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Growth curve pea in different seasons as a function of accumulated thermal sum

Francieli de Lima Tartaglia[1], Alessandro Dal'Col Lúcio[1], Maria Inês Diel[1], Darlei Michalski Lambrecht[1]*, André Luís Tischler[1], Jaqueline Sgarbossa[1]

[1]Universidade Federal d Santa Maria, Santa Maria-RS, Brasil
*Corresponding author, e-mail: darleilambrecht@gmail.com

Abstract

The objective of this study was to determine the performance of peas grown in the field, in three growing seasons, by adjusting the nonlinear logistic model and its critical points. Uniformity trials were conducted in the field in the years 2016, 2017 and 2018 in the experimental area of the Crop Science Department of the Federal University of Santa Maria. The cultivar used was the Pea Grain 40. The values of the average mass of pods per plant, obtained in each harvest, were accumulated successively for each row of cultivation. After adjusting the nonlinear logistic model, the average pod mass per plant as a function of the accumulated thermal sum and the critical points were estimated by the partial derivatives of the adjusted function. The adjustment of the parameters of the logistic model and the critical points calculated by bootstrap resampling allowed comparisons to be made between the times of pea cultivation. The pea crop is influenced by environmental conditions, which interferes with the crop cycle and productivity. Season 1 was the most productive, with maximum increases in production in the shortest period (592.5 °C days^{-1} to produce 119.52 g plant^{-1}), causing a high production peak in relation to the other seasons analyzed. The adjustment of the logistic model allowed to describe the pea production cycle over time at different growing seasons.

Keywords: non-linear models, *Pisum sativum L.*, production rate, thermal sum

Introduction

The production of the pea crop is strongly affected by climatic conditions, mainly by temperature, radiation and humidity (Roro et al., 2016). The ideal temperature for its development is between 13 ° C and 18 ° C, where temperatures above 27 ° C impair productivity (Nascimento, 2016).

In general, plants respond non-linearly to air temperature (Paine et al., 2012). In this way, the pea culture, which has a temperature as the main determining factor of production, needs to have a greater detail of its cycle and mainly of the description of the production of the culture over time. A suitable biological time measure is the accumulated thermal sum, being possible to simulate the consequence of air temperature on the growth and development of plants (Mendonça et al., 2012).

In crops of multiple harvests, when their production is accumulated throughout the production cycle, it is common to present sigmoid responses, typical of non-linear models (Sari et al., 2018; Diel et al., 2019). In addition, the accumulation of harvests throughout the production cycle contributes to the decrease in the number of observations with zero values, common in these types of crops. In a database with high amounts of zero values, problems occur in meeting the assumptions of the analysis of variance, with an advantageous alternative being the evaluation using non-linear regression models (Sari et al., 2018; Diel et al., 2020).

Nonlinear regression models are indicated to study the response of cultures over time, as they allow inferences to be made from the estimates of parameters and critical points, which have biological interpretations (Mischan & Pinho, 2014; Sari et al., 2018). To adjust nonlinear regression models, it is necessary to meet the assumptions of normality, heteroscedasticity and residue independence. When there are controversies regarding

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the fulfillment of the model's assumptions, the use of the bootstrap resampling technique which generates confidence intervals is an alternative to the inferential process and also a diagnostic tool (Souza et al., 2010), being the best way to analyze the distributional properties.

Several studies using non-linear models to describe crop production over time have already been developed as for *Allium sativum* L. (Reis et al., 2014), *Lycopersicon esculentum* L. (Lúcio et al., 2016a) *Fragaria* x *ananassa* Duch. (Diel et al., 2019), *Capsicum chinense* L. (Diel et al., 2020), *Phaseolus vulgaris* L. (Lúcio et al., 2016b) *Cucurbita pepo* L. and *Capsicum annuum* L. (Lúcio et al., 2015). For the pea crop, no studies were found on the description of crop production over time.

