Nonlinear models. An approach to model irrigated and non-irrigated common bean (*Phaseolus vulgaris* L.) growth

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Abstract

Common beans reduce their development and productivity when facing soil water deficit. Comprehension about growth response under this condition can be a tool for cultivar selection and escape from scarcity periods. Therefore, the objective was to characterize bean growth in different water conditions using logistic and chanter models. Two experiments (crop season= EI and fallow season = EII) were carried out in Santa Maria, RS, Brazil in a bifactorial scheme (cultivars: Triunfo, Garapiá, FC104; water condition: irrigated, not irrigated) in a completely randomized design. Fortnightly evaluations of height, number of nodes, stem diameter, root length, aerial part, roots, and nodules dry matter were carried out. The data were adjusted according to the accumulated thermal sum by the logistic and chanter models. From the results, it is noted that there was a dissimilar performance between water conditions, cultivars, and experiments. The best adjustment occurred for stem diameter, node number, and aerial part dry matter. Between models, the logistic is the most suitable to describe common bean growth.

Keywords: water deficit; chanter; logistic; *Phaseolus vulgaris* L.

1. Introduction

The common bean (Phaseolus vulgaris) is a staple food with a high protein and mineral content, consumed daily by the majority of the Brazilian population. Despite its socio-economic importance, the oscillation of its supply is associated with weather conditions, mainly to water deficit (Miorini et al., 2011), which reduces growth and, therefore, productivity. The use of tolerant genotypes to this water condition can be a sustainable alternative. For that, it is necessary to carry out analyzes that explain the genotypes growth in water deficit conditions. Growth analysis makes it possible to measure plants' variable responses during the biological cycle without having to destroy them (Cardoso et al., 2006). Among the methodologies used for this purpose, non-linear models have the advantage over linear models, as they present biological interpretation parameters, which help explain plants' growth and development cycle (Regazzi, 2003). In annual plants, the growth phases over time or thermal accumulation present a sigmoid curve, with a slow initial growth, followed by an exponential, linear, and again slow growth with variable palsy, due to the plant senescence (Peixoto et al., 2011).

Nonlinear models are used to describe growth curves, which correspond to measurements in sequence over a given time (Fernandes et al., 2014). Growth functions are an applicable alternative to study plants' response and explain complex temporal and spatial interactions, and through computational modeling, it is possible to make predictions that can be used to generate new experimental hypotheses (Chickarmane et al., 2010). Growth models can assist in management planning, by forecasting the phenological stages occurrence time and possible escapes from stress periods, such as water deficit (WD) (Rodrigues et al., 2001). Besides, growth evaluation throughout its cycle makes it possible to identify and select inherent characteristics of each genotype (Deprá et al., 2016).

Among the curves used, Regazzi (2003) surveyed some of the most used models, such as the logistic. The author references that the sigmoid curves are distinctive of phenomena found in agriculture, characterized by a growth until the modulation point when the growth begins to decrease until a final value called an asymptote. The choice of the best model is complex and quality assessments of fit and knowledge about the study object should be considered (Puiatti et al., 2013). In bean cultivars, Martins Filho et al. (2008) evaluated the growth by Bayesian logistic regression models. Another model that has been studied is the chanter, which has the potential to adjust for measurements over time (Silva and Savian, 2019).

Models that simulate plant growth and development are studied to support the new needs of digital agriculture. Studies on common beans growth are rare, mostly in different water regimes. The frequent droughts, and the increasing water deficit periods forecast (Vicente-Serrano et al., 2020) justify this approach. Thus, the objective of the study was to characterize bean cultivar growth under different water conditions using logistic and chanter models.

2. Material and methods

The experiment was conducted at the Federal University of Santa Maria (UFSM) Crop Sciences Department, Santa Maria, RS, Brazil (29 ° 43 'S. 53 ° 43' W. 95 m) in a 150 m² shelter covered with 200 µm low-density polyethylene, with side walls covered with an anti-aphid screen. Climate, according to the Köppen classification, is of the Cfa type, humid subtropical with hot summers and undefined dry season (Kuinchtner and Buriol, 2001).

Two experiments were carried out with Triunfo and Garapiá from the State Agricultural Research Foundation (FEPAGRO), and FC104 from Brazilian public Agricultural Research Corporation (Embrapa) cultivars. The sowing of the first experiment (EI), corresponding to main season, was carried out on 08/31/2019 (Triunfo and Garapiá) and 09/20/2019 (FC104), and the second experiment (EII), corresponding to fallow season, on 27/01/2020 (Triunfo and Garapiá) and 02/16/2019 (FC104). FC104 sowing occurred on a different date because of its very early cycle, so that the pre-flowering of both cultivars concurred.

The experimental design was completely randomized with 6 treatments, in a 3x2 factorial format: 3

cultivars (Triunfo, Garapiá, and FC104) and two water regimes (WR) (irrigated and non-irrigated). Each experimental unit consisted of a vessel with a capacity of 8 L filled with Argissolo Bruno-Acinzentado alítico típico soil (Santos et al., 2018) with one plant. The basic fertilization and nitrogen-fixing bacteria inoculation were following the technical recommendations for bean cultivars (Commission of Chemistry and Soil Fertility RS / SC, 2016).

Water conditions were forced in the pre-flowering stage (R5) (Fernandez et al., 1986) through the fraction of transpirable soil water (FTSW) methodology, in which plants with WD were not irrigated until they presented 10% of transpiration of the irrigated plants that had their daily amount of transpired water refilled, according to the methodology proposed by Sinclair and Ludlow (1986). After the non-irrigated plants reached 10% of the irrigated transpiration, all plants were rehydrated and maintained in field capacity until the end of the development cycle.

The meteorological data referring to the air temperature were obtained in the automatic meteorological station A803 of the Brazilian National Institute of Meteorology (INMET) located 100m from the experiment. The daily thermal sum was determined by the number of degrees days (°C day-1) using the equation (Eq. 1):

$$DD_i = \left(\frac{TM+Tm}{2}\right) - Tb \quad (1)$$

where DD_i is the degree day (°C day^{-1}), *TM* is the daily maximum air temperature (ºC), *Tm* is the minimum daily air temperature (ºC) and Tb is the lower basal temperature of the cultivar, 10ºC (Renato et al., 2013). The accumulated DD or thermal sum (DD, ºC) were obtained by the sum of the DD_i (Eq. 2):

$$DD = \sum DD_i \quad (2)$$

For growth analysis, three plants per treatment were collected every 15 days after emergence (dae) (V1) until maturation (R9). In the EI, the harvest started on 9/23/2019 for Triunfo and Garapiá and 10/12/2019 for FC104 and ended on 12/10/2019 for all cultivars. For EII, it started on 02/14/2020 for Triunfo and Garapiá and 03/04/2020 for FC104 and ended on 04/14/2020 for all cultivars. So, for the Triunfo and Garapiá cultivars there were six harvests in the EI and EII, and for the FC104, five harvests in the EI and four in the EII.

Plants were evaluated for: height (H) of the main stem (cm), with the aid of a millimeter ruler from ground level to the last node; the number of nodes (NN), from the node of the unifoliolate leaves to the last node with fully expanded trefoil; diameter of the main stem (MSD) (cm), with the aid of a caliper, measured between the cotyledon node and the unifoliolate leaves node; root length (RL) (cm) with the aid of a millimeter ruler; aerial part (APDM) and roots (RDM) dry matter (g), in which the plants were oven-dried at 65ºC until constant weight; fresh nodules dry matter (NDM) (g); fresh nodules with a diameter greater or equal to 2 mm were oven-dried at 65ºC until constant weight.

These variables were considered as dependent variable *Y* and the *DD* (ºC day^{-1}), the independent variable X, in the logistic model (Eq. 3):

$$Y = \frac{a+4b(\exp\left(-\frac{(X-c)}{d}\right))}{(1+(\exp\left(-\frac{(X-c)}{d}\right))^2} \quad (3)$$

The data were also adjusted to the chanter model as described by Silva and Savian (2019) (Eq. 4):

$$Y = \frac{ab}{a+(b-a)\exp\{-\frac{c}{c}[1-\exp(-dX)]\}} \quad (4)$$

where: a, b, c, and d are parameters of the model.

