclimatic conditions of Alagoas (SANTIAGO et al. 2019).

The evolution of soybean cultivation in Brazil was due to its socioeconomic value and the technification of production processes. However, due to the high number of cultivars, with different growth habits and maturation groups, launched by breeding companies, many producers find it difficult to obtain agronomic specifications, especially their behavior in new agricultural regions (SEDIYAMA et al. 2015, BOFF et al. 2019).

The achievement of soybean crops with high productive potential depends on the detailed knowledge of crop growth and development, its (edaphoclimatic requirements, as well as the genetic potential of cultivars (ZANON et al. 2016, TAGLIPHIETRA et al. 2018). Furthermore, the choice of each cultivar should take into view a certain production objective, since its productive components will undergo regional variations that will overcome a certain aspect(s) over another(s) (CRUZ et al. 2015).

Grain cultivation in Alagoas is conducted under dry conditions, when the region's rainy season begins, between the months of May to September (SOUZA et al. 2004, CARVALHO et al. 2013, PROCÓPIO et al. 2018). However, during this period of water seasonality, the water needs for plants are not met, affecting crop growth and productivity, which justifies the need for complementary irrigation (BATTISTI et al. 2018, SENTELHAS et al. 2015).

Monitoring soybean growth requires destructive and time-demanding techniques, especially when plants close between rows, making it unfeasible in large agricultural areas. However, the study and monitoring of growth variables can support profitable production techniques, both qualitative and quantitative, focused on crop management (LYRA et al. 2014, TAGLIPHIETRA et al. 2018).

An important tool for the study of the growth, development, and productivity of a crop is the use of mathematical modeling, which allows the description of the processes involved in the system and the simulation of situations that help decision-making in plant management, such as irrigation, fungicide application, fertilizer use, among others (TOLEDO et al. 2010, TRENTIN et al. 2013, BENDER et al. 2020).

The environmental conditions and agricultural techniques employed influence soybean growth and productivity, which is highly dependent on genotype-environment interaction. Thus, the objective of this work was to evaluate the adjustment of semiempirical growth models, as well as the productivity of soybean cultivars, influenced by irrigation conduction and in rainfed.

MATERIAL AND METHODS

Experimental and climatic characterization

The field experiments were conducted during two agricultural years (2018/2019 and 2019/2020) at the Engineering and Agrarian Sciences Campus of the Federal University of Alagoas (CECA/UFAL) (Figure 1A and 1B). The region's climate is classified as humid, mega thermal, with moderate water deficiency in summer and large excess water in winter (THORNTHWAITE & MATHER 1955).

The predominant soil of the area is characterized as Argissolic Cohesonic Yellow Latosol, of medium/clayey texture, with basic infiltration speed (VIB) of 52 $mm.h^{-1}$, available water capacity (CAD) of 58.20 mm, and average slope of 2%. The chemical analysis of the soil at a depth of 0-20 cm was used as a basis for planting fertilization (Table 1). The region's average annual rainfall is 1,800 mm, with the rainy season beginning in the first half of April and ending in the second half of August. The average air temperature is 23.14 °C, the average daily radiation balance is equal to 20 $MJ.m^{-2}$, relative humidity is around 70% (FERREIRA JÚNIOR et al. 2014).

Figure 1. Aerial photography of the experimental area, Rio Largo, Alagoas.

Table 1. Chemical characteristics of the soil of the experimental area, Rio Largo, Alagoas.

[1]Prof.	pH	P	K	Na	Ca	Mg	Al	H + Al	[2]CTC_t
m	H_2O	---------mg dm^{-3}-------			-----------------cmol.dm^{-3}---------------				
0 – 0.2	5.5	3	20	10	1.89	1.23	0.09	4.66	3.3
Prof.	[3]CTC_T	MO			Saturation --------------------------------%----------------------------------				
m	cmol.dm^{-3}	g kg^{-1}	[4]V	[5]m		Ca	Mg	K	Na
0 – 0.2	7.87	26.3	41	3		24	15.6	0.6	0.5

[1]Effective cation exchange capability (CTC_t); [2]Total cation exchange capacity (CTC_T); [3]Base saturation (V); [4]Aluminium saturation (m).

Irrigated experiment

The first experiment was conducted with supplementary irrigation so that plant growth occurred without water deficiency between November 2018 and April 2019 (i.e., 11/14/2018 to 04/03/2019, 140 days). Irrigation was performed by sprinkler method, with the squeaking spacing of 12.0 x 12.0 m, service pressure of 30 m.c.a., mean flow of 0.50 $m^3.h^{-1}$ and application intensity of 3.6 $mm.h^{-1}$. Irrigation management was based on crop evapotranspiration (ET_c), according to Equation 1:

$$ET_C = ET_0 K_C \tag{1}$$

in which: ET_0: Reference evapotranspiration (mm day^{-1}); K_c: crop coefficient of each development phase. The values of: 1.0, 1.2 and 0.50 were considered, respectively, for the initial, vegetative, and final phases, according to the FAO-56 bulletin (ALLEN et al. 1998).

Rainfed experiment

Dry land cultivation was installed in the region's rainy season, from June to October 2019 (i.e., 06/20/2019 to 10/28/2019, 130 days). As a result, the water demand of the plants was met only through rainfall.

Cultivation system

Soil preparation in both experiments was conducted by means of two gradations, aiming at the disaggregation and leveling of the soil and, later, the grooves were opened for fertilization. The basic fertilization followed the Agronomic Institute of Pernambuco (IPA 2008) recommendations for soybean crop.

Sowing was conducted on 11/14/2018 and 20/06/2020 for the irrigated and sianda cycle, respectively. The seeds received industrial treatment (TSI), and were inoculated with *Bradyrhizobium japonicum* for biological nitrogen fixation (BNF).

Sowing was performed manually, row spacing was 0.50 m, and plant population varied according to cultivar and germination tests (BRASIL 2009).

For the control of weeds, it was used in pre-emergence (Flumioxanain 500 g/L) and in post-emergence (glyphosate N-(phosphonomethyl) glycine-370 g/L+ Glyphosate 445 g/L). Pest control was performed with the application of insecticides (Imidacloprid 700 g/kg, and Lambda-cyalotrine 50 g/L). Fungal disease control was performed with fungicide (Tebuconazole 200 g/L+Trifloxistrobin 100 g/L).

Experimental design

The experimental design used was in randomized blocks, with five replications and the treatments were six soybean cultivars of high productive potential, different growth habits, and maturation groups, according to Table 2.

Table 2. Soybean cultivars, maturation group, and growth habit used at work. Rio Largo, Alagoas.

Cultivate	Maturation group	Growth Habit
M 6210*	6.2	Indeterminate
M 6410	6.4	Indeterminate
BMX-Potência RR	6.7	Indeterminate
AS 3730	7.3	Indeterminate
M 8349	8.3	Determinate
BRS-9383	9.3	Determinate

*M-Monsoy; BRS - National Soybean Research Center (Embrapa Soja); BMX-Brasmax; AS- Agroeste Sementes.

The growth of soybean cultivars may present a determined, semi-determinate, or indeterminate form. The experimental area was 35.0 m long by 33.0 m wide, totaling 1,155 m^2. In each block, six plots composed of 10 rows with 5.0 m length were fixed, spaced at 0.50 m, totaling 25.0 m^2, where soybean cultivars were seeded.