Therefore, the objective of this study was to determine the performance of peas grown in the field, in three growing seasons, by adjusting the nonlinear logistic model and its critical points.

Material and Methods

Uniformity tests were carried out in the field in the years 2016, 2017 and 2018 in the experimental area of the Crop Science Department at Federal University of Santa Maria - UFSM (S: 29° 42' 23"; W: 53° 43' 15" 95 meters above sea level) in the municipality of Santa Maria – RS, Brazil, where according to the Köppen classification climate of the region is the Cfa type - rainy temperate, with rains well distributed throughout the year and subtropical from the thermal point of view (Alvares et al., 2013).

The soil of the experimental area is classified as Alfisols (Soil Survey Staff, 1999). The soil preparation in the experimental area was carried out with the rotary hoe, and the basic fertilization was carried out according to the soil analysis, following the technical recommendations of the crop (Rolas, 2004).

The three uniformity tests were carried out on construction sites, without using irrigation. In the first and second years (2016 and 2017), beds with two sowing lines were used, using the spacing of 0.45 m between plants and 0.80 m between rows, with each row consisting of 30 pits, containing four plants per pit, each pit was considered a basic unit (UB). For the year 2018 ridges with a row were used, using the spacing of 0.45 m between plants and 0.80 m between the ridges, and each row was composed of 30 pits, containing four to five plants per pit where, each pit was also considered a UB. The cultivar used was Pea Grain 40, which has an indeterminate growth habit, with a cycle of 75 to 90 days and a cylindrical pod. The sowing was carried out on the dates of 03/05/2016, 16/05/2017 and 06/04/2018.

The pods were harvested in all UBs when they had a light green color. After being collected, they were packed in identified plastic bags and sent to the laboratory for counting and measurement the pods mass (PM, in g).

Dataset and models Fitting

The values of the average mass of pods per plant (g plant $^{-1}$), obtained in each harvest, were accumulated successively for each row of cultivation. The logistic model was selected in other works that suggest this Logistic model for multiple harvest vegetables (Lúcio et al., 2015; Sari et al., 2018; Diel et al., 2019). The parameterization of the adjusted logistic model by Eq 1.

$$yi^1 = \frac{\beta 1}{1 + e^{(\beta 2 - \beta 3 xi)}} + \varepsilon_{i.....} \quad (1)$$

Were yi^1 = the dependent trait (accumulated number or weight of pods per plant); x_i= accumulated thermal sum (STa), in degree days, an elapsed time of transplant of seedlings to harvest (independent trait); β_1 represents the horizontal asymptote, that is, the point of stabilization of plant growth; β_2 is the parameter that indicates the distance (in relation to abscissa) between the initial value and the asymptotes; β_3 is a parameter associated with the growth rate; and ε_i represents the random error.

The parameter estimates were obtained using the ordinary least squares method, using the Gauss-Newton iterative process. Subsequently, the adjusted determination coefficient (R^2aj) and the Akaike Information criterion were estimated. After adjusting the model, the confidence interval (CI) was calculated by bootstrap, with 10,000 resamples using the *nls tools* package in software R. Due to the violation of one of the assumptions of the statistical model in season 2 (normality of errors), it was decided to generate intervals using the bootstrap resampling method.

The coordinates (x, y) of the critical points of the logistic growth curve, known as the maximum acceleration point (MAP), the inflection point (PI), the maximum deceleration point (MDP) and the asymptotic deceleration point (ADP) were obtained by making the derivatives equal to zero $\frac{d^2Y}{dx^2}$ $\frac{d^3Y}{dx^3}$ $\frac{d^4Y}{dx^4}$, according to the methodology described in Mischan et al., 2011. Statistical and graphical analyzes were performed using the software R (R CORE TEAM, 2023).

