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Production of cucumber cultivars according to the accumulated thermal sum

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Abstract

Cucumber is a species appreciated in cooking, in addition to providing various nutrients for health. In view of this, it is important that research on its growth is carried out, prioritizing statistical analyzes that effectively demonstrate the results. The objective was to verify the differences by analyzing of the variance and nonlinear models, in addition to characterizing the production, early production and production rate of cultivars of cucumber using of nonlinear models. An experiment was carried out in a randomized block design (RBD), with three cultivars ('Atlantico', 'Caipira' and 'Fuyu') in six replications. Two types of analysis of variance were performed for the variable mass of cucumber fruits. In the first the RBD design was considered with three cultivars and six replications and in the second the RBD design was considered in a split subdivided over time (cultivars x harvests). Afterwards, the Logistic growth model was adjusted for the fruit mass variable as a function of accumulated thermal sum, and determination of the critical points of the model. The use of nonlinear models to evaluate experiments with cultures of multiple harvests has advantages in relation to anova and complementary tests. The cultivar 'Fuyu', has higher productivity compared to the cultivars 'Atlantico' and 'Caipira', in addition to presenting greater precocity and production rate. The adjustment of the logistic model and its critical points allowed to identify the production, precocity and production rate of the evaluated cultivars of the cucumber.

Keywords: anova, *Cucumis sativus* L., logistic, nonlinear regression, productivity

Introduction

The cucumber (*Cucumis sativus* L.) belongs to the Cucurbitaceae family, is an herbaceous plant of annual cultivation, being originally from India (Carvalho et al., 2013). Worldwide, approximately 75 million tons are produced, with the largest producers being Asia (84.4%), Europe (9.8%), the Americas (3.7%) and Africa (2.1%) ("Food and Agriculture Organization of the United Nations," 2020). In Brazil, approximately 184 thousand tons are produced, where the largest productions are located in the Southeast, South and North regions of the country, respectively (IBGE, 2020).

The crop adapts to regions of mild to hot climate, where temperatures are between 20 to 30 ° C, and lower temperatures hinder the growth and development of young plants, resulting in a reduction in productivity. Mild temperatures benefit the formation of female flowers and elevated temperatures the formation of male flowers (Carvalho et al., 2013). The crop production is directly related to female flowering, which are controlled by genetic factors and also by external factors, with temperature and photoperiod as the main ones. (Menezes, 1994).

Fruit harvest starts between 40 and 50 days after sowing and can last for up to 80 days depending on the nutritional and health conditions of the plants (Carvalho et al., 2013). In crops with multiple harvests, such as cucumbers, fruits are harvested in stages as they grow. Plant growth responds to temperature in a nonlinear way, being the use of nonlinear models promising to model the crop cycle (Paine et al., 2012).

Nonlinear regression models are useful to describe the productive response of the culture over time, as they present parameters of biological interpretation of the critical points of the adjusted function, allowing inferences about the culture cycle (Diel et al., 2020;

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Mischan & Pinho, 2014), and they have the advantage that the interpretations are broader in relation to the analysis of variance and additional tests, besides to increasing the reliability of the results. Analyzes can be easily employed, as there are several R software routines available to the entire scientific community (Diel et al., 2020; Sari et al., 2019b, 2018).

Common problems found in nonlinear regression analyzes, such as non-compliance with the model's assumptions, can be solved with bootstrap adjustments, and the comparison between treatments can be performed using confidence intervals, bringing greater reliability to the results obtained (Seber & Wild, 2003; Fernandes et al., 2015; Sari et al., 2018). Thus, the aim of this study was to verify the differences by analyzing data from multiple harvest crops by analyzing variance and nonlinear models, in addition to characterizing the production and differences in early production and production rate of three cucumber cultivars grown in off-season, in a subtropical climate region.

Material and Methods

Plant material, site description, and experimental design

The experiment was conducted in the experimental area of the Plant Science Department at Federal University of Santa Maria - UFSM (S: 29 ° 42 '23''; W: 53 ° 43' 15'' and 95 meters of altitude at sea level). The climate of the region is the Cfa type, according to the Koppen classification, with characteristics of rainy subtropical, with mean for annual precipitation of 1800mm, well distributed throughout the year, and subtropical for thermic consideration (Alvares et al., 2013).