Biometric data and modeling

Growth data were collected every 10 days, within the plots, useful areas of 1.0 m^2 were marked, selecting five plants of each treatment. The following variables were evaluated: plant height (PH, cm), dry mass of plants (PDM, g), and leaf area index (LAI).

The PH was measured with a graduated ruler from the root neck to the highest part considering the vegetative canopy, and the observed data were adjusted to the Logistic growth model. The determination of the initial (W0), final (Wf) and relative growth rates (r) were based on the methodology used by LYRA et al. (2014), according to Equation 2:

$$W = \frac{\mathrm{W_f}}{\left[1 + (\frac{W_f}{W_0} - 1)\exp(-\mathrm{r} \sum \mathrm{DAS})\right]} \quad (2)$$

in which: W (cm): is the growth variable; W_o and W_f (cm): correspond, respectively, to the initial and final growth rate of the crop cycle; r (cm $^{day-1}$): is the maximum relative growth rate, calculated on the basis of Equation 3; ΣDAS: represents the growth period in days after sowing.

$$TCR = \frac{Ln(h_2) - Ln(h_1)}{T_2 - T_1} \quad (3)$$

in which: h_2: is the current height of the plant (cm); h_1:is the previous height of the plant (cm); T_2 is the current time (days); T_1 is the previous time (days).

The PDM had a destructive character, and the plants were separated into leaves, stems and pods. This material was packed in craft paper bags, and weighed on a precision scale, then taken to the forced ventilation oven at 65 °C for 72 h (BENINCASA 2003). The observed data were adjusted to the Sigmoidal model of four parameters, according to Equation 4:

$$PDM = \frac{a}{(1 + \exp(-\frac{(DAS - x_0)}{b})} \quad (4)$$

in which: PDM: is the dry mass of plants (g); a: final dry matter (g); x_0: inflection point (g) and represents the asymptote, that is, the maximum value of the growth variable to be reached by plants; b: initial growth and x is the value to estimate DAS.

The leaf area (PA) of the plants was calculated by adding the area of individual leaves, measured by the product between the length and width of a leaflet multiplied by three, and then multiplied by the correction factor of 0.70, then multiplied by the number of leaves of each plant to estimate the leaf area, according to Equation 5:

$$LA = C * L * 3 * 0{,}7 * NF * NP \quad (5)$$

where: LA: is the leaf area (m^2); C is the length of the leaflet (m); L: is the width of the leaflet (m); 3: is the number of leaflets per sheet; 0.7: is the leaf shPHe correction factor; NF: leaf numbers per plant; NP: is the number of plants per m^2.

The LAI was obtained by the relation between the leaf area and the area occupied by m², according to Equation 6, and then adjusted for one hectare. For adjustment, the Pic Log Normal model, Equation 7, was used.

$$LAI = \frac{LA}{AOP} \quad (6)$$

in which: LAI: Leaf Area Index; LA: leaf area (m²); AOP: Occupied collection area in each treatment (1 m²).

$$LAI = a \exp\left[-0{,}5 \left\{\ln \frac{\left(\frac{\sum DAS}{xo}\right)}{b}\right\}^2\right] \quad (7)$$

in which: a: maximum LAI value; b: minimum AFI value; x_0: represents the asymptote, that is, the DAS in which the maximum LAI occurs; ΣDAS: represents the sum of days after sowing in the growth period.

The models were submitted to student's t-test (p≤0.05), and their accuracy was evaluated using the adjusted regression coefficient (R^2_{ajs}), Willmott's agreement index, (d) and Pearson's correlation coefficient (r). For the evaluation of the data estimated by the models, we used the standard error of the estimate (EPE), which provides the mean deviation between the observed and estimated values.

R^2_{ajs} is the percentage of variation in response that is explained by the model, adjusted for the number of predictors in relation to the number of observations, according to Equation 8. The higher the value of $R^2_{ajs,}$ the better the model's performance.

$$R^2_{ajs} = 1 - \left[\frac{(1 - R^2)(n - i)}{n - p}\right] \quad (8)$$

in which, p: is the number of parameters assumed by the model; n: is the number of samples or measurements, I: is the ratio of interception of the curve of the values observed with the curve of the model, considering 1 if there is interception of the curves with the points.

The agreement index proposed by WILLMOTT (1982) evaluates the agreement between the simulated points and observed points through the approximation or distance of the data, this coefficient is represented by the letter "d", which varies from zero to one, in which zero indicates nullity, and one indicates the accuracy, according to the Equation 9.

$$d = 1 - \left[\frac{\sum_{i=1}^{N}(Si - Oi)^2 \qquad 1}{\sum_{i=0}^{N}(|Si\ -\ \bar{o}| + |Oi\ -\ \bar{o}|)^2}\right] \quad (9)$$

in which: Si: is the value estimated by the model on day i; Oi: is the value observed on day *i* and ō is the average of the observed values.

Pearson's correlation coefficient "r" values the degree of association between two variables, indicating the correlation between observed and simulated data, this correlation can be positive or negative according to, Equation 10.

$$r = \frac{\sum OiSi - \frac{\sum Si \times \sum Oi}{N}}{(N - 1) \times Soi\ * Ssi} \quad (10)$$

in which, *r:* is Pearson's correlation coefficient; ΣOi: is the sum of the products between the observed and estimated values; ΣOi * ΣSi: is the product of the sum of the values of oi and si; N: is the number of observations; SOi: is the standard deviation of the oi values and the SSi: is the standard deviation of the si values.

The Standard Error of Estimation provides the mean deviation between the observed and estimated values, Equation 11.

$$EPE = \sqrt{\frac{(Si - Oi)^2}{N - 2}} \quad (11)$$

in which: Si: is the value estimated by the model on day i; Oi: is the value observed on day i and ō is the average of the observed values; N is the number of samples.

Grain yield

Agricultural Productivity (PH) ($Mg.ha^{-1}$) was calculated from the dry mass of the grains (13%), collected in the useful area of 4.0 m^2 of each plot and subsequently estimated for one hectare, Equation 12.

$$Y = \frac{M}{C * E} * 10.000 \quad (12)$$

in which: Y: is agricultural productivity (Mg ha^{-1}); M: is the mass collected in the sampled area (t); C: is the total length of the harvested lines (m); E: is the spacing between lines (m).

The data were submitted to analysis by the F test, and when there was a significant effect, the univariate cluster analysis was used by the Scott-Knott test (p-0.05), to avoid ambiguities in the comparison of means.

RESULTS AND DISCUSSION

Weather conditions and water availability

The average air temperature, maximum daily, recorded in the irrigated experiment was 30.2 ºC at 126 DAS (03/20/2019), with an average value of 26.50 ºC and a minimum of 23.9 ºC at 75 DAS (01/28/2019). The air temperature during the rainfed experiment was lower than the irrigated one (Figure 2A).