Results and Discussion

For season 1, the maximum temperature was 33.2 °C, the minimum temperature was 0 °C and the average temperature was between 6.9 °C to 28.1 °C (**Figure 1**a), while radiation oscillated from 0 to 10 W m^{-2} and the total precipitation during the culture cycle was 345.2 mm

(Figure 1b). For season 2, the temperature fluctuated from -1.2 °C to 35.4 ° C, while the average temperature was between 6.2 °C to 28.7 °C (Figure 1c), whereas the radiation fluctuated from 0 to 10.2 W m^{-2} and precipitation during the culture cycle was 654 mm (Figure 1d). While for season 3 the temperature fluctuated from -1 °C to 35.4 °C, and the average temperature fluctuated from 5.8 °C to 29.2 °C (Figure 1e) while the radiation 0 to 10.4 W m^{-2} and the total precipitation during the cycle was 496.5 mm (Figure 1f). In the logistic growth model adjusted for pod mass (g plant $^{-1}$), the assumption of the non-linear model normality of errors was not met for the second growing season, in addition to presenting a low coefficient of determination. To circumvent this problem, the model was adjusted by bootstrap resampling (**Table 1**).

Table 1. *p values* for normality, heteroscedasticity and error independence tests, coefficient of determination, and Akaike information criterion of the logistic model adjusted for pod mass (g plant^{-1}) for peas in three growing seasons. SW (Shapiro Wilk), BP (Breush Pagan), DW (Durbin Watson), R^2aj (Adjusted coefficient of determination), AIC (Akaike Information Criterion).

Season	SW	BP	DW	R^2aj	AIC
Season 1	0.350579	0.204827	0.334	0.928792	193.04
Season 2	0.022831	0.839657	0.396	0.426235	273.52
Season 3	0.453953	0.400007	0.54	0.648139	98.29

The adjustment of the parameters of the logistic model and the critical points, estimated by bootstrap resampling, allowed comparisons between the pea cultivation times (**Table 2** and **Figure**s **2** and **3**). It is possible to observe that the highest production of pods