The design used was in randomized blocks with six replications and three treatments, with four plants per plot. The treatments consisted of three cucumber cultivars, 'Atlantico', 'Caipira' and 'Fuyu'. The sowing was carried out in trays on 04/01/2019 using the substrate Carolina. The soil of the experimental area is classified as Alfisols (Soil Survey Staff, 1999), andthe preparation of the experimental area was carried out with a rotary hoe and the basic fertilization was carried out according to soil analysis, following the recommendations of the fertilization and liming manual for the states of Rio Grande do Sul and Santa Catarina (CQFS -Comissão de química e fertilidade do solo, 2016). The seedlings were transplanted to beds on 01/28/2019 with a spacing of 0.80m between plants and 0.80m between beds.

Assessments Completed

The plants were tutored individually and the drip irrigation was carried out according to the needs of the crop. The harvesting started 38 days after transplantation, being repeated every two days. The fruit size for the harvest was standardized, averaging 15 cm. After harvesting, the fruits were packed in identified plastic bags and, later, taken to the laboratory for weighing.

Temperature data were collected from the automatic meteorological station of the National Institute of Meteorology (INMET), located approximately 50 m away from the experiment site. The mean air temperature calculation was estimated by the following equation:

$$T_{ave} = (T_{\max} + T_{\min})/2 \tag{1}$$

where T_{ave} is the air average temperature; T_{max} is the maximum air temperature; and T_{min} is the minimum air temperature.

The daily thermal sum (TS_d) in °C day^{-1} was calculated according to the following equation:

$$TS_d = T_{ave} - T_b \tag{2}$$

where TS_d is the daily thermal sum (°C day^{-1}); T_{ave} is the air average temperature; and Tb is the base temperature.

The base temperature (T_b) is set as the temperature below which the plant cannot develop, or its development is so slow that it can be ignored (Rosa et al., 2011). Strawberries have a base temperature of 10°C (Marcelis & Hofman-Eijer, 1995).

The daily thermal sum was calculated from the date of sowing, and the accumulated thermal sum (TS_a, in °C day^{-1}) up to the *i*th day was calculated by:

$$TS_a = \sum_{i=1}^{i} TS_d \tag{3}$$

Harvests were carried out every two days during the complete maturity stage for a total of 11 harvests. The commercial fruits harvested in each experimental unit were weighed with the aid of a scale.

Analysis of variance (ANOVA)

Two anova were performed for the variable mass mean of the total production of cucumber fruits. In the first, a randomized block design was used, with three cultivars and six replications, and, after analyzing the residuals and meeting the assumptions of the mathematical model, the comparison of means by Scott & Knott. For the second anova, a randomized block design was considered in a split plot design over time, with cultivars in the plot and harvests in the subplot. After analyzing the residues, it was found that the assumptions of the anova were not met and the non-parametric analysis was carried out using the Friedman test.

Adjustment of growth model

The mean mass of fruits per plant (g plant^{-1}) obtained in each harvest was consecutively accumulated for each experimental unit (H1, H1+H2, H1+H2+H3,....H1+ H2+…H11). Afterward, a logistic model was fitted to each experimental unit according to the following equation:

$$Y_i = \frac{\beta_1}{1+e^{(\beta_2-\beta_3 x_i)}} + \varepsilon_i, \qquad \text{(Eq. 1)}$$

where y_i = is the dependent trait (accumulated number or weight of fruits per plant); X_i = is the accumulated thermal sum (STa), in degree days, 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 random error.

The parameter estimates were obtained using the ordinary least squares method with a Gauss-Newton algorithm. Later, the coefficient of determination (R²) and the intrinsic (c^I) and parametric (c^θ) nonlinearity were calculated by the curve method suggested by Bates and Watts (1988) . Afterward,

$$c^I \times \sqrt{F_{(\alpha;p,n-p)}} \qquad \text{(Eq. 2)}$$

and $$c^\theta \times \sqrt{F_{(\alpha;p,n-p)}} \qquad \text{(Eq. 3)}$$

values were estimated, where $F_{(\alpha,p,n-p)}$ = F tabulated as a quantile of the F distribution in which *α* is 0.05, p is the number of parameters in the model and n is the number of observations. When these values are under 0.3 and 1.0, respectively, the parameters are close to being unbiased. The normality and homogeneity of residuals were tested by Shapiro-Wilk and Bartlett tests, respectively.

Due to the violation of one of the assumptions of nonlinear models, the confidence intervals were obtained by a bootstrap approach, 10,000 estimates of each parameter were obtained for each treatment. The confidence intervals were obtained by the difference between the 97.5th and 2.5th percentiles of the bootstrap parameter estimates. When the confidence intervals did not cross, the treatments were considered different.