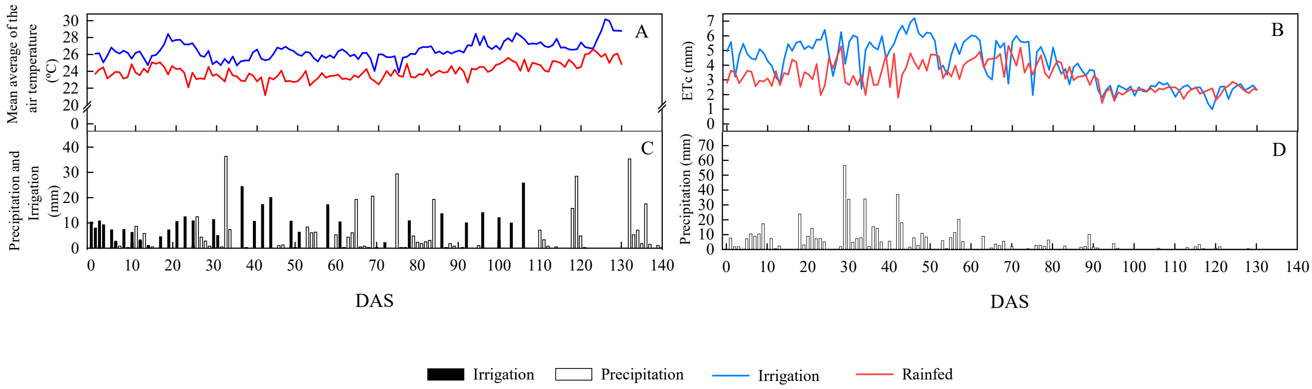


Figure 2. Meteorological variables temperature (A), crop evapotranspiration (B), Precipitation and irrigation (C) in the period from November 14, 2018, to April 4, 2019, and Precipitation (D). Rio Largo, Alagoas.

The maximum average daily air temperature recorded was 26.6 ºC at 123 DAS (10/21/2019), average of 24 ºC and minimum average of 21.2 ºC at 42 DAS (08/01/2019). Therefore, there were no thermal limitations for soybean growth, whose thermal range is adequate for its growth and development is between 20 and 30 °C (FARIAS et al. 2009).

Crop evapotranspiration (ETc) during the irrigated cycle was higher in relation to the dry land, which can be justified by the higher incidence of solar radiation and temperature on the vegetative canopy and soil increases transpiration and evaporation of water into the atmosphere. Figure 2B shows the variation of ETc in both experiments. In the irrigated, the maximum ETc value was 7.20 mm day^{-1}, at 46 DAS, with an average of 3.90 mm day^{-1} and a minimum of 0.99 mm day^{-1}, at 119 DAS, at the end of the experiment, 554 mm were added, during 140 days of cultivation. In the ground, the ETc totaled 422 mm, in 130 days of cultivation, with a maximum of 5.31 mm day^{-1} at 69 DAS, a mean 3.22 mm, and a minimum of 1.42 mm day^{-1} at 92 DAS.

In relation to rainfall, in the irrigated experiment, rainfall events occurred in 28 days (20%) of the 140 days of the cultivars' cycle. Rainfall totaled 375 mm, November was the least rainy month (25.0 mm) and January the wettest (109.20 mm). The largest precipitation event was 36.32 mm day^{-1} at 33 DAS (12/17/2018) and the average of 2.70 mm day^{-1} (Figure 2C).

It took 345.30 mm to meet the water demand of the plants since 70 days occurred without rain, which corresponds to 50% of the cultivar cycle, the largest blade applied was 25.85 mm, the average blade was 10.46 mm and minimum value was 2.26 mm. There was an increase in water availability to the crop, observed by the total depth (effective precipitation + irrigation) of 720 mm.

Regarding the cycle in the land, there was excess in 24 days of cycle (18.46%) and 44 days without rain (33%). The highest rainfall occurred at 29 DAS, equivalent to 56 mm (Figure 2D). Rainfall totaled 547.37 mm.

For this cycle, rainfall events occurred in 87 days (67%) of the 130 days of cultivation, Figure 2D. In July there were 26 days with rain, with total precipitation of 269.50 mm, while in September and October the precipitations were 39.1 and 11.20 mm, respectively.

Biometric data and modeling

Plant height

The coefficients of the model adjusted for PH ($W_{f\,and}$ r) were significant by student's t test (p<0.01) (Table 3). The estimated data presented R^2_{ajs} between 0.94 and 0.99, Willmott agreement index (d) higher than 0.99, Person correlation index of 0.99 and EPE ranged from ± 7.38 (BRS-9383) to ± 2.45 (M 6410) and mean of ± 4.46 (Table 3).

Table 3. The logistic model estimated plant height (PH) for soybean, irrigated and rainfed cultivars. Rio Largo, Alagoas.

Cultivars	Parameters – Plant height (cm)				
	Wf_O	W_f	W_0	R	R^2_{ajs}
	Irrigated				
M 6210	90.12	93.65**	2.52*	0.108**	0.99
M 6410	90.48	92.40**	2.46*	0.106**	0.99
BMX-Potência	96.34	101.16**	2.11^{ns}	0.11**	0.98
AS 3730	98.10	101.24**	2.025*	0.105**	0.99
M 8349	96.13	107.42**	2.76^{ns}	0.115**	0.96
BRS-9383	98.45	110.35**	2.72^{ns}	0.101**	0.95
	Rainfed				
M 6210	42.60	48.32**	1.68^{ns}	0,118*	0.93
M 6410	42.97	49.90**	1.87^{ns}	0,116*	0.91
BMX-Potência	46.42	52.51**	1.45^{ns}	0,130*	0.91
AS 3730	41.45	44.54**	1.72*	0,116*	0.97
M 8349	58.10	67.32**	2.03^{ns}	0,118**	0.94
BRS-9383	62.91	72.85**	1.59^{ns}	0,130**	0.94

Cultivars	r		d		EPE	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
M 6210	0.997	0.978	0.998	0.988	± 3.00	± 4.02
M 6410	0.998	0.944	0.999	0.973	± 2.45	± 5.78
BMX-Potência	0.995	0.974	0.997	0.987	± 4.35	± 4.85
AS 3730	0.998	0.985	0.999	0.993	± 2.75	± 2.95
M 8349	0.989	0.980	0.994	0.993	± 6.38	± 5.21
BRS-9383	0.984	0.978	0.992	0.989	± 7.83	± 5.99

**significant at the level of 1%; *significant at the level of 5%; ns: not significant by t-test. Final height observed (Wf_o, cm), initial (W_0, cm) and final (W_f, cm) and relative growth rate, r (cm cm day^{-1}), adjusted by the Logistic model. Adjusted regression coefficient (R^2_{ajs}), Pearson correlation efficient c (r), Willmott agreement index (d) and Standard Estimation Error (EPE).

The values of this study are close to those found by BENDER et al. (2020), who evaluated the adjustment of the logistic model for the PH of cotton fertilized with different nitrogen sources in the Cerrado of Bahia. These authors verified a good accuracy with R^2_{ajs} ranging from 0.996 to 0.946, and EPE ranging from ± 3.65 to ± 2.97. Similarly, MORAIS et al. (2017) found a good adjustment of the logistic model for PA in corn crop in sowed seasons in Alagoas, with R^2_{ajs} ranging from 0.985 to 0.991. LYRA et al. (2014) also found a good adjustment of the logistic model for PH in corn crops under nitrogen levels, with R^2_{ajs} ranging from 0.989 to 0.992. Finally, ANDRADE NETO et al. (2010) also adjusted the logistic model for PA, in the culture of scorch under green fertilization and obtained R^2_{ajs} between 0.910 and 0.990.