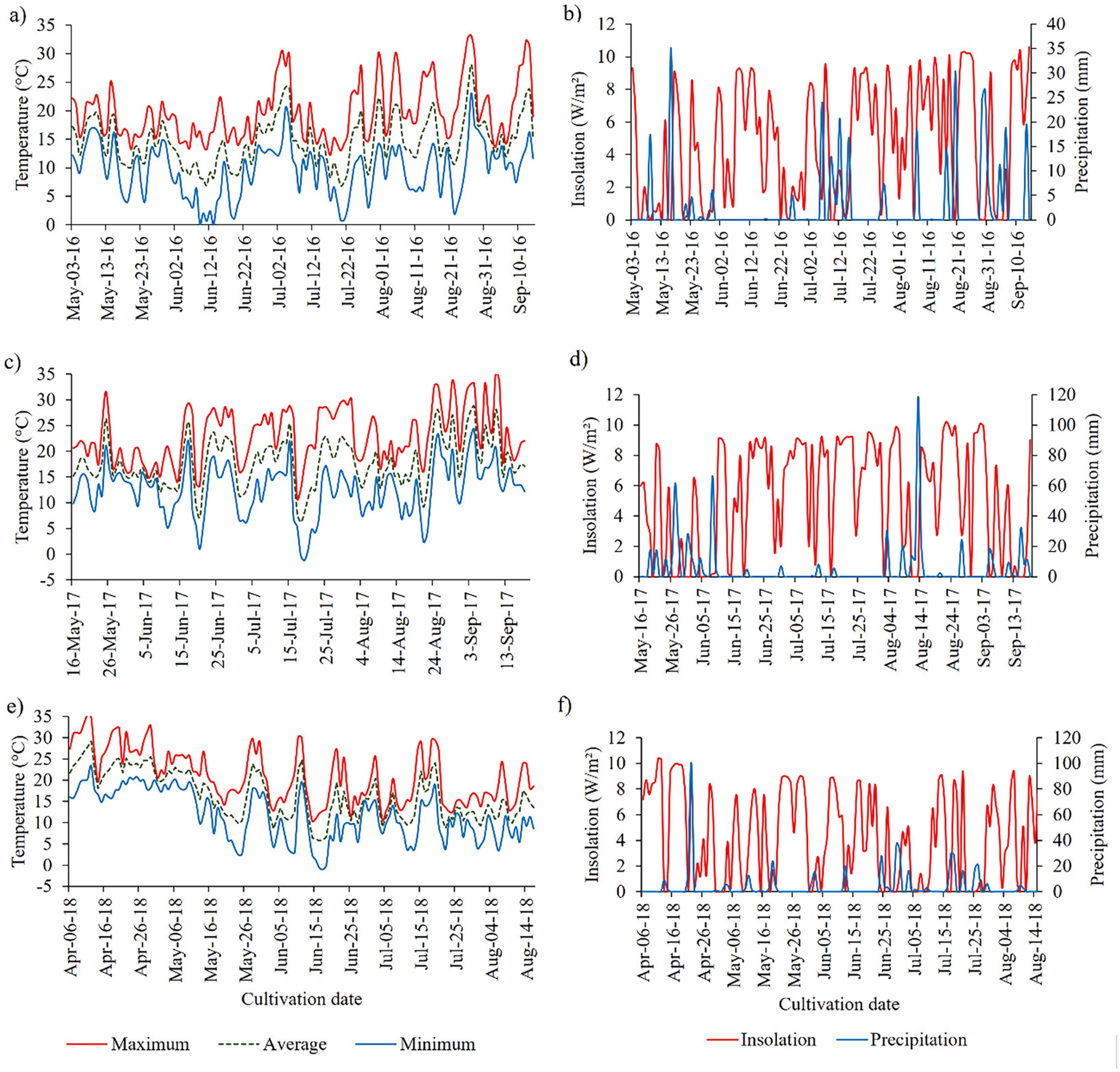

Figure 1. Maximum, average and minimum temperature, radiation and precipitation for the growing years 2016, 2017 and 2018. (a) Maximum, average and minimum temperature and (b) radiation and precipitation for season 1, (c) maximum, average and minimum temperature and (d) radiation and precipitation for season 2, (e) maximum, average and minimum temperature and (f) radiation and precipitation for the season 3.

Table 2. Parameters of the estimated Logistic model for the mass of pea pods grown in 3 planting times (β_1= represents production, β_2 = in biological terms it represents the precocity of production and β_3 = represents the rate of pod production) and its critical points (PI = inflection point, MAP = maximum acceleration point, MDP = maximum deceleration point, ADP = asymptotic deceleration point.

Season	β_1	β_2	β_3	PI	MAP	MDP	ADP
Season 1	119.52	15.91	0.02	645.98	592.50	699.45	739.06
Season 2	69.38	11.03	0.01	912.70	803.69	1021.72	1102.46
Season 3	52.59	19.90	0.02	961.41	897.80	1025.03	1072.15