The coordinates (X and Y) of the critical points of the logistical model, known as the maximum acceleration point (MAP), inflection point (PI), maximum deceleration point (MDP) and asymptotic deceleration point (ADP) were obtained by setting the following derivatives as equal to zero, according to methodology described in (Mischan et al., 2011a): inflection point (PI):

$$\frac{d^2 y(x)}{dx^2} = 0 \qquad \text{(Eq. 4)}$$

point of maximum acceleration (MAP) and point of maximum deceleration (MDP):

$$\frac{d^3 y(x)}{dx^3} = 0 \qquad \text{(Eq. 5)}$$

and point of asymptotic deceleration (ADP):

$$\frac{d^4 y(x)}{dx^4} = 0 \qquad \text{(Eq. 6)}$$

The precocity was defined when the PI was achieved (this point was related to the moment at which the rate production of fruit was maximal). The concentration of production was defined by the difference between MAP and MDP, corresponding to the time during which the production increased exponentially (Sari et al., 2018). Statistical and graphical analyzes were performed using R software (R Core Team, 2021).

Results

The minimum and maximum absolute air temperature recorded in the evaluation period were 11 and 37 ° C respectively. The average temperature, however, remained between 17.3 and 30.4 °C (Figure 1A). During the culture cycle, 1027.45 °C day^{-1} was accumulated, being that cucumber is a culture of relatively short cycle, which responds to TSa (Figure 1B). It can be highlighted that during the evaluation period the temperatures did not exceed the lower basal temperature for the cucumber culture, which is 10°C.

The analysis of variance for the fruit mass variable per plant of the three cucumber cultivars did not show any significant effect (Table 1). The assumptions of the analysis of variance, normality (SW - *p-value*, 0.64), homoscedasticity (BP - *p-value*, 0.40) and error independence (DW - *p-value*, 0.54) were met. The averages of the yields achieved in each cultivar have a certain amplitude, even though it does not have a significant effect by ANOVA (Table 2).

Taking into account an experiment in split plot design over time, the analysis of variance did not have a significant effect for the factors cultivar x harvests, but it did have a significant effect separately for the harvests factor (Table 3). Anova assumptions were not met and, therefore, the Friedman test was used as a non-parametric alternative to the traditional means comparison tests.

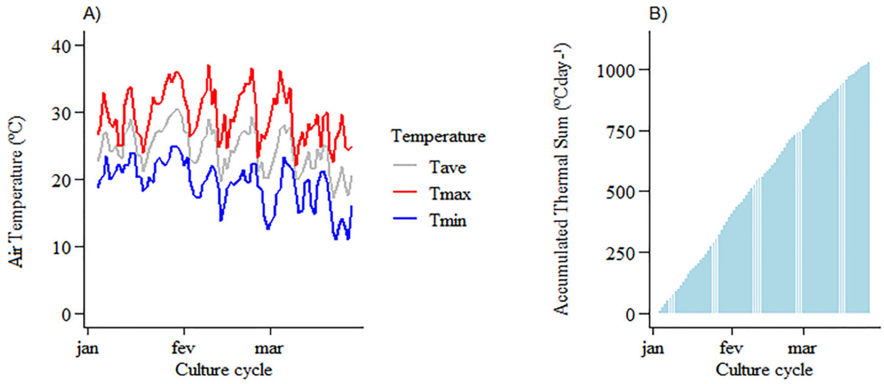

Figure 1. Average temperatures (Tave), maximum (Tmax) and minimum (Tmin) A) and accumulated thermal sum B) during the period of conducting the experiment with three cucumber cultivars conducted in the off-season.

Table 1. Analysis of variance for the fruit mass variable of three cucumber cultivars grown in off-season.

FV	GL	SQ	QM	Fc	Pr>Fc
Treatment	2	1807025	4	2.5257	0.12945
Block	5	2348555	3	1.3131	0.33296
Residue	10	3577214	2		
Total	17	7732794	1		

* significant at 5% probability.

Table 2. Fruit mass of three cucumber cultivars grown in off-season.

Cultivars	Mass of fruit (gplant^{-1})
'Fuyu'	1957.5 a
'Caipira'	1249.9 a
'Atlantico'	1327.6 b

* Means followed by the same letter do not differ by the Scott & Knott test at 5%. probability of error.

Table 3. Analysis of variance in a randomized block design in split plot over time, for the fruit mass variable of three cucumber cultivars grown in off-season.