The highest initial growths (W_0) were 2.72 and 2.76 cm for the cultivars of determined growth (M 8349 and BRS-9383), while for the indeterminate growth the averages ranged from 2.03 to 2.46 cm (Table 3). The highest final PH (W_f) was estimated in cultivars BRS-9383 and M 8349, with 110.35 and 107.42 cm, respectively.

The determined growth cultivars cease vegetative activity soon after photoperiod-induced floral induction. Because of this, they usually have a more veneered canopy with a longer main trunk length. Studies conducted by HEATHERLY & SMITH (2004) and ZANON et al. (2016) found that the determined cultivars presented a higher growth rate until flowering, while the indeterminate cultivars showed slower initial growth, but only ceased at the beginning of grain filling.

However, it was verified that irrigation favored cultivars of indeterminate growth with W_f averages estimated by the model, close to those of determined growth ranging from 93.60 to 101.16 cm. The maximum relative growth rate ranged from 0.116 to 0.130 cm^{-1} day^{-1} among cultivars. Comparing the highest W_f under irrigation of 110.35 cm, with Wf_O of 98.45 cm, at 100 DAS, in cultivar BRS-9383, it was verified that the logistic model overestimated in 10.80% the highest PH.

The overall average PH of cultivars in the ground during vegetative soybean growth was reduced by 36% in relation to irrigated, which can be attributed to water deficiency, which can reduce the size of plants due to reduced cell expansion (MONTOYA et al. 2017).

The logistic growth model showed good fit, and the final height coefficient ($W_{f)}$ was statistically significant by the t-test (p<0.01) (Table 3). R^2_{ajs} ranged from 0.94 to 0.97, Person correlation index of 0.98, Willmott 0.98 and EPE went from ± 2.95 (AS 3710) to ± 6.0 (BRS-9383), and mean of 4.80 for cultivars.

The growth cultivars BRS-9383 and M 8349 had the highest W_f, with 72.85 and 67.32 cm, respectively. The lowest PH in rainfed were estimated at 44.54 and 48.32 cm in cultivars AS 3730 and M 6210. W_0 in rainfed ranged from 1.45 to 2.03 cm; however, they were not significant for most cultivars, except for as 3730 significant at 5% probability. The maximum relative growth rate for PA in the rainfed ranged from 0.116 to 0.130 cm^{-1} day^{-1}.

Figure 3 shows that the highest PH in the rainfed was also observed in cultivar BRS-9383, with minimum, average and maximum value of: 9.00, 52.70 and 80.00 cm, at 10, 40 and 60 DAS, respectively. The logistic model described the average initial growth of 1.59 cm and average maximum canopy height as 72.85 cm with R^2_{ajd} of 0.95.

Most soybean cultivars launched in the Brazilian market have an indeterminate type of growth with lower branches. The required height of 60 cm is the minimum that soybeans should reach at harvest time, since lower values make mechanized harvesting difficult, which increases grain losses (TORRES et al. 2014, WERNER et al. 2016, PROCÓPIO et al. 2018).

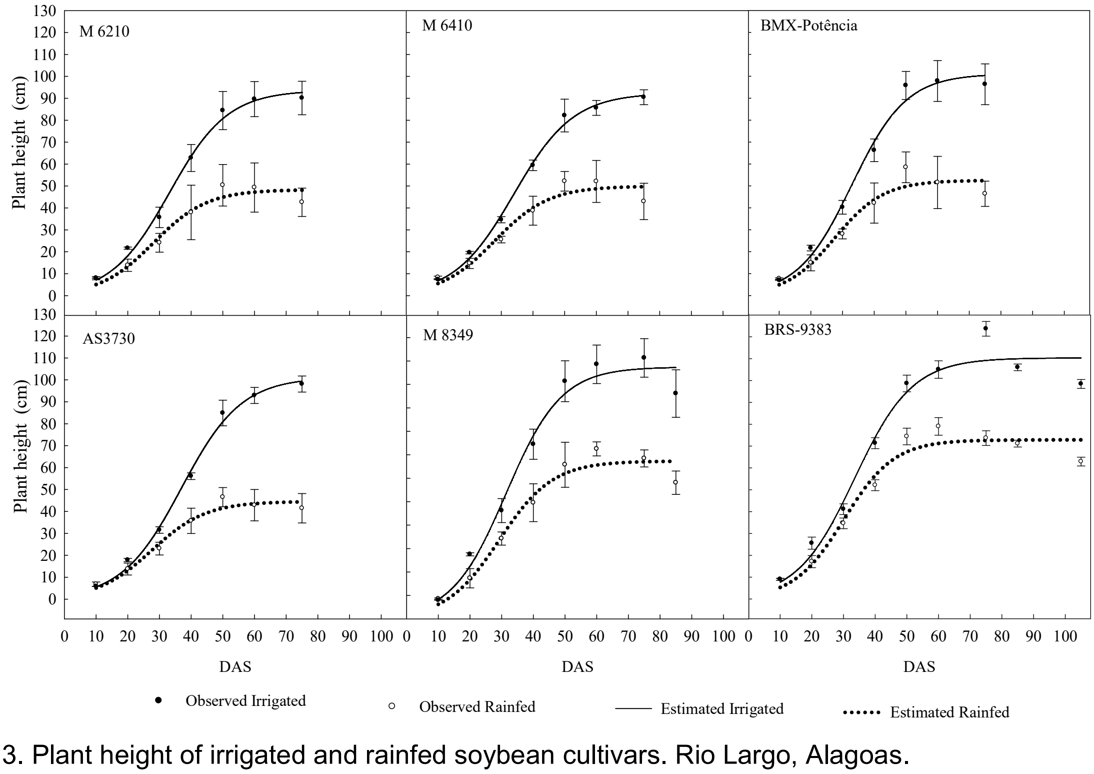


Figure 3. Plant height of irrigated and rainfed soybean cultivars. Rio Largo, Alagoas.

Plant dry matter

The different expressions of PDM accumulation in soybean cultivars, and in the conditions studied, present the sigmoidal tendency, since the increase in plant dry matter is an irreversible variable.

Figure 4 shows that the accumulation of PDM of cultivars in the initial phases is low, and it is noted that there is similarity between the experiments in this period (20 to 30 DAS), corroborating with OLIVEIRA et al. (2013), who used the Sigmoidal model for corn PDM, and verified that the initial phase of PDM allocation is slow, followed by a rapid growth phase, with an accumulation of 80-90% of the entire PDM. It can be observed the superiority in the means of PDM by cultivars when irrigated; comparing the maximum values observed, there was a considerable reduction in the order of 44.3% of the seed in relation to the irrigated one, which is justified by the lack of water along the growth of plants (Table 4).