To estimate the model parameters, the Table Curve 2D version 5.01 program was used (Table Curve 2D, 2021), which uses the iterative Levemberg-Marquardt technique for nonlinear least squares. Parameter estimations were compared between experiments for each cultivar and WC, and between cultivars and WC in each experiment, by overlapping the confidence intervals (CI) of the parameter estimates in each model. For this, the lower and upper limits of the 95% confidence interval were calculated. The fit quality of models was evaluated based on the statistics: root mean square error (RMSE), mean absolute error (MAE), Willmott's index of agreement (d), and Pearson's correlation (r) through the hydroGOF package of the R software (R Core Team, 2020).
The highest values of d and r and the lowest values of RMSE and MAE were considered for model selection. The RMSE and MAE express the magnitude of the error produced by the model, values close to zero indicate better models. Index of agreement (d) indicates the agreement of the estimated data with those observed. The r indicates the degree of dispersion and association of the simulated data in relation to the observed data.

3. Results and discussion

From the criteria for assessing the model's quality of fit (Table 1), growth curves that presented satisfactory adjustments with r above 0.70 were selected to be presented in Tables 2, 3, 4, and 5. R values above 0.90, and MEA and RMSE below 5.0 were more frequent in cultivars in WC (Table 1, 2, 3, 4, and 5), while the general curves displayed the worst performances and will not be presented. Like this, the specific curves for each cultivar vs WC are more accurate and indicated.

Table 1. Mean absolute error (MAE), root mean square error (RMSE), index of agreement (d), and Pearson's correlation coefficient (r) of the Logistic (L) and Chanter (C) models for variables as a function of accumulated thermal sum (DD) (°C day-1) of bean cultivars (Triunfo, Garapiá and FC104) in two water regimes (irrigated and non-irrigated) in experiment I (EI) and II (EII).

		EI				EII			
Character	Model	MAE	RMSE	d	r	MAE	RMSE	d	r
		Irrigated Triunfo							
H	L	10.85	13.00	0.98	0.97	13.67	16.30	0.98	0.96
H	C	6.70	10.51	0.99	0.98	44.87	72.55	0.56	0.33
MSD	L	0.03	0.04	0.99	0.98	0.03	0.04	0.99	0.98

MSD	C	0.03	0.05	0.99	0.97	0.03	0.04	0.99	0.98
NN	L	0.56	0.81	0.99	0.98	0.52	0.71	0.99	0.99
NN	C	0.55	0.70	0.99	0.99	0.45	0.60	1.00	0.99
RL	L	5.04	5.71	0.98	0.96	16.61	23.36	0.11	0.12
RL	C	3.55	4.87	0.98	0.97	7.61	10.67	0.94	0.89
APDM	L	2.82	4.28	0.97	0.95	3.04	3.80	0.95	0.91
APDM	C	5.81	8.67	0.85	0.82	2.28	3.22	0.97	0.94
RDM	L	1.62	2.32	0.95	0.91	0.94	1.16	0.98	0.95
RDM	C	2.00	2.98	0.91	0.84	1.34	1.78	0.94	0.89
NDM	L	0.06	0.08	0.95	0.91	0.07	0.19	0.94	0.89
NDM	C	0.05	0.08	0.94	0.89	0.07	0.19	0.94	0.89
Non-irrigated Triunfo									
H	L	6.96	9.77	0.98	0.96	12.92	16.20	0.94	0.89
H	C	6.48	9.51	0.98	0.96	12.13	15.13	0.95	0.91
MSD	L	0.45	0.48	0.10	0.18	0.04	0.05	0.98	0.97
MSD	C	0.02	0.03	0.99	0.98	0.05	0.06	0.98	0.96
NN	L	0.37	0.52	1.00	0.99	0.70	0.93	0.98	0.97
NN	C	0.39	0.44	1.00	0.99	0.66	0.97	0.98	0.96
RL	L	8.03	10.64	0.95	0.91	16.33	20.81	0.48	0.36
RL	C	8.13	11.18	0.95	0.90	7.01	9.51	0.95	0.90
APDM	L	1.38	1.97	0.98	0.97	1.72	2.16	0.98	0.97
APDM	C	4.00	5.26	0.84	0.74	1.81	2.18	0.98	0.97
RDM	L	2.34	4.05	0.89	0.82	1.08	1.29	0.97	0.94
RDM	C	3.36	5.39	0.74	0.64	1.14	1.62	0.94	0.90
NDM	L	0.02	0.05	0.97	0.94	0.07	0.09	0.77	0.66
NDM	C	0.04	0.07	0.91	0.85	0.05	0.08	0.80	0.68
Irrigated Garapiá									
H	L	4.56	7.15	0.99	0.98	12.05	16.01	0.95	0.91
H	C	12.98	17.40	0.92	0.85	9.00	11.48	0.98	0.96
MSD	L	0.04	0.05	0.98	0.96	0.05	0.07	0.94	0.89
MSD	C	0.04	0.05	0.98	0.97	0.03	0.05	0.97	0.94
NN	L	0.67	2.80	0.99	0.98	0.52	0.71	0.99	0.99
NN	C	0.76	1.07	0.98	0.97	0.61	0.78	0.99	0.97
RL	L	6.80	9.34	0.95	0.92	7.18	8.55	0.96	0.92
RL	C	3.55	4.87	0.98	0.97	10.50	13.37	0.82	0.92
APDM	L	2.07	2.44	0.98	0.97	6.83	17.11	0.57	0.54
APDM	C	3.94	5.41	0.89	0.83	6.78	16.23	0.61	0.63
RDM	L	2.23	3.21	0.93	0.87	2.13	3.17	0.48	0.71
RDM	C	2.23	3.48	0.91	0.84	1.20	1.89	0.91	0.85

NDM	L	0.08	0.12	0.94	0.90	0.14	0.17	0.94	0.89
NDM	C	0.09	0.15	0.90	0.83	0.22	0.32	0.65	0.53
Non-irrigated Garapiá									
H	L	9.83	11.95	0.92	0.86	11.61	15.10	0.96	0.92
H	C	9.67	14.38	0.87	0.78	7.70	9.12	0.99	0.97
MSD	L	0.05	0.05	0.97	0.94	0.08	0.09	0.89	0.81
MSD	C	0.03	0.04	0.98	0.96	0.04	0.06	0.95	0.92
NN	L	0.52	0.71	0.99	0.98	0.91	1.15	0.97	0.94
NN	C	0.50	0.71	0.99	0.98	0.93	1.23	0.97	0.94
RL	L	7.11	10.01	0.94	0.90	15.43	20.22	0.49	0.39
RL	C	6.94	9.72	0.95	0.90	9.89	12.14	0.87	0.93
APDM	L	1.52	2.04	0.97	0.94	2.82	3.53	0.93	0.88
APDM	C	1.93	2.58	0.95	0.90	2.25	3.16	0.95	0.90
RDM	L	1.82	2.85	0.96	0.92	1.31	1.90	0.92	0.86
RDM	C	2.57	4.12	0.90	0.83	1.16	1.76	0.93	0.88
NDM	L	0.05	0.10	0.94	0.89	0.17	0.24	0.74	0.62
NDM	C	0.05	0.10	0.94	0.89	0.18	0.26	0.67	0.55
Irrigated FC104									
H	L	8.07	11.42	0.98	0.96	12.05	16.01	0.95	0.91
H	C	9.67	17.43	0.95	0.91	9.00	11.48	0.98	0.96
MSD	L	0.09	0.12	0.42	0.92	0.05	0.07	0.94	0.89
MSD	C	0.04	0.04	0.97	0.94	0.03	0.05	0.97	0.94
NN	L	2.67	3.29	0.59	0.81	0.52	0.71	0.99	0.99
NN	C	0.76	1.07	0.98	0.97	0.61	0.78	0.99	0.97
RL	L	6.80	9.34	0.95	0.92	7.18	8.55	0.96	0.92
RL	C	4.13	5.15	0.98	0.95	10.50	13.37	0.82	0.92
APDM	L	2.95	5.35	0.85	0.72	6.83	17.11	0.57	0.54
APDM	C	3.33	5.03	0.86	0.75	6.78	16.23	0.61	0.63
RDM	L	3.00	4.52	0.89	0.82	2.13	3.17	0.48	0.71
RDM	C	3.40	5.60	0.81	0.71	1.20	1.89	0.91	0.85
NDM	L	0.05	0.09	0.96	0.93	0.14	0.17	0.94	0.89
NDM	C	0.12	0.19	0.73	0.61	0.22	0.32	0.65	0.53
Non-irrigated FC104									
H	L	8.33	10.82	0.98	0.96	6.08	9.00	0.99	0.99
H	C	8.07	10.91	0.98	0.96	6.08	9.28	0.99	0.98
MSD	L	0.05	0.05	0.94	0.89	0.02	0.03	0.98	0.96
MSD	C	0.04	0.05	0.94	0.90	0.04	0.06	0.95	0.92
NN	L	0.52	0.71	0.99	0.98	0.33	0.58	1.00	0.99
NN	C	0.50	0.71	0.99	0.98	1.83	3.06	0.93	0.92