FV	GL	SQ	QM	Fc	Pr(>Fc)
Cultivars	2	164275	7	2.5257	0.1295
Block	5	213505	6	1.3131	0.333
Error a	10	325201	5		
Harvests	10	2975790	4	19.911	<2e^{-16} ***
Cultivars*Harvests	20	381653	3	1.2768	0.2029
Error b	150	2241815	2		
Total	197	6302239	1		

For the results of Friedman test for the harvests factor, harvests 7 and 8 obtained the largest sums, remaining in a group, these results can be attributed to the fact that in these harvests the greatest fruit production may have occurred. In harvests 1 to 4 the smallest yields, because in this phase of the beginning of the harvest, production is generally lower (Table 4). This result was already expected, since harvests in multiple harvest crops tend to be heterogeneous.

Table 4. Friedman test for the fruit mass variable of three cucumber cultivars from 11 harvests.

Harvest	Sum of ranks	Groups
8	62	a
7	58	a
5	47	ab
10	39	bc
11	37	bc
6	36	bc
9	31	bcd
1	26	cd
2	25.5	cd
4	19	d
3	15.5	d

The analysis of the fruit mass variable by analysis of variance and complementary tests are simple, however it does not allow inferences about the crop production cycle. In the analysis of the experiment considering plots subdivided over time, harvests in subplots did not guarantee that Anova assumptions were met. A common problem in experiments with vegetables is the variability between crops resulting in heteroscedastic residuals. In cases of repeated measurements in crops of multiple harvests the anova is insufficient, for this, the adjustment of nonlinear models is a promising alternative that allows to characterize the entire cultivation cycle, making inferences about the production rate, precocity and concentration production throughout the crop cycle.

The logistic growth model adjusted for fruit mass (g plant^{-1}) showed low intrinsic and parametric nonlinear results, indicating the quality of the adjustment. However, the assumptions of the nonlinear model were not fully met for the cultivar 'Caipira', that the residues were heteroscedastic by the Breusch-Pagan test (Table 5). For this adjusted by bootstrap resampling.

Table 5. *p* values for the normality, heteroscedasticity and error independence tests, coefficient of determination of parameterization 1 of the logistic model adjusted for fruit mass (g plant^{-1}) of cucumber cultivars grown in off-season.

Cultivars	SW	BP	DW	R^2aj
'Atlantico'	0.37	0.16	0.94	0.99
'Caipira'	0.97	0.05	0.73	0.99
'Fuyu'	0.95	0.29	0.20	0.99

'SW: Shapiro-Wilk, BP: Breusch-Pagan, DW: Durbin Watson, R^2aj: adjusted coefficient of determination

The confidence interval estimates for the parameter β_1, which means in biological terms the production achieved (asymptote), show that the cultivars 'Caipira' and 'Atlantico' have no differences in production, while for the cultivar 'Fuyu' the production was higher (Figure 2).

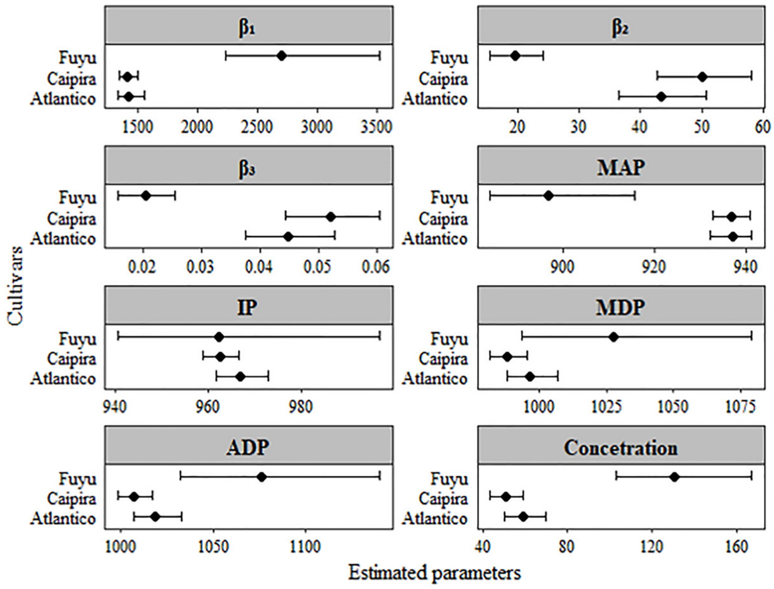

Figure 2. Confidence intervals for the parameters and critical points of the nonlinear logistic model (parameterization 1) estimated by bootstrap. β_1 (represents the production), β_2 (represents the precocity of production), β_3 (represents the fruit production rate), MAP (point of maximum acceleration), IP (point of inflection), MDP (point of maximum deceleration), ADP (point of asymptotic deceleration) and Concentration (MDP-MAP), for cultivars of cucumber grown in off-season.