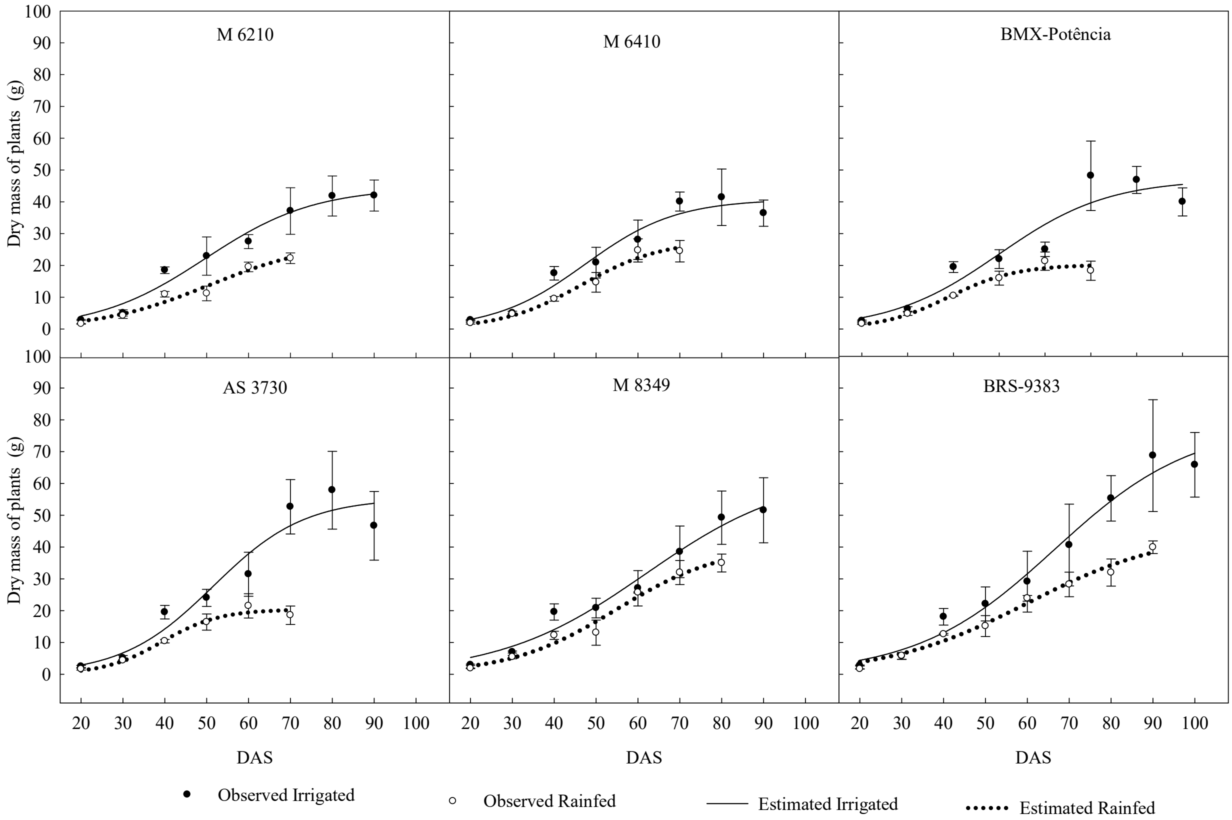


Figure 4. Dry mass of plants of irrigated and rainfed soybean cultivars. Rio Largo, Alagoas.

The Sigmoidal model showed a good fit for the PDM, and the final dry matter (a) and inflection point (x_0) parameters were statistically significant by the student's t test (p<0.01). The initial growth rate (b) had no significant effect for the cultivar BMX-Power; however, there was significance (p<05) for cultivars AS 3730 and M 6410, and significance (p<0.01) for the other cultivars, which indicates that the model describes almost the entire variability of the PDM data (Table 4).

The final PDM observed in this experiment oscillated between 36.44 and 65.88 g. The estimated data presented R^2_{ajs} ranging from 0.86 to 0.97, Willmott agreement indexes (d) higher than 0.97, Pearson correlation index from 0.95 to 0.98. The EPE was ± 1.35 (AS 3730) to ± 2.09 (M 8349), and a mean of ± 1.69 (Table 4).

The maximum PDM values were estimated at 78.70 and 63.44 g at 100 and 90 DAS, respectively, for cultivars BRS-9383 and M 8349 (Figure 4). However, when the values of the final PDM observed are compared (a_O) with those of the estimated final PDM (a), there is an apparent overestimation in the order of 16.30 and 18.70%, respectively.

Likewise, the PDM under irrigation, the Sigmoidal model also showed a good setting in the ground (Table 4), with R^2_{ajs} ranging from 0.93 to 0.97. The Person correlation had values higher than 0.94; the Willmott index ranged from 0.96 to 0.99 and EPE from ± 1.72 (M 6410) to ± 4.89 (BMX-Power) and mean of ± 3.15 among cultivars.

The highest PDM were observed in the cultivars of determined growth, BRS-9383 and M 8349, with estimated values of 44.91 and 40.76 g, at 70 and 80 DAS, respectively. Among the cultivars of indeterminate growth, the observed values ranged from 20.26 to 27.91 g to 60 DAS (Table 4).

The maximum values observed for The PDM were 40.0 and 35.0 g in the cultivars BRS-9383 and M 8349, at 100 and 90 DAS, respectively. However, when comparing the observed data (ao) with the estimated ones (a) for the same cultivars, there is an overestimation in the order of 10.90 and 14.10%. The parameters of final dry matter (a) and inflection point (x_0) were statistically significant (p<0.01). The initial growth rate (b) had no significant effect for M 6210; however, there was significance (p<0.01) for cultivar BRS-9383, and significance (p<0.05) for the other cultivars.

Table 4. Dry mass of plants (PDM), estimated by the Sigmoidal model of 3 parameters, for irrigated and sequeiro soybean cultivars. Rio Largo, Alagoas.

Cultivars	Parameters – Plant Dry Mass (g)				
	a_O	a	x_0	b	R^2_{ajs}
	Irrigated				
M 6210	41.98	44.42**	49.70**	13.03**	0.96
M 6410	36.44	40.82**	47.40**	10.89*	0.94
BMX-Potência	40.0	47.06**	49.90**	11.92ns	0.86
AS 3730	46.70	55.30**	51.54**	10.91*	0.90
M 8349	51.59	63.44**	62.00**	17.54**	0.96
BRS-9383	65.88	78.70**	66.58**	16.50**	0.97
	Rainfed				
M 6210	22.28	27.58*	50.57*	13.14ns	0.93
M 6410	24.50	27.91**	46.61**	9.62*	0.96
BMX-Potência	18.35	20.26**	39.06**	7.35*	0.96
AS 3730	18.59	20.41**	39.31**	6.90*	0.96
M 8349	35.0	40.76**	54.86**	12.86*	0.96
BRS-9383	40.0	44.91**	60.13**	16.95**	0.97

	r		d		EPE	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
M 6210	0.988	0.961	0.992	0.978	± 1.72	± 1.81
M 6410	0.980	0.947	0.990	0.969	± 2.46	± 1.61
BMX-Potência	0.950	0.987	0.974	0.993	± 4.89	± 1.43
AS 3730	0.967	0.989	0.983	0.994	± 4.79	± 1.35
M 8349	0.988	0.963	0.994	0.977	± 2.22	± 2.09
BRS-9383	0.991	0.992	0.995	0.996	± 2.82	± 1.86

**significant at the level of 1%; *significant at the level of 5%; ns: not significant by t-test. a_O: final dry matter observed (g); a: estimated final dry matter (g); x_0: inflection point (g); e b: initial dry mass, adjusted by the Sigmoidal model of 3 parameters. Adjusted regression coefficient (R^2_{ajs}), Pearson correlation coefficients (r), Willmott agreement index (d) and Standard Estimation Error (EPE).