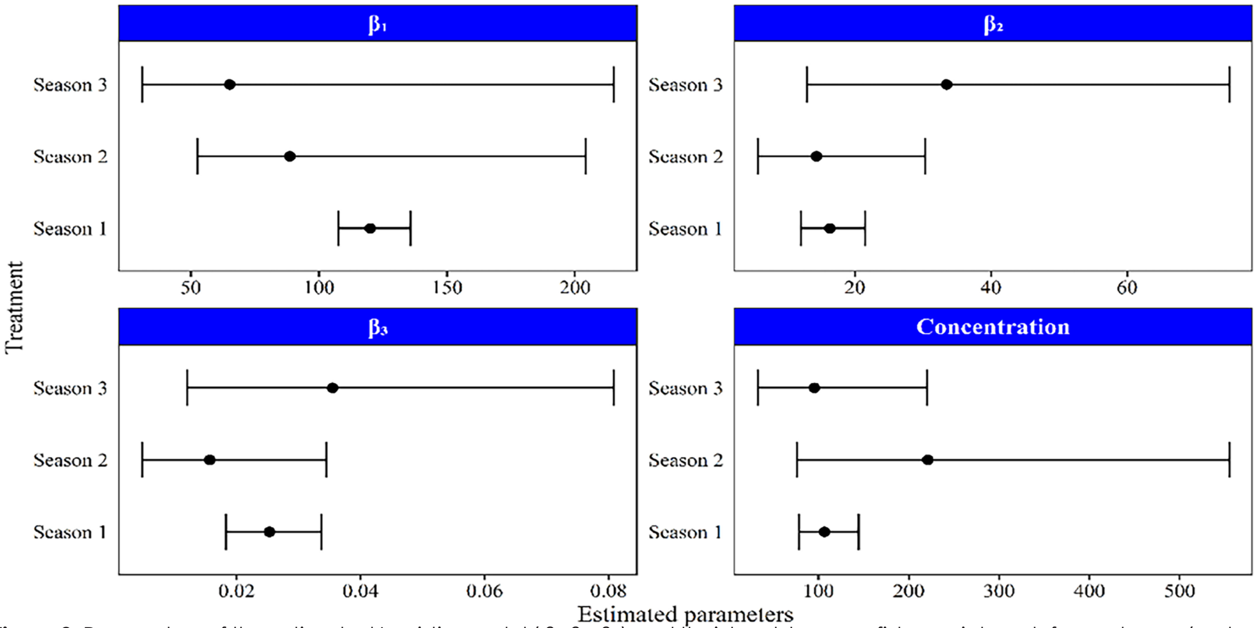

Figure 2. Parameters of the estimated Logistic model (β_1,β_2, β_3) and their bootstrap confidence intervals for pod mass (g plant^{-1}) and the concentration of harvests determined by the differences between MAP and MDP (MDP-MAP) for the cultivation of peas grown three growing seasons.

was obtained in season 1, which showed production of 119.52 g plant $^{-1}$, while the lowest production was found for season 3 (52.59 g plant $^{-1}$). Season 2, on the other hand, presented an average production of 69.38 g plant^{-1} and these values can be observed through the parameter β_1 (Table 2 and figure 2). Season 1, further to being more productive, was still significantly higher than the seasons 2 and 3, which did not differ (Figure 2). These results may have occurred thanks to the frequency and amount of rainfall in each period, in addition to the amount of solar radiation (Figure 1).

In relation to the pod production rate (β_3) and the concentration of production, it was found that in season 1 the culture spent less time producing, but obtained the highest production according to the . In the season 3 the production remained for a longer time, but with lower production than season 1 while in season 2 the culture spent a longer time producing when compared to other seasons, but with a low production throughout the period (Table 1, figure 2 and 3).

As for the critical points of the logistic model, the point of maximum acceleration (MAP) showed differences between the growing seasons indicating that season 1 showed maximum increases in production in a shorter period, needing 592.5 °C days $^{-1}$ to produce 119.52 g, causing a high production peak in relation to the other analyzed seasons while season 3 required 897.80 °C days $^{-1}$ to produce 52.59 g. This can be confirmed through the inflection point (PI), where it is observed that the PI was reached earlier in season 1 in relation to the other seasons, indicating greater precocity, since this parameter indicates where the maximum peak of production occurs (Table 1 and figure 3).

The maximum deceleration point (MDP) and the asymptotic deceleration point (ADP) showed a difference between the periods evaluated where it can be seen that season 1 decreased its production earlier than seasons 2 and 3, needing fewer degrees days to complete the cycle, whereas in seasons 2 and 3 these points were similar (Table 2 and figure 3), due to the characteristics of the environment in these times.