RL	L	5.93	7.21	0.95	0.91	6.58	8.53	0.32	0.29
RL	C	5.20	6.69	0.96	0.92	9.89	12.14	0.87	0.93
APDM	L	0.89	1.24	0.98	0.97	1.62	2.47	0.93	0.88
APDM	C	1.16	1.41	0.98	0.96	2.25	3.16	0.95	0.90
RDM	L	1.04	1.66	0.96	0.93	1.10	1.20	0.92	0.85
RDM	C	2.67	3.76	0.68	0.57	1.16	1.76	0.93	0.88
NDM	L	0.03	0.07	0.86	0.77	0.02	0.03	0.90	0.84
NDM	C	0.05	0.09	0.55	0.47	0.18	0.26	0.67	0.55

Table 2. Parameters estimates a, b, c, and d, lower limit and upper limit of the confidence interval (CI 95%), inflection point (IP), and asymptote (AS) of the Logistic model for variables as a function of accumulated thermal sum (in °C) of bean cultivars (Triunfo, Garapiá and FC104) in two water regimes (irrigated and non-irrigated) in experiment I (EI).

	a	b	c	d	IP	AS
Height						
Upper limit	17.85	153.50	192.35	38.46		
Irrigated Triunfo	-0.61^{ns}	132.57*	184.68*	29.33*	146.05	215.6
Lower limit	-19.06	111.64	177.02	20.21		
Upper limit	17.49	107.10	200.37	41.34		
Non-irrigated Triunfo	3.67^{ns}	91.75*	190.46*	30.33*	150.51	215.6
Lower limit	-10.15	76.39	180.54	19.32		
Upper limit	15.32	108.78	173.47	25.83		
Irrigated Garapiá	6.69^{ns}	96.33*	169.71*	21.11*	141.91	197.50
Lower limit	-1.94	83.88	165.95	16.38		
Upper limit	24.74	81.98	168.74	37.69		
Non-irrigated Garapiá	6.27^{ns}	60.29*	156.84*	24.60*	124.45	189.23
Lower limit	-12.21	38.59	144.94	11.50		
Upper limit	22.47	141.90	142.25	31.36		
Irrigated FC104	0.60^{ns}	118.29*	136.26*	23.51*	105.29	167.22
Lower limit	-21.26	94.69	130.26	15.67		
Upper limit	27.03	135.64	159.38	47.36		
Non-irrigated FC104	-4.26^{ns}	107.30*	148.15*	31.24*	107.01	170.84
Lower limit	-35.55	78.96	136.92	15.12		
Main stem diameter						
Upper limit	0.25	0.63	189.90	47.14		
Irrigated Triunfo	0.17*	0.56*	183.10*	37.58*	133.61	215.6
Lower limit	0.09	0.49	176.31	28.02		
Upper limit	-	-	-	-		
Non-irrigated Triunfo	-	-	-	-	-	-

Lower limit	-	-	-	-		
Upper limit	0.38	0.69	224.38	81.86		
Irrigated Garapiá	0.19*	0.51*	198.52*	50.08*	132.57	215.6
Lower limit	0.00	0.33	172.66	18.29		
Upper limit	0.42	0.68	216.20	90.77		
Non-irrigated Garapiá	0.18 ^{ns}	0.46*	190.60*	51.40*	122.90	215.6
Lower limit	-0.06	0.24	164.99	12.04		
Upper limit	62.57	62.83	497.48	11081.96		
Irrigated FC104	0.08 ^{ns}	0.43 ^{ns}	141.29 ^{ns}	132.63 ^{ns}	35.78	170.84
Lower limit	-62.41	-61.97	-214.89	-10816.70		
Upper limit	25.21	28.34	175.45	1242.87		
Non-irrigated FC104	-1.34 ^{ns}	1.82 ^{ns}	141.29*	135.26 ^{ns}	35.78	170.84
Lower limit	-27.89	-24.69	107.14	-972.35		
Node number						
Upper limit	1.64	19.18	198.15	71.33		
Irrigated Triunfo	-2.40 ^{ns}	15.46*	187.27*	52.65*	117.93	215.6
Lower limit	-6.44	11.75	176.38	33.96		
Upper limit	0.33	17.25	191.45	66.21		
Non-irrigated Triunfo	-2.45 ^{ns}	14.70*	184.50*	53.24*	114.39	215.6
Lower limit	-5.23	12.14	177.55	40.27		
Upper limit	2.05	17.50	184.23	622.76		
Irrigated Garapiá	-1.67 ^{ns}	14.23*	176.07*	46.82*	114.41	215.6
Lower limit	-5.40	10.75	167.91	30.87		
Upper limit	1.16	19.37	189.73	79.77		
Non-irrigated Garapiá	-3.57 ^{ns}	14.95*	180.97*	59.17*	103.05	215.6
Lower limit	-8.30	10.52	79.77	38.56		
Upper limit	13.42	8.75	224.98	75.09		
Irrigated FC104	9.30*	2.41 ^{ns}	145.09*	15.96 ^{ns}	124.07	166.12
Lower limit	5.18	-3.94	65.20	-43.16		
Upper limit	-	-	-	-		
Non-irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Root length						
Upper limit	9.65E+05	2.69E+06	1.86E+06	1.63E+06		
Irrigated Triunfo	-5.84E+05 ^{ns}	1.18E+06 ^{ns}	1712700*	813880 *	64.09	215.6
Lower limit	-2.13E+06	-3.36E+05	1.57E+06	1.75E+03		
Upper limit	5.18E+05	1.50E+06	2.04E+06	1.06E+06		
Non-irrigated Triunfo	-1.61E+05 ^{ns}	872460*	1808100*	555640*	107.63	215.6

Lower limit	-8.39E+05	2.44E+05	1.57E+06	5.07E+04		
Upper limit	1.03E+09	1.07E+09	2.22E+06	1.17E+08		
Irrigated Garapiá	-1.84E+07 ns	1.91E+07 ns	1803400*	4.01E+06 ns	37.63	215.6
Lower limit	-1.07E+09	-1.03E+09	1.39E+06	-1.09E+08		
Upper limit	2.10E+10	2.11E+10	2.42E+06	1.20E+09		
Non-irrigated Garapiá	-7.55E+07 ns	7.61E+07 ns	1847800*	8.53E+06 ns	37.63	215.6
Lower limit	-2.11E+10	-2.10E+10	1.28E+06	-1.18E+09		
Upper limit	-	-	-	-		
Irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	2.44E+11	2.44E+11	1.92E+06	7.12E+09		
Non-irrigated FC104	-2.17E+08 ns	2.17E+08 ns	1475300*	1.26E+07 ns	35.78	170.84
Lower limit	-2.44E+11	-2.44E+11	1.03E+06	-7.09E+09		
Aerial part dry matter						
Upper limit	5.43	44.27	258.42	54.07		
Irrigated Triunfo	-0.10 ns	34.34*	218.79*	31.11*	177.82	37.63
Lower limit	-5.62	24.40	179.16	8.15		
Upper limit	2.77	22.05	215.02	38.56		
Non-irrigated Triunfo	0.40 ns	19.17*	202.33*	28.37*	164.97	215.6
Lower limit	-1.97	16.28	189.65	17.18		
Upper limit	4.32	29.57	190.52	19.59		
Irrigated Garapiá	2.16*	25.51*	185.59*	16.35*	164.05	207.12
Lower limit	0.01	21.46	180.65	13.11		
Upper limit	3.75	19.48	215.42	62.53		
Non-irrigated Garapiá	-0.64 ns	15.37*	194.63*	38.90*	143.41	215.6
Lower limit	-5.03	11.26	173.84	15.27		
Upper limit	5.17	23.10	155.34	25.33		
Irrigated FC104	1.95 ns	18.49*	147.49*	18.24*	123.47	170.84
Lower limit	-1.33	13.88	139.65	11.15		
Upper limit	6.88	25.10	204.59	89.99		
Non-irrigated FC104	-2.11 ns	15.95*	167.18*	46.46*	106.00	170.84
Lower limit	-11.09	6.80	129.77	2.92		
Root dry matter						
Upper limit	2.75	18.40	181.66	35.51		
Irrigated Triunfo	-0.29 ns	14.51*	172.57*	24.32*	140.55	204.59
Lower limit	-3.32	10.62	163.48	13.12		
Upper limit	4.63	25.31	194.76	19.57		
Non-irrigated Triunfo	1.22 ns	17.20*	181.67*	12.54*	165.17	198.18