LAI

Regarding the LAI for irrigated soybean cultivars, the adjustment of the normal Pic log model R^2_{ajs} varied between 0.989 and 0.994. The estimated data showed high agreement with those observed, by Pearson correlation indexes (r) ranging from 0.92 to 0.97, and Willmott agreement (d), between 0.94 and 1.0. The EPE varied between ± 0.51 (M 6410) and ± 1.04 (BRS-9383) (Table 5). The parameters of estimated maximum FNA (a), estimated minimum (b), and inflection point (x_0) were statistically significant (p<0.01).

BENDER et al. (2020) adjusted the pic log model for the LAI of cotton crop submitted to two nitrogen sources and verified R^2_{ajs} from 0.889 to 0.921, with P e E ranging from ±0.14 to ±1,23. LYRA et al. (2014) adjusted the pic log model for corn under six nitrogen doses and verified a good adjustment of R^2_{ajs} between 0.81 and 0.92, and EPE between ± 0.320 and ± 0.542. FERREIRA JÚNIOR et al. (2014) also evaluated the normal pic log model for the LAI of sugarcane RB98710 irrigated by drip in two types of spacing and verified R^2_{ajs} ranging from 0.989 to 0.980.

The maximum estimated point among cultivars for the LAI under irrigation occurred on average, at 52 DAS, with an estimated average value of 5.8, which is equivalent to 5.8 m² of leaves for 1 m² of soil. The cultivars of determined growth BRS-9383 and M 8349 presented the highest LAIs, of 7.60 and 6.27, respectively, at 58 and 50 DAS. The cultivar M 6410 had the lowest maximum LAI value (4.75), estimated at 50 DAS (Table 5).

The highest value of maximum LAI observed under irrigation was 7.68, observed in cultivar BRS-9383. In cultivar M 6410, the lowest maximum INA observed was identified, which was 5.3 (Figure 5). Studies conducted by BALBINOT JUNIOR et al. (2018), TAGLIPHIETRA et al. (2018) indicate that the optimum LAI to maximize productivity in modern cultivars ranges from 6.0 to 6.5.

Table 5. Leaf area index (LAI), estimated by the Normal Pic Log model, for soybean, irrigated rainfed cultivars. Rio Largo, Alagoas.

Cultivars	Parameters				
	Leaf Area Index (LAI)				
	a_o	a	b	x_0	R_{ajs}^2
	Irrigated				
M 6210	5.98	5.55**	0.39**	50.24**	0.94
M 6410	5.31	4.75**	0.40**	49.82**	0.93
BMX-Potência	6.73	5.76**	0.44**	49.16**	0.86
AS 3730	5.26	5.13**	0.39**	51.62**	0.96
M 8349	7.23	6.27**	0.46**	50.33**	0.94
BRS-9383	7.68	7.60**	0.44**	57.84**	0.89
	Rainfed				
M 6210	2.86	2.70**	0.36**	46.93**	0.87
M 6410	2.76	2.49**	0.28**	54.50**	0.92
BMX-Potência	3.25	3.17**	0.34**	47.00**	0.81
AS 3730	1.83	1.83**	0.28**	53.35**	0.92
M 8349	5.67	4.76**	0.35**	56.00**	0.90
BRS-9383	6.34	6.26**	0.38**	61.58**	0.87

	R		d		EPE	
	Rainfed	Irrigated	Rainfed	Rainfed	Irrigated	Rainfed
M 6210	0.972	0.751	0.983	0.967	± 0.53	± 0.14
M 6410	0.966	0.941	0.983	0.968	± 0.51	± 0.14
BMX-Potência	0.928	0.906	0.96	0.950	± 0.92	± 0.34
AS 3730	0.933	0.954	0.948	0.976	± 0.94	± 0.06
M 8349	0.967	0.954	1.00	0.976	± 0.58	± 0.39
BRS-9383	0.942	0.935	0.969	0.965	± 1.04	± 0.89

**significant at the level of 1%; *significant at the level of 5%; ns: not significant by the maximum observed LAI t. test (a_o), LAI estimated maximum (a), LAI estimated minimum (b), and the DAS in which the maximum LAI occurs (x_0), adjusted by model Normal Pic Log. Adjusted regression coefficient (R^2_{ajs}), Pearson correlation coefficients (r), Willmott agreement index (d) and Standard Estimation Error (EPE).