The ideal temperature for the development of the pea oscillates between 13 °C and 18 °C, the seeds of the crop germinate with temperatures above 4 °C and their development is strongly influenced by the degree-days (Nascimento, 2016). Already temperatures above

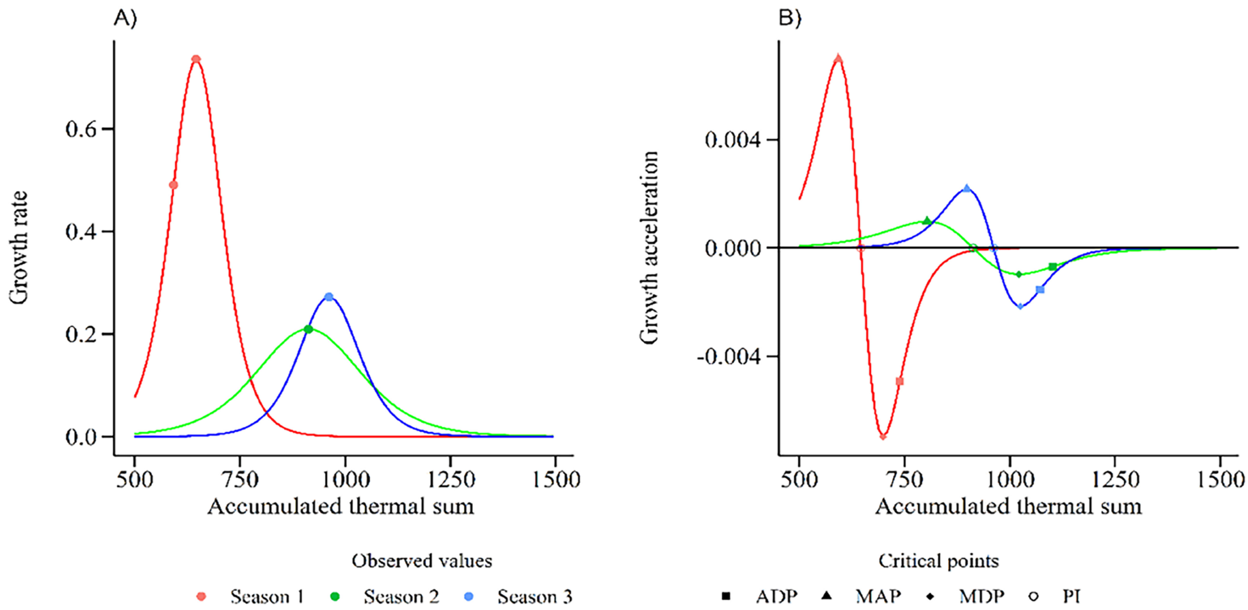

Figure 3. Logistic model adjusted for pea pod mass in three growing seasons (A), fruit production rate and (B) critical points MDP = maximum deceleration point, ADP = asymptotic deceleration point).

31 °C in the critical period of the crop, which is six days after opening the flower, reduce the number of seeds per pod (Jeuffroy et al., 1990) and temperatures below 0 °C reduce germination and increase the mortality of cultivars not resistant to cold (Zhang et al., 2016). It can be observed that in the three growing seasons of the crop, a large temperature variation was observed, where the plants were affected by temperatures below and above the optimum temperature for their development in all growing seasons, which may have led to low crop productivity.

Other factors that can influence crop production are the availability of water and radiation. In times of cultivation when there is a shortage of rain, they reduce the weight of 1000 seeds, the number of pods per plant (Santín-Montanyá et al., 2014), of the specific leaf area (Roro et al., 2016) presenting a drop in production of 38.50 % when the water deficit occurs in the vegetative phase and 43.04 % in the reproductive phase, which the characteristics of the crop are favored when the soil is kept moist, close to the field capacity (Carvalho et al., 2012). Furthermore, UV radiation affects the number of branches per plant and the leaf area in dry seasons (Roro et al., 2016). Thus decreasing the number of flowers in the plant and consequently decreasing the number of pods, causing a decrease in crop production. As in the present study, the cultivation was carried out in rainfed being dependent only on precipitation, which was low and poorly distributed during the culture cycle, causing low productivity, together with the other factors mentioned above.