Lower limit	-2.19	9.09	168.59	5.50		
Upper limit	3.41	20.48	196.38	37.86		
Irrigated Garapiá	-0.23 ns	15.33*	183.40*	24.18*	151.56	215.24
Lower limit	-3.86	10.17	170.42	10.49		
Upper limit	3.03	23.88	193.19	21.03		
Non-irrigated Garapiá	0.53 ns	19.14*	185.53*	16.09*	164.33	206.72
Lower limit	-1.97	14.41	177.87	11.16		
Upper limit	6.10	27.63	150.03	30.37		
Irrigated FC104	-0.04 ns	18.75*	136.99*	18.46*	112.67	161.30
Lower limit	-6.18	9.86	123.94	6.55		
Upper limit	2.59	15.94	146.84	15.70		
Non-irrigated FC104	0.79 ns	11.99*	137.49*	11.05*	122.93	152.04
Lower limit	-1.00	8.04	128.14	6.40		
Nodes dry matter						
Upper limit	0.06	0.59	190.25	33.13		
Irrigated Triunfo	-0.02 ns	0.46*	180.68*	23.02*	150.37	211
Lower limit	-0.11	0.34	171.11	12.91		
Upper limit	0.04	208.28	369.64	298.31		
Non-irrigated Triunfo	0.00 ns	1.24	199.44*	4.71 ns	193.24	205.64
Lower limit	-0.04	-205.79	29.23	-288.89		
Upper limit	0.09	0.85	195.05	23.43		
Irrigated Garapiá	-0.01 ns	0.66*	185.94*	17.11*	163.40	208.47
Lower limit	-0.11	0.47	176.83	10.79		
Upper limit	0.08	0.77	210.40	29.69		
Non-irrigated Garapiá	0.00 ns	0.52*	202.48*	14.36*	183.57	215.6
Lower limit	-0.08	0.27	194.55	-0.97		
Upper limit	0.09	1.31	141.84	16.90		
Irrigated FC104	0.00 ns	0.75*	132.44*	9.90*	119.41	145.48
Lower limit	-0.10	0.20	123.04	2.89		
Upper limit	0.07	28350.90	4693.69	10232.16		
Non-irrigated FC104	0.00 ns	2.32 ns	155.44 ns	3.37 ns	150.99	159.88
Lower limit	-0.07	-28346.27	-4382.81	-10225.41		

* Significant at 0.05 error probability by the t-test. ns = not significant. - indicates no adjustment or adjustment with *r* less than 0.7.

Table 3. Parameters estimates a, b, c, and d, lower limit and upper limit of the confidence interval (CI 95%), inflection point (IP), and asymptote (AS) of the Logistic model for variables as a function of accumulated thermal sum (in °C) of bean cultivars (Triunfo, Garapiá and FC104) in two water regimes (irrigated and non-irrigated) in experiment II (EII).

	a	b	c	d	IP	AS
Height						
Upper limit	32.94	197.15	868.53	215.52		
Irrigated Triunfo	-6.01 ns	160.72*	826.08*	154.51*	622.60	973.95
Lower limit	-44.97	124.29	783.63	93.49		
Upper limit	64.19	183.41	955.75	410.37		
Non-irrigated Triunfo	-14.25 ns	110.41*	841.59*	217.21*	555.54	973.95
Lower limit	-92.69	37.41	727.44	24.04		
Upper limit	418.33	810.20	920.61	1011.62		
Irrigated Garapiá	-145.20 ns	255.90 ns	807.44*	385.92 ns	299.20	973.95
Lower limit	-708.72	-298.39	694.27	-239.78		
Upper limit	1148.95	1760.32	954.31	1173.29		
Non-irrigated Garapiá	-256.13 ns	364.12 ns	819.05*	505.22 ns	227.40	973.95
Lower limit	-1661.21	-1032.08	683.79	-762.85		
Upper limit	61.46	184.74	607.50	179.03		
Irrigated FC104	0.85 ns	120.83*	542.90*	101.57*	409.13	657.78
Lower limit	-59.77	56.93	478.31	24.12		
Upper limit	26.33	162.62	613.73	107.08		
Non-irrigated FC104	9.49 ns	139.21*	597.46*	71.03*	503.91	657.78
Lower limit	-7.36	115.80	581.18	34.98		
Mean stem diameter						
Upper limit	0.43	1.23	908.23	415.24		
Irrigated Triunfo	0.01 ns	0.83*	843.79*	273.17*	484.03	973.95
Lower limit	-0.40	0.43	779.34	131.11		
Upper limit	0.59	1.41	1016.68	551.79		
Non-irrigated Triunfo	0.00 ns	0.82*	893.87*	311.30*	483.90	973.95
Lower limit	-0.60	0.24	771.06	70.81		
Upper limit	970861.93	971804.04	897.70	9.93E+06		
Irrigated Garapiá	-470.70 ns	471.45 ns	775.84*	9621.09 ns	227.40	973.95
Lower limit	-971803.34	-970861.13	653.97	-9.91E+06		
Upper limit	3431.67	3882.15	1.74E+06	2.51E+06		
Non-irrigated Garapiá	-4.68 ns	6.67 ns	5263.29 ns	4820.37 ns	227.40	973.94
Lower limit	-3441.03	-3868.81	-1.73E+06	-2.50E+06		
Upper limit	0.77	1.16	638.88	429.08		
Irrigated FC104	0.11 ns	0.53 ns	556.93*	188.22 ns	309.05	657.78
Lower limit	-0.56	-0.09	474.99	-52.64		
Upper limit	0.41	0.45	713.95	275.43		
Non-irrigated FC104	0.25*	0.31*	612.05*	146.54*	419.07	657.78

Lower limit	0.10	0.16	510.16	17.64		
Nodes number						
Upper limit	8.90	45.23	937.90	630.24		
Irrigated Triunfo	-10.88 ns	25.73*	866.12*	384.74*	467.39	973.95
Lower limit	-30.66	6.24	794.33	139.25		
Upper limit	472.04	602.11	1099.76	4587.91		
Non-irrigated Triunfo	-58.74 ns	71.55 ns	898.04*	865.39 ns	227.40	973.95
Lower limit	-589.51	-459.01	696.31	-2857.13		
Upper limit	-	-	-	-		
Irrigated Garapiá	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	1.62E+06	1.62E+06	1185417.02	1.66E+06		
Non-irrigated Garapiá	-3105.54 ns	3119.12 ns	898.97*	6134.43 ns	227.40	973.95
Lower limit	-1.62E+06	-1.62E+06	612519.15	-1.59E+06		
Upper limit	27.78	51.55	681.53	543.12		
Irrigated FC104	-5.17 ns	20.05 ns	570.16*	206.27 ns	298.51	657.78
Lower limit	-38.12	-11.45	458.78	-130.59		
Upper limit	2.85	20.80	645.10	214.77		
Non-irrigated FC104	-0.73 ns	17.44*	609.30*	163.42*	394.08	657.78
Lower limit	-4.31	14.07	573.51	112.13		
Root length						
Upper limit	-	-	-	-		
Irrigated Triunfo	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	-	-	-	-		
Non-irrigated Triunfo	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	-	-	-	-		
Irrigated Garapiá	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	7.10E+05	9.45E+09	1.51E+09	3.49E+09		
Non-irrigated Garapiá	542920*	3.41E+05 ns	4.36E+06 ns	1.49E+05 ns	416.71	455.83
Lower limit	3.76E+05	-9.45E+09	-1.51E+09	-3.49E+09		
Upper limit	9.73E+06	9.30E+06	1.56E+07	2.31E+08		
Irrigated FC104	4.26E+05 ns	6.42E+04 ns	3.56E+06 ns	2.58E+06 ns	149.60	657.78
Lower limit	-8.88E+06	-9.18E+06	-8.45E+06	-2.25E+08		
Upper limit	-	-	-	-		
Non-irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		