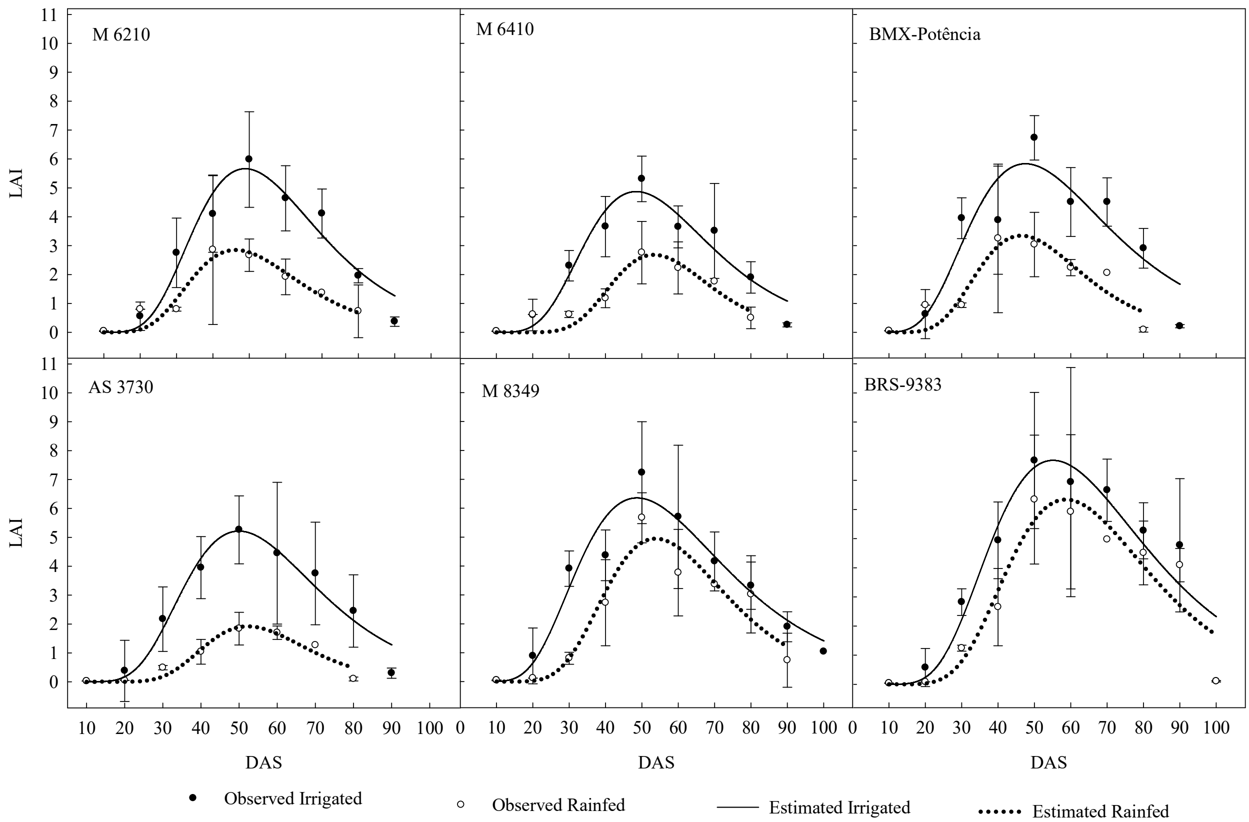


Figure 5. Leaf area index (LAI) of irrigated and rainfed soybean cultivars. Rio Largo, Alagoas.

The leaf area of soybean is a critical variable for yield and is influenced by abiotic (solar and temperature radiation) and biotic (pest and disease) factors, and the maximum soybean yield is determined by the ability of plants to intercept solar radiation through the leaf area index (LAI) and convert this radiation into dry matter by the photosynthetic process (ZANON et al. 2016, TAGLIPHIETRA et al. 2018).

However, excess leaves can compromise photosynthetic efficiency since there is shading of the abaxial parts of the canopy, in addition, an ideal microclimate for fungal diseases is created (ZOTTIS 2015, BALBINOT JUNIOR et al. 2018).

The estimated DATA of LAI of cultivars in rainfed showed accuracy, with R^2_{ajs} between 0.81 and 0.92 (Table 5), with Pearson correlation index (r) ranging from 0.75 to 0.95 and Willmott's agreement (d) was higher than 0.95. The EPE ranged from ± 0.51 (AS3730) to ± 0.89 (BRS-9383), with an average of 0.33 among cultivars. The parameters of estimated maximum LAI (a), estimated minimum (b), and inflection point (x_0) were statistically significant ($p<0.01$).

In general, it was observed in this research that the LAI of soybean cultivars is reduced by water stress, comparing the means of the maximum points observed under irrigation with those of the rainfed, there was a reduction in the order of 43% (Table 5).

The growth cultivars BRS-9383 and M 8349 had the highest LAIs observed of 6.34 and 5.67, respectively, at 50 DAS, and estimated of 6.34 and 4.76, at 62 and 56 DAS. Among the cultivars of indeterminate growth, the highest LAI, observed and estimated was 3.25 and 3.17, respectively, in the cultivar BMX-Potência; and the lowest observed and estimated point was 1.83 (AS 3730) at 50 and 53 DAS.

Grain yield

Regarding yield, the cultivars showed a significant difference at 1% probability in both experiments (Table 6).

Table 6. Analysis of variance for agricultural productivity (PA) (Mg ha^{-1}) of irrigated and rainfed soybean cultivars. Rio Largo, Alagoas.

Sources of variation	GL[1]	Average Square Values[2]	
		Agricultural Productivity (Mg ha^{-1})	
		Irrigated	Rainfed
Cultivars (C)	5	3.29**	1.130**
Block	4	0.18^{ns}	0.048^{ns}
Residue	20	0.43	0.067
Total	29	-	-
CV (%)		12.33	8.75

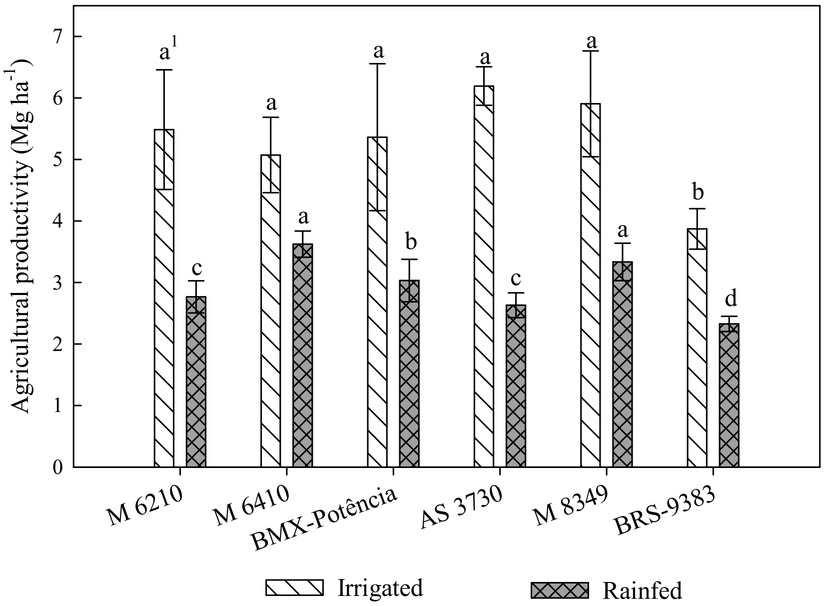
[1]Degrees of freedom; [2]**Significant at the level of 1% by the F test.

The observed means of BP were grouped into two groups by the Scott-Knott test ($p\leq0.05$). The highest yields were observed in cultivars AS 3730 (6.19 Mg ha^{-1}) and M 8349 (5.90 Mg ha^{-1}), cultivars M 6210, BMX-Potência and M 6410 presented BP of 5.48, 5.36 and 5.07 Mg ha^{-1}, respectively (Figure 6). The second group with the lowest yield mean (3.48 Mg ha^{-1}) was observed in cultivar BRS-9383. In general, the average of 5.32 Mg ha^{-1} was observed for cultivars under irrigation.

For PA in rainfed, the Scott-Knott test formed four distinct groups. The first with cultivars M 6410 and M 8349, with BP of 3.62 and 3.34 Mg.ha^{-1}, respectively. The second group with cultivar BMX-Potency, with BP of 3.03 Mg ha^{-1}. The third group with cultivars M 6210 and AS 3730, with BP of 2.76 and 2.63 Mg ha^{-1}, respectively. The fourth group had the lowest yield value, observed in cultivar BRS-9383, with 2.33 Mg ha^{-1}. PROCÓPIO et al. (2018) evaluated the BP of 8 soybean cultivars in rainfed and verified averages ranging from 1.783 (BRSGO-8660) to 4.332 Mg ha^{-1} (BRS-9280).

Sharp reductions in the order of 44.3% in the yield of the cultivars of seed soybean (2.95 Mg ha^{-1}) were observed when compared to the general average of cultivars under irrigation (5.30 Mg ha^{-1}) (Figure 6). Possibly, in rainfed conditions there were problems for crop yield, considering the relationships between water availability and its influence on different soybean cultivars.

Further work should be developed to evaluate the productivity of cultivars in different water fractions, which evidently improves the understanding of soybean growth and productivity within an economic level of water use in the agricultural environment.



[1]The averages followed by the same letter do not differ from each other by the Scott-Knott test (1974) at $p<0.05$.