The use of non-linear regression models makes it possible to know the development of culture through its growth curves which are represented by a sequence of measurements over time. (Mischan & Pinho, 2014). Thus, the knowledge of this curve allows us to determine the production cycle and to carry out the best management for the studied culture. The use of non-linear models, such as logistics, can provide information about the cycle and the development of culture, which would not be possible with the use of linear regression models (Diel et al., 2020).

When the model's assumptions are not met, the adjustment with the bootstrap resampling can be performed in order to circumvent this problem and make the estimates of the parameters of the non-linear model to be reliable and represent the reality of the culture cycle (Souza et al., 2010). As for the difference in pod production between the growing seasons represented by the parameter β_1 of the logistic model, the highest production was found in season 1 while the other seasons had a lower production which can be explained by the environmental conditions in those times, such as high temperatures and also negative temperatures, in addition to rains that are not widely distributed throughout the cycle cultivation, negatively affecting crop production.

Great variability is noticed in the production of the pea crop. The yield depends on the cultivar used and the cultivation techniques, where for green grains the productivity of the pea ranges from 3.0 ton ha $^{-1}$ to 7.0 ton ha $^{-1}$ (Nascimento, 2016). Schiavon et al., (2018) found average productivity of 929.7 kg ha $^{-1}$ for pea cultivation when studying 35 double-purpose pea genotypes. Already Gassi et al., (2009) studying different spacing between plant and number of rows found that fresh mass production of pods ranging from 5.23 ton ha $^{-1}$ to 7.48 ton ha $^{-1}$ for pea cultivation.

The parameters β2 and β3 and concentration, indicate the precocity and rate of crop production were different in each growing season and that the crop cycle increased at times when the temperature had a greater range of oscillation and that when the crop was subjected to very low temperatures, as in the case of seasons 2 and 3, the production cycle of the crop was greater. Similar results were found by Vieira et al., (2000) when studying different planting times for the pea crop, found that very low temperatures can prolong the reproductive period and increase the crop cycle. In addition, the cycle and the production can be reduced sooner irrigation stop (Marquelli et al., 1990). which may have occurred in this study, since the 1st season was the least precipitation.

According to Sari et al., (2018), values of β_3 higher increases increase the slope of the curve and reduce the time between the beginning and end of the harvests, the production rate is higher and the PI happening earlier which takes less time between the MAP and the MDP, indicating that this parameter can be used to interpret the precocity of production. This was contacted in the present study for season 1, indicating that at that time you had more production are concentrated in less time. Furthermore, in season 1, ADP was earlier than in other seasons, that is, the decrease in production occurred earlier. Resende & Vieira, (1999) testing different pea cultivation times found that in the year in which they had lower temperatures during the reproductive period, they had an increase in the cycle of a pea cultivar. Second Nascimento (2016) the vegetative cycle of the crop depends on the cultivar and the climatic conditions necessary for its development, ranging from 90 to 140 days.

Growth models allow, in addition to defining the most productive season or genotype, it is also elucidated which of the seasons evaluated to have the best production indicators, such as precocity and the production rate in each season. Hypothetically, the choice of the best growing season or genotype will depend, in addition to the total production, on the producer's planning to insert the product sooner into the consumer market and extend it for a long period or have maximum production rates with a high peak and production in less time.

Conclusions

The pea crop is influenced by environmental conditions, which interferes with the crop cycle and productivity.

Season 1 was the most productive, with maximum increases in production in the shortest period (592.5 °C days $^{-1}$ to produce 119.52 g plant $^{-1}$), causing a high production peak in relation to the other seasons analyzed.

The adjustment of the logistic model allowed to describe the pea production cycle over time in different growing seasons.

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