Aerial part dry matter						
Upper limit	9.76	39.99	941.45	338.90		
Irrigated Triunfo	-4.31 ns	27.03*	847.20*	195.66*	589.52	973.95
Lower limit	-18.37	10.06	752.95	52.42		
Upper limit	6.48	36.55	1291.29	386.51		
Non-irrigated Triunfo	-0.98 ns	25.21*	1026.56*	213.25*	745.72	227.40
Lower limit	-8.44	13.88	761.82	39.99		
Upper limit	-	-	-	-		
Irrigated Garapiá	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	590.89	749.29	1017.69	3331.91		
Non-irrigated Garapiá	-70.51 ns	89.94 ns	825.43*	608.99 ns	227.40	973.95
Lower limit	-731.92	-569.40	633.17	-2113.93		
Upper limit	-	-	-	-		
Irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	30.17	219227.58	173028.67	3223.96		
Non-irrigated FC104	-0.58 ns	345.79 ns	1788.60 ns	244.99 ns	657.78	149.60
Lower limit	-31.34	-218536.01	-169451.48	-2733.97		
Root dry matter						
Upper limit	2.05	15.57	777.63	199.65		
Irrigated Triunfo	-1.22 ns	12.36*	746.07*	150.31*	548.12	944.01
Lower limit	-4.49	9.16	714.50	100.96		
Upper limit	3.15	14.14	859.51	247.92		
Non-irrigated Triunfo	-0.57 ns	10.65*	806.97*	166.61*	587.54	973.95
Lower limit	-4.29	7.17	754.42	85.31		
Upper limit	10.59	11.70	1506.01	611.97		
Irrigated Garapiá	6.59*	2.60 ns	718.51 ns	57.74 ns	642.47	794.55
Lower limit	2.59	-6.49	-68.99	-496.48		
Upper limit	2.48E+06	2.49E+06	1237.39	2.41E+06		
Non-irrigated Garapiá	-3026.22 ns	3035.72 ns	868.41*	5864.92 ns	227.40	973.95
Lower limit	-2.49E+06	-2.48E+06	499.42	-2.40E+06		
Upper limit	33.53	51.96	616.76	772.92		
Irrigated FC104	-6.04 ns	13.40 ns	533.15*	234.61 ns	224.18	657.78
Lower limit	-45.61	-25.15	449.53	-303.70		
Upper limit	6.52	698090.70	275216.09	1452.41		
Non-irrigated FC104	1.64 ns	421.17 ns	1579.04 ns	159.83 ns	657.78	149.60
Lower limit	-3.24	-697248.36	-272058.02	-1132.75		

Nodes dry matter						
Upper limit	0.19	27.38	2735.15	696.78		
Irrigated Triunfo	0.01 ^{ns}	1.11 ^{ns}	711.02 ^{ns}	31.07 ^{ns}	699.95	744.32
Lower limit	-0.18	-25.15	-1313.11	-634.64		
Upper limit	-	-	-	-		
Non-irrigated Triunfo	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	0.26	3.01	662.19	119.01		
Irrigated Garapiá	0.04 ^{ns}	1.43 ^{ns}	610.73*	60.51*	531.04	690.42
Lower limit	-0.17	-0.15	559.27	2.02		
Upper limit	-	-	-	-		
Non-irrigated Garapiá	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	0.02	9.42	3285.44	2171.32		
Irrigated FC104	0.00 ^{ns}	0.10 ^{ns}	617.60 ^{ns}	31.65 ^{ns}	575.92	657.78
Lower limit	-0.02	-0.92	-2050.23	-2108.02		
Upper limit	0.04	5.36	2473.77	1514.32		
Non-irrigated FC104	0.00 ^{ns}	0.12 ^{ns}	620.31 ^{ns}	36.66 ^{ns}	572.03	657.77
Lower limit	-0.04	-5.12	-1233.15	-1441.00		

* Significant at 0.05 error probability by the t-test. ns = not significant. - indicates no adjustment or adjustment with r less than 0.7.

Table 4 Parameters estimates a, b, c, and d, lower limit and upper limit of the confidence interval (CI 95%), inflection point (IP), and asymptote (AS) of the Chanter model for variables as a function of accumulated thermal sum (in °C) of bean cultivars (Triunfo, Garapiá and FC104) in two water regimes (irrigated and non-irrigated) in experiment I (EI).

	a	b	c	d	IP	AS
Height						
Upper limit	20.98	124.84	0.00	0.00		
Irrigated Triunfo	8.46 ^{ns}	114.41*	0.00 ^{ns}	-0.04 ^{ns}	137.99	203.46
Lower limit	-4.06	103.99	0.00	-0.08		
Upper limit	20.53	96.91	0.01	0.01		
Non-irrigated Triunfo	7.82 ^{ns}	87.44*	0.00 ^{ns}	-0.03 ^{ns}	143.35	215.6
Lower limit	-4.89	77.97	-0.01	-0.07		
Upper limit	41.73	84.90	0.04	0.40		
Irrigated Garapiá	6.62 ^{ns}	70.78*	0.00 ^{ns}	-0.04 ^{ns}	118.62	182.11
Lower limit	-28.49	56.65	-0.03	-0.49		
Upper limit	35.79	60.33	0.04	0.26		
Non-irrigated Garapiá	6.12 ^{ns}	48.68*	0.00 ^{ns}	-0.04 ^{ns}	111.81	182.11

Lower limit	-23.55	37.04	-0.04	-0.33		
Upper limit	45.31	112.64	0.05	0.12		
Irrigated FC104	7.62 ns	94.45*	0.00 ns	-0.04 ns	96.57	166.84
Lower limit	-30.08	76.26	-0.05	-0.19		
Upper limit	33.34	107.21	0.05	0.08		
Non-irrigated FC104	7.56 ns	95.67*	0.00 ns	-0.03 ns	102.78	170.84
Lower limit	-18.23	84.13	-0.04	-0.14		
Main stem diameter						
Upper limit	0.27	0.73	0.01	0.00		
Irrigated Triunfo	0.19*	0.68*	0.00 ns	-0.02*	124.93	215.6
Lower limit	0.10	0.64	0.00	-0.04		
Upper limit	0.23	0.69	0.02	0.04		
Non-irrigated Triunfo	0.16*	0.64*	0.01 ns	-0.01 ns	115.41	215.6
Lower limit	0.08	0.58	0.00	-0.02		
Upper limit	0.33	0.73	0.01	0.00		
Irrigated Garapiá	0.25*	0.68*	0.00 ns	_0.02*	126.44	215.6
Lower limit	0.16	0.63	0.00	-0.04		
Upper limit	0.34	0.64	0.00	0.75		
Non-irrigated Garapiá	0.28*	0.61*	0.00 ns	-0.12 ns	110.70	139.39
Lower limit	0.23	0.58	0.00	-0.99		
Upper limit	19.03	0.57	2.07	33.64		
Irrigated FC104	0.21 ns	0.52*	0.00 ns	-0.06 ns	73.98	126.51
Lower limit	-18.60	0.48	-2.06	-33.76		
Upper limit	2.48	0.52	0.38	2.39		
Non-irrigated FC104	0.20 ns	0.47*	0.00 ns	-0.05 ns	70.82	138.67
Lower limit	-2.07	0.42	-0.37	-2.48		
Nodes number						
Upper limit	1.68	13.09	0.03	0.00		
Irrigated Triunfo	0.75 ns	12.40*	0.01 ns	-0.01 ns	114.60	215.6
Lower limit	-0.18	11.70	-0.01	-0.03		
Upper limit	1.33	12.01	0.03	0.00		
Non-irrigated Triunfo	0.71*	11.57*	0.01 ns	-0.01*	111.42	215.6
Lower limit	0.09	11.14	0.00	-0.02		
Upper limit	2.67	12.38	0.05	0.02		
Irrigated Garapiá	0.84 ns	11.38*	0.01 ns	-0.02 ns	108.81	215.6
Lower limit	-0.99	10.38	-0.02	-0.05		
Upper limit	1.52	11.41	0.05	0.01		
Non-irrigated Garapiá	0.57 ns	10.77*	0.02 ns	-0.01 ns	102.90	215.6