Figure 6. Agricultural productivity (Mg ha^{-1}) of irrigated and rainfed soybean cultivars. Rio Largo, Alagoas

CONCLUSION

The Logistic, Sigmoidal, and normal Pic log models showed statistically significant adjustments for plant height, plant dry matter and leaf area index, and can be used to evaluate soybean plant growth over the days after planting.

The growth of soybean cultivars varied under irrigation and rainfed conditions, and the irrigated presented the highest growth rates, regardless of the growth habit of the cultivars.

The cultivars M 6410 and M 8349 were more productive, and are indicated for planting in the region under irrigation and rainfed conditions.

The data from this research present significant contributions to the literature and can be used in future academic and/or fieldwork.

ACKNOWLEDGEMENTS

The authors would like to thank the Fundação de Amparo à Pesquisa do Estado de Alagoas – FAPEAL, the Council for Scientific and Technological Development – CNPq and the Coordination for the Improvement of Higher Education Personnel – CAPES.

REFERENCES

ANDRADE NETO RC et al. 2010. Crescimento e produtividade do sorgo forrageiro BR 601 sob adubação verde. Revista Brasileira de Engenharia Agrícola e Ambiental 14: 124-130.

ALLEN RG et al. 1998. Crop Evapotranspiration (guidelines for computing crop water requirements). Roma: FAO. Irrigation and Drainage Paper 56.

BALBINOT JUNIOR AA et al. 2018. Phenotypic plasticity in a soybean cultivar with indeterminate growth type. Pesquisa Agropecuária Brasileira 53: 1038-1044.

BENINCASA MMP. 2003. Análise de crescimento de plantas: noções básicas. 2.ed. Jaboticabal: FUNEP. 41p.

BENDER EP et al. 2020. Modelagem do crescimento e produtividade do algodão em cultivo comercial no cerrado baiano. Nativa 8: 403-412.

BOFF H et al. 2019. Ensaio de cultivares em rede. Passo Fundo: Revista ECR Soja. p.1-44.

BATTISTI R et al. 2018. Sensitivity and requirement of improvements of four soybean crop. International Journal of Biometeorology 62: 823-832.

BRASIL. 2009. Ministério da Agricultura, Pecuária e Abastecimento. Regras para análise de sementes**.** Brasilia: MPHA/ACS. 398p.

CARVALHO AL et al. 2013. Ocorrência de períodos secos na região de Rio Largo, Alagoas. Revista Brasileira de Meteorologia 28: 173-180.

CONAB. 2022. Companhia Nacional de Abastecimento. Acompanhamento da Safra Brasileira de Grãos. 8º Levantamento - Safra 2021/22. Disponível em: https://www.conab.gov.br/info-agro/safras/graos/boletim-da-safra-de-graos. Acesso em: 14 mai. 2022.

CRUZ JC et al. 2015. Quatrocentos e setenta e sete cultivares de milho estão disponíveis no mercado de sementes do Brasil para a safra 2015/16. Sete Alagoas: EmbrPHa Milho e Sorgo. 28p. (Documentos 184).
FARIAS JRB et al. 2009. Soja. In: MONTEIRO JIBA (org.). Agrometeorologia dos cultivos. Brasília: INMET. p. 263-277
FERREIRA JÚNIOR RA et al. 2014. Cana de açúcar com irrigação por gotejamento em dois espaçamentos entrelinhas de plantio. Revista Brasileira de Engenharia Agrícola e Ambiental 18: 798-804.
HEATHERLY LG & SMITH JR. 2004. Effect of soybean stem growth habit on height and node number after beginning bloom in the midsouthern USA. Crop Science 44: 1855-1859.
IPA. 2008. Instituto Agronômico de Pernambuco. Recomendação de adubação para o Estado de Pernambuco: 2ª aproximação. 3.ed. Recife: IPA. 212p.
LYRA GB et al. 2014. Crescimento e produtividade do milho, submetido a doses de nitrogênio nos Tabuleiros Costeiros de Alagoas. Revista Ceres 61: 578-586.
MONTOYA F et al. 2017. Effects of irrigation regime on the growth and yield of irrigated soybean in temperate humid climatic conditions. Agricultural Water Management 193: 30-45.
MORAIS RBG et al. 2017. Crescimento e produtividade de milho em diferentes épocas de plantio, nos Tabuleiros Costeiros de Alagoas. Revista Brasileira de Milho e Sorgo 16: 109-119.
OLIVEIRA P et al. 2013. Crescimento e produtividade de milho em função da cultura antecessora. Pesquisa Agropecuária Tropical 43: 239-246.
PROCÓPIO SO et al. 2018. Estudos de população de plantas de soja na região do SEALBA. Aracaju: EmbrPHa Tabuleiros Costeiros. 24p. (Boletim de Pesquisa 134).
SANTIAGO AD et al. 2019. Desempenho de cultivares de soja em áreas com histórico de produção de cana-de-açúcar no Sealba. Aracajú: Embrapa Tabuleiros Costeiros. 30p. (Boletim de Pesquisa 142).
SENTELHAS PC et al. 2015. The soybean yield gPH in Brazil - magnitude, causes and possible solutions for a sustainable production Journal of Agricultural Science. p. 1-18.
SEDIYAMA T et al. 2015. Soja: do plantio à colheita. Viçosa: UFV. 333p.
TAGLIPHIETRA EL et al. 2018. Optimum leaf area index to reach soybean yield potential in subtropical environment. Agronomy Journal 110: 932-938.
THORNTHWAITE CW & MATHER JR. 1955.The water balance. Publications in Climatology, New Jersey: Drexel Inst. Of Technology. 104p.
TOLEDO NT et al. 2010. Ajuste do modelo fototérmico de estimativa do desenvolvimento e do índice de área foliar de soja. Revista Brasileira de Engenharia Agrícola e Ambiental 14: 288-295.
TORRES FE et al. 2014. Desempenho de genótipos de soja nas condições edafoclimáticas do ecótono Cerrado-Pantanal. Interações 15: 71-78.
TRENTIN R et al. 2013. Subperíodos fenológicos e ciclo da soja conforme grupos de maturidade e datas de semeadura. Pesquisa Agropecuária Brasileira 48: 703-713.
USDA. 2022. United States Department of Agriculture. A produção mundial de soja na safra 2019/2020. Disponível em: <http://www.usdabrazil.org.br/home/>. Acesso em: 02 Mai. 2022.
WERNER F et al. 2016. Soybean growth affected by seeding rate and mineral nitrogen. Revista Brasileira de Engenharia Agrícola e Ambiental 19: 734-738.
WILLMOTT CJ. 1982. Some comments on the evaluation of model performance. Bulletin of the American Meteorological Society 63:1309-1313.
ZANON AJ et al. 2016. Efeito do tipo de crescimento no desenvolvimento de cultivares modernas de soja pós o início do florescimento no Rio Grande do Sul. Bragantia 75: 446-458.
ZOTTIS R. 2015. Sistema de combinação de cultivares de soja, 2015. Disponível em: http://www.pioneersementes.com.br/mediacenter/artigos/183/sistema-de-combinacao-de-cultivares-de-soja. Acesso em: 20 Nov. 2020.