Lower limit	-0.37	10.13	-0.01	-0.03		
Upper limit	-	-	-	-		
Irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	-	-	-	-		
Non-irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Root length						
Upper limit	12.10	59.02	0.05	0.01		
Irrigated Triunfo	3.62 ns	55.05*	0.01 ns	-0.02 ns	90.60	215.57
Lower limit	-4.85	51.09	-0.02	-0.05		
Upper limit	11.32	84.34	0.22	0.05		
Non-irrigated Triunfo	1.38 ns	67.60*	0.04 ns	0.00 ns	90.73	215.6
Lower limit	-8.55	50.86	-0.13	-0.05		
Upper limit	-	-	-	-		
Irrigated Garapiá	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	4.29	74.59	0.41	0.06		
Non-irrigated Garapiá	0.36 ns	60.99 *	0.08 ns	0.01 ns	71.62	215.6
Lower limit	-3.57	47.39	-0.25	-0.05		
Upper limit	2.21	793.41	8.23	0.76		
Irrigated FC104	0.02 ns	63.17 ns	0.30 ns	0.03 ns	43.76	170.84
Lower limit	-2.17	-667.06	-7.64	-0.69		
Upper limit	8.64	1474.97	11.97	1.33		
Non-irrigated FC104	0.05 ns	63.10 ns	0.25 ns	0.03 ns	43.89	170.84
Lower limit	-8.53	-1348.76	-11.48	-1.27		
Aerial part dry matter						
Upper limit	13.54	27.83	0.86	1.36		
Irrigated Triunfo	0.09 ns	19.36*	0.01 ns	-0.04 ns	93.62	148.41
Lower limit	-13.35	10.89	-0.85	-1.44		
Upper limit	7.29	16.85	0.44	0.70		
Non-irrigated Triunfo	0.11 ns	12.59*	0.01 ns	-0.04 ns	94.69	155.41
Lower limit	-7.08	8.32	-0.43	-0.77		
Upper limit	4.33	22.98	0.22	0.15		
Irrigated Garapiá	0.14 ns	17.60*	0.01 ns	-0.02 ns	133.52	215.6
Lower limit	-4.06	12.22	-0.20	-0.19		
Upper limit	5.10	14.67	0.07	0.47		
Non-irrigated Garapiá	0.37 ns	12.57*	0.00 ns	-0.04 ns	110.55	166.09

Lower limit	-4.35	10.48	-0.06	-0.56		
Upper limit	9.17	20.92	0.33	0.30		
Irrigated FC104	2.04 ^{ns}	17.34*	0.00 ^{ns}	-0.04 ^{ns}	115.26	170.84
Lower limit	-5.10	13.56	-0.03	-0.38		
Upper limit	2.42	20.07	0.11	0.03		
Non-irrigated FC104	0.56 ^{ns}	14.53*	0.03 ^{ns}	0.00 ^{ns}	100.73	170.84
Lower limit	-1.31	8.99	-0.05	-0.04		
Root dry matter						
Upper limit	5.37	12.85	0.53	1.15		
Irrigated Triunfo	0.09 ^{ns}	10.44*	0.00 ^{ns}	-0.03 ^{ns}	115.82	185.68
Lower limit	-5.19	8.02	-0.52	-1.21		
Upper limit	-	-	-	-		
Non-irrigated Triunfo	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	3.67	15.89	0.14	0.13		
Irrigated Garapiá	0.18 ^{ns}	12.41*	0.01 ^{ns}	-0.02 ^{ns}	140.31	215.6
Lower limit	-3.31	8.93	-0.12	-0.17		
Upper limit	5.86	18.61	0.04	0.26		
Non-irrigated Garapiá	0.54 ^{ns}	14.49 ^{ns}	0.00*	-0.03 ^{ns}	154.63	215.3
Lower limit	-4.78	10.37	-0.03	-0.32		
Upper limit	4.35E+06	181559.72	2.57E+06	4.76E+06		
Irrigated FC104	0.03 ^{ns}	12.27*	0.01 ^{ns}	-0.05 ^{ns}	73.31	115.71
Lower limit	-4.35E+06	63871.39	-2.57E+06	-4.76E+06		
Upper limit	-	-	-	-		
Non-irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Node dry matter						
Upper limit	0.09	0.42	0.45	7.71		
Irrigated Triunfo	0.00 ^{ns}	0.34*	0.00 ^{ns}	-0.05 ^{ns}	144.96	185.67
Lower limit	-0.09	0.25	-0.45	-7.80		
Upper limit	0.02	0.34	428.73	1029.77		
Non-irrigated Triunfo	0.00 ^{ns}	0.24*	0.00 ^{ns}	-0.03 ^{ns}	168.84	208.80
Lower limit	-0.02	0.14	-428.73	-1029.84		
Upper limit	0.15	0.64	1.28	4.46		
Irrigated Garapiá	0.00 ^{ns}	0.49*	0.00 ^{ns}	-0.03 ^{ns}	151.07	212.88
Lower limit	-0.15	0.34	-1.27	-4.53		
Upper limit	0.02	0.56	0.97	0.41		
Non-irrigated Garapiá	0.00 ^{ns}	0.42*	0.01 ^{ns}	-0.01 ^{ns}	169.71	37.63

Lower limit	-0.02	0.29	-0.95	-0.43		
Upper limit	-	-	-	-		
Irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	-	-	-	-		
Non-irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		

* Significant at 0.05 error probability by the t-test. ns = not significant. - indicates no adjustment or adjustment with r less than 0.7.

Table 5. Parameters estimates a, b, c, and d, lower limit and upper limit of the confidence interval (CI 95%), inflection point (IP), and asymptote (AS) of the Chanter model for variables as a function of accumulated thermal sum (in °C) of bean cultivars (Triunfo, Garapiá and FC104) in two water regimes (irrigated and non-irrigated) in experiment II (EII).

	a	b	c	d	IP	AS
Height						
Upper limit	-	-	-	-		
Irrigated Triunfo	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	45.81	102.64	0.01	0.03		
Non-irrigated Triunfo	8.56 ns	90.13*	0.00 ns	-0.01 ns	519.07	930.51
Lower limit	-28.69	77.63	-0.01	-0.04		
Upper limit	26.10	113.14	0.00	0.00		
Irrigated Garapiá	8.53 ns	103.83*	0.00 ns	-0.02 ns	449.50	609.49
Lower limit	-9.03	94.52	0.00	-0.03		
Upper limit	22.46	110.06	0.00	0.00		
Non-irrigated Garapiá	8.56	102.67*	0.00 ns	-0.02*	448.69	609.49
Lower limit	-5.34	95.28	0.00	-0.03		
Upper limit	78.86	207.08	0.00	448.22		
Irrigated FC104	11.75 ns	140.00*	0.00 ns	-0.05 ns	489.78	551.98
Lower limit	-55.35	72.92	0.00	-448.31		
Upper limit	-	133.76	-	-		
Non-irrigated FC104	10.50 ns	123.08*	0.00 ns	-0.06 ns	367.42	419.85
Lower limit	-	112.41	-	-		
Main stem diameter						
Upper limit	0.41	0.84	0.00	0.00		
Irrigated Triunfo	0.31*	0.81*	0.00 ns	-0.01 ns	508.73	804.36
Lower limit	0.22	0.78	0.00	-0.03		
Upper limit	0.44	0.84	0.00	0.04		

Non-irrigated Triunfo	0.29*	0.79*	0.00 ns	-0.01 ns	529.92	973.95
Lower limit	0.14	0.73	0.00	-0.02		
Upper limit	486.95	0.75	0.01	51060.51		
Irrigated Garapiá	0.33 ns	0.71*	0.00 ns	-0.05 ns	411.63	490.04
Lower limit	-486.29	0.67	-0.01	-51060.60		
Upper limit	15.29	0.78	0.00	824.55		
Non-irrigated Garapiá	0.33 ns	0.73*	0.00 ns	-0.04 ns	413.32	497.51
Lower limit	-14.62	0.68	0.00	-824.63		
Upper limit	-	-	-	-		
Irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	-	-	-	-		
Non-irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Node number						
Upper limit	2.75	15.04	0.01	0.00		
Irrigated Triunfo	1.40*	14.44*	0.00 ns	0.00 ns	467.39	973.95
Lower limit	0.05	13.83	0.00	-0.01		
Upper limit	3.87	195.82	0.23	0.05		
Non-irrigated Triunfo	0.18 ns	16.54 ns	0.02 ns	0.00 ns	305.01	973.95
Lower limit	-3.51	-162.73	-0.19	-0.05		
Upper limit	5.62	13.85	0.01	0.00		
Irrigated Garapiá	2.68 ns	13.22*	0.00 ns	-0.01 ns	431.30	903.98
Lower limit	-0.27	12.59	0.00	-0.02		
Upper limit	7.33	14.00	0.01	0.01		
Non-irrigated Garapiá	2.20 ns	13.00*	0.00 ns	-0.01 ns	428.44	892.50
Lower limit	-1.90	12.00	0.00	-0.02		
Upper limit	-	-	-	-		
Irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	7.96	20.98	0.00	1.00		
Non-irrigated FC104	3.03 ns	16.06*	0.00 ns	-0.03 ns	488.20	577.38
Lower limit	-1.89	11.14	0.00	-1.07		
Root length						
Upper limit	2.29E+09	72.49	1349.42	8.13E+08		
Irrigated Triunfo	8.17 ns	64.99*	0.00 ns	-0.04 ns	390.32	460.18
Lower limit	-2.29E+09	57.50	-1349.42	-8.13E+08		
Upper limit	8.41E+08	69.15	524.94	3.02E+08		

Non-irrigated Triunfo	8.15 ns	62.47*	0.00 ns	-0.04 ns	391.09	460.18
Lower limit	-8.41E+08	55.79	-524.94	-3.02E+08		
Upper limit	2.78E+10	75.86	139.56	7.12E+10		
Irrigated Garapiá	39.06 ns	66.47*	0.00 ns	-0.06 ns	375.01	437.78
Lower limit	-2.80E+10	57.09	-139.56	-7.12E+10		
Upper limit	-	-	-	-		
Non-irrigated Garapiá	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	-	-	-	-		
Irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	-	-	-	-		
Non-irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Aerial part dry matter						
Upper limit	7.33	23.96	0.01	0.03		
Irrigated Triunfo	1.04 ns	21.08*	0.00 ns	-0.01 ns	549.63	938.18
Lower limit	-5.24	18.20	-0.01	-0.05		
Upper limit	3.24	43.26	0.02	0.01		
Non-irrigated Triunfo	0.65 ns	26.74*	0.00 ns	0.00 ns	723.10	227.40
Lower limit	-1.93	10.23	-0.01	-0.01		
Upper limit	-	-	-	-		
Irrigated Garapiá	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	5.48	20.90	0.00	0.01		
Non-irrigated Garapiá	0.74 ns	18.34*	0.00 ns	-0.01 ns	442.13	661.75
Lower limit	-4.01	15.78	0.00	-0.04		
Upper limit	-	-	-	-		
Irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	-	-	-	-		
Non-irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Root dry matter						
Upper limit	3.72	10.40	0.00	0.03		
Irrigated Triunfo	0.91 ns	8.95*	0.00 ns	-0.02 ns	477.89	646.82
Lower limit	-1.90	7.51	0.00	-0.07		
Upper limit	3.45	9.98	0.00	0.03		
Non-irrigated Triunfo	0.83 ns	8.67*	0.00 ns	-0.01 ns	476.46	654.32

Lower limit	-1.78	7.36	0.00	-0.06		
Upper limit	142685.11	9.48	1.01	4731130.00		
Irrigated Garapiá	0.35 ns	8.15*	0.00 ns	-0.05 ns	418.41	502.63
Lower limit	-142684.41	6.83	-1.01	-4731100.00		
Upper limit	2.26	10.45	0.02	0.02		
Non-irrigated Garapiá	0.16 ns	9.02*	0.00 ns	-0.01 ns	435.61	743.87
Lower limit	-1.95	7.59	-0.02	-0.04		
Upper limit	-	-	-	-		
Irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	-	-	-	-		
Non-irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Nodes dry matter						
Upper limit	0.52	0.67	49608.63	3.26E+12		
Irrigated Triunfo	0.00 ns	0.37*	3.40E-11	-0.04 ns	542.82	572.16
Lower limit	-0.52	0.07	-49608.63	-3.26E+12		
Upper limit	-	-	-	-		
Non-irrigated Triunfo	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	-	-	-	-		
Irrigated Garapiá	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	-	-	-	-		
Non-irrigated Garapiá	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	-	-	-	-		
Irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		
Upper limit	-	-	-	-		
Non-irrigated FC104	-	-	-	-	-	-
Lower limit	-	-	-	-		

* Significant at 0.05 error probability by the t-test. ns = not significant. - indicates no adjustment or adjustment with r less than 0.7.

Among the cultivars, FC104 showed the worst adjustment. This result is explained by the fact that the cultivar has a very early cycle, resulting in a lower number of collections over time and greater variability of the data. Poor adjustments reflect the greater heterogeneity of plants in the field, as also observed for creole maize genotypes by Deprá et al. (2016). IP corresponds to the point where the maximum growth rate occurs. Due to the difference in the growth of the genotypes, this value differs between the cultivars. In EI, the average DD for plants to reach PI in FC104 was lower than in other cultivars (98.27 ºC day^{-1} in logistics and 80.12 ºC day^{-1} in chanter), and the highest values were found in the logistic model for Triunfo (140.49 ºC day^{-1}) and the chanter model in Garapiá (123.90 ºC day^{-1}). In the EII, the water deficit was imposed in FC104 during vegetative growth, which resulted in growth delay and greater DD to reach the IP. In this experiment, the cultivar Garapiá showed the lowest IP (325.38 ºC day^{-1} in logistic and 425.40 ºC day^{-1} in the chanter) and Triunfo the peak IP average (546.52 ºC day-1 in logistic and 490.12ºC day^{-1} in the chanter). Among the variables, the RL required less DD to reach the IP, mainly because this variable is established earlier in the culture. It is important to highlight that the experiment was conducted in pots and to consider greenhouses conditions and pot sizes used before extrapolating the results to field conditions are fundamental (Casadebaig et al., 2008) because the root development in the pots experiments and field conditions can be different. APDM and RDM showed a higher IP, indicating that these variables needed greater DD to achieve maximum growth. Consequently, initially, the RL establishment occurs, and then the maximum H, NN, and MSD are reached to allow the plant to reach the highpoint of APDM and RDM.

The NDM variable also showed high IP values concerning the other variables, indicating that nodulation does not become present at the beginning of the crop growth, weakening the plant nitrogen supply in the initial stages. Common beans have a low capacity for biological nitrogen fixation compared to other legumes (Olivera et al., 2004). Pelegrin et al. (2009) noted that the use of nitrogen fertilization combined with nitrogen-fixing bacteria inoculation at the beginning of the crop cycle is fundamental for this nutrient supply and to reach the maximum genotypes productivity.

The cultivars Triunfo and Garapiá have a cycle of 87 and 86 days, respectively, from emergence to maturation (Fundação Estadual de Pesquisa Agropecuária, 2021 a, b), while FC104, 65 days until physiological maturation (Melo et al., 2017). DD required to reach IP in cultivars shows that the FC104 cycle is shorter than that of other cultivars in EI. Nevertheless, in the fallow season (EII), this cultivar was sown 20 days after the other cultivars, as there was a shortening of the days after December's summer solstice, this may have resulted in intermediate IP to the other cultivars since it took more time to accumulate required DD. The cultivars Triunfo and Garapiá, presented DD to reach the IP and similar cycles in the two experiments. The cultivars Triunfo and Garapiá, presented DD to reach the IP and similar cycles in the two experiments.

Regarding WC, when observing the IP of the irrigated and non-irrigated models, they showed, on average, lower values of 122.83 ºC day^{-1} in the EI and 429.66 ºC day-1 in the EII in the logistic model and of 110.27 ºC day^{-1} in the EI and 454.89 ºC day^{-1} in the EII in the chanter model for the non-irrigated condition and 122.83, 442.38, 111.34 and 467.04 ºC day^{-1}, respectively for the irrigated condition. Plants under water restriction limit their development, firstly inhibiting leaf and root system expansion (Taiz et al., 2017). The short time water deficit exposure can influence a greater roots-related expansion characteristic due to the plant water seeking to maintain its cellular turgor.

Comparing sowing times, the EI had a higher r in most variables compared to the EII (Table 1). The variables presented d and r less than 0.9 and MAE and RMSE above 5.0, mainly in the EII, off-season, in the chanter model, indicating that the logistic was the most accurate model. The EII showed a higher IP than the EI. This is because the sowing occurred after the summer solstice, with the shortening days and less daily solar radiation supply. After the IP, the plant generally reached the asymptote, which represents the maximum IP of the adjustment curve, and decreased the increment of the variable with the continuity of the plant's development, as observed by Deprá et al. (2016). Plant growth is influenced by photosynthesis and water and nutrient absorption (Taiz et al., 2017), which has a biological limit.

The referenced studies did not seek to adjust growth curves to many variables per experiment, demonstrating the distinction of this research. In common beans, it was adjusted for total phytomass, leaf area, leaf area index, leaf area ratio, and liquid assimilation rate (Nobrega et al., 2001). In garlic, leaf, pseudostem, bulb, and root dry matter data were adjusted (Reis et al., 2014). In corn, the height and number of leaves were evaluated (Deprá et al., 2016). For tomatoes, the weight and number of fruits per plant were studied (Sari et al., 2019). In lettuce, leaves, and shoots fresh and dry matter were adjusted (Carini et al., 2020). From the aforementioned research, it can be observed that the adjustment of growth curves for variables related to the plant stem, such as stem diameter and a number of nodes, and root variables, have not been studied. In general, the response variables that demonstrated the best fit (Tables 2, 3, 4, and 5) and the lowest error (Table 1) were: MSD, NN, and APDM, and should preferably be used to evaluate bean growth. The estimates parameters (a, b, c, d) of each cultivar vs WC were compared between each experiment (Tables 2, 3, 4 and 5) using the overlapping confidence intervals (CI) criteria, used by Deprá et al. (2016) and Carini et al. (2020). It was considered that when one of the estimates was within the CI of the other, the effect was not significant.

In the logistic model, for H, MSDNN, APMD, and RDM, parameters c, and d were the ones that most differed between experiments. In RL, only the c differed and for the NDM, the parameters a, b, c, d differed between the cultivar variations vs WC. In the chanter model, most variations cultivar x WC did not differ between experiments, and when it occurred, parameter b was the one that most fluctuated. These results indicate that the models showed different behavior between the experiments and within each variable. Similar results have also been stated for tomato genotypes (Sari et al., 2019) and lettuce (Carini et al., 2020).Analyzing the response variables within each experiment, it was possible to observe that the logistic model presented a greater number of parameters, differing between cultivars and between WC in the two experiments. In this model, parameter c was the one that most differed between cultivars in the two experiments. For the chanter model, parameter b was the one that most differed between cultivars. Between WC, in both models, in most variables, the parameters did not differ.

The chanter model marginally differed in the parameters by the t-test ($p < 0.05$) (Tables 4 and 5). Significance frequently occurred for parameter b, whereas in the logistic model, parameters b, c, d was more frequently significant (Tables 2 and 3), indicating that the chanter model shows a modest difference between the combinations. In a study with lettuce, Carini et al. (2020) perceived that the Gompertz model showed less difference between some cultivars than the logistic one and observed the need to determine specific models by character and cultivar. The models showed the same behavior for most variables. For example, for the cultivar Triunfo (irrigated) in the EI, both overestimated the value of the asymptote for H, in the logistic, there was an overestimation of 16.17 cm and in the chanter around 15.23 cm. In an experiment with lettuce, Carini et al. (2020) found that the Gompertz model overestimated the values of the variables, dissimilar to the logistic.

From our results, it is perceived that it is not possible to use an equation for different sowing dates, as the parameters differed between experiments. At large, all models tested presented low MAE and RMSE and high d and r for all the observed variables. Conversely, the logistic model was the one that showed the best performance for most of the variables, combinations of cultivars x WC and experiments. Other authors also concluded that the logistic model was the most appropriate, as in lettuce cultivars, Carini et al. (2020) analyzing Gompertz and logistic models for leaves and roots fresh and dry matter, concluded that the logistic better described growth. Seeking to adjust a model that represented the weight and number of tomato fruits per plant over the harvest time, Sari et al. (2019) tested the Brody, Gompertz, logistic, and von Bertalanffy models and concluded that the logistic was better suited to both variables. In garlic, evaluating the mirtscherlich, Gompertz, logistic, brody, and von Bertalanffy models, Reis et al. (2014) concluded that the logistics better adjusted to the data to describe the behavior of the bulb, root, and total plant dry mass accumulation. Instead, to describe the length and diameter of the cocoa fruit over time, Silva and Savian (2019) observed that the logistic models, Gompertz, and chanter adequately represented these variables, nevertheless, the chanter proved to be more flexible and accurate.

From the adjustment indicators (MAE, RMSE, d, and r) (Table 1) and the limitation of chanter model adjustment in the EII (Table 5), it is possible to conclude that the logistic model is the most appropriate to describe different bean cultivars growth within irrigated and non-irrigated WC. To exemplify logistic model growth, three variables were selected from the Triunfo cultivar in the EI Irrigated water regime (Figure 1). The other growth curves can be constructed with the parameters estimates (Table 2, 3, 4, and 5).

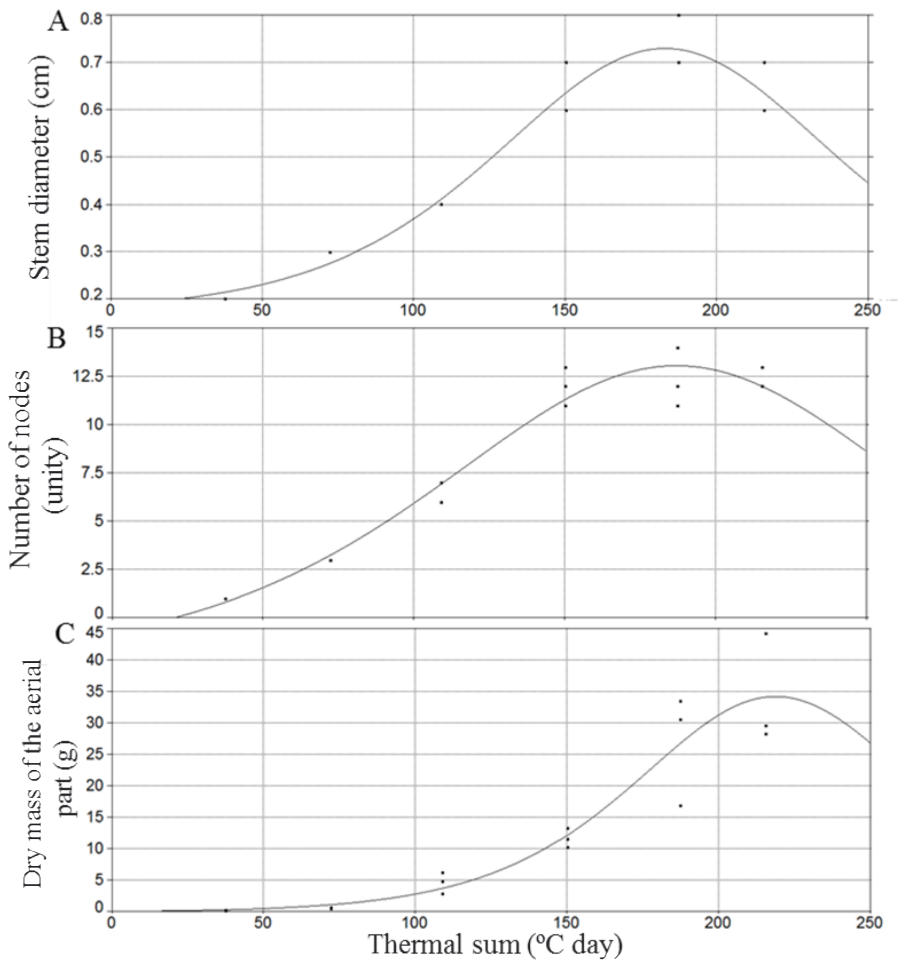

Figure 1. Logistic model for stem diameter (cm) (A), number of nodes (unity) (B), and aerial part dry matter (g) (C) as a function of accumulated thermal sum (in °C day-1) of Triunfo bean Irrigated in experiment I.

4. Conclusions

The results of this study demonstrate that the logistic non-linear growth model can be used to describe the growth of common beans. The parameter estimates (a, b, c, d) can be used to simulate the growth of cultivars Triunfo, Garapiá, and FC104 over irrigated and non-irrigated conditions. Furthermore, due to the lack of studies on the subject of common beans, the general and specific parameters of the irrigated and non-irrigated water conditions can be extrapolated to other cultivars as a reference.

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