The results of the parameters β_2, β_3 e MAP followed the same behavior. The parameter β_2 indicates the distance (in relation to the abscissa) between the initial value and the asymptotes, in biological terms, indicate fruit ripening at the beginning of the harvest, because when the value of β_2 is lower, IP and MAP are reached earlier, indicating a higher degree of plant maturity at the beginning of the harvest. In practice, this parameter can be used to determine the productive precocity of the crop, indicating greater precocity for the cultivar 'Fuyu' in relation to the cultivars 'Atlantico' and 'Caipira' (Figure 2). Likewise, the parameter β_3 when it presents higher values, they increase the slope of the curve, reducing the time between the beginning and the end of the harvests, biologically, this represents the fruit production rate, thus, the cultivars 'Atlantico' and 'Caipira' presented a lower production rate in relation to 'Fuyu' which had a higher rate of fruit production, that is, it remained longer producing (Figure 2). Regarding the point of maximum acceleration (MAP), it showed significant differences between the cultivar 'Fuyu' and the cultivars 'Atlantico' and 'Caipira', which in biological terms this means that 'Fuyu' presented maximum increases in production, causing a high peak of production in relation to the other cultivars (Figure 2 and 3C).

For the inflection point (PI), the results of the three cultivars evaluated did not show significant differences (Figure 2 and 3B). Regarding the critical points maximum deceleration point (MDP) and asymptotic deceleration point (ADP), it can be seen that the cultivars 'Atlantico' and 'Caipira' decreased their production well before the cultivar 'Fuyu' (Figua 2 and 3C). In the same way for the production concentration, measured by the differences in MDP-MAP, it is possible to visualize the highest concentration in the cultivar 'Fuyu', that is, this cultivar remained longer producing fruit in relation to the other cultivars evaluated (Figure 2 and Figure 3C).

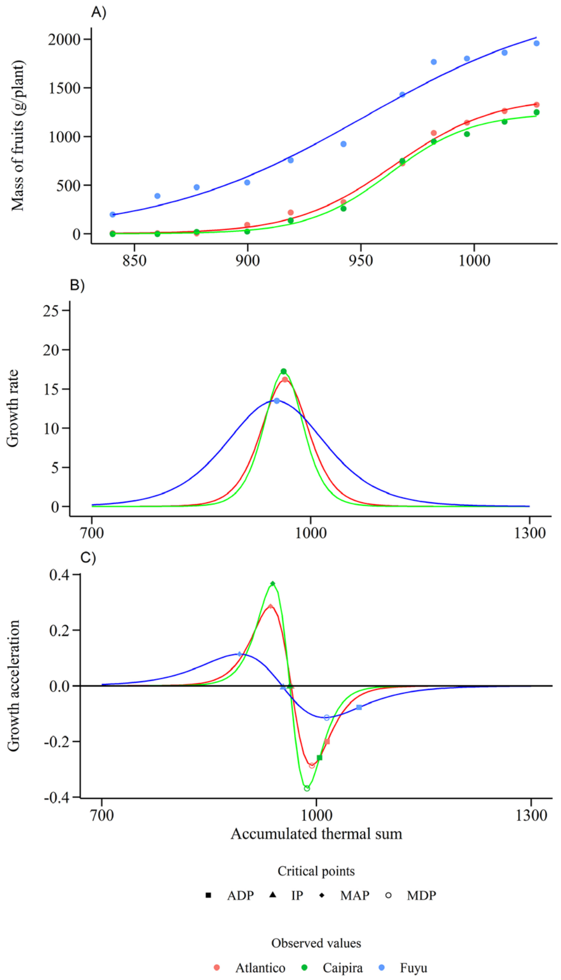

Figure 3. Logistic model adjusted for fruit mass of cucumber cultivars grown in the off-season (A), fruit production rate (B) and critical points of the adjusted model (PI): inflection point, MAP: maximum acceleration point , ADP: asymptotic deceleration point, MDP: maximum deceleration point (C).

Discussion

In regions with a subtropical climate, the cucumber culture is usually grown in the spring-summer. In regions of high latitude, the temperature and the photoperiod interfere in the development of the culture, and in long days the plants tend to emit larger quantities of male flowers (Carvalho et al., 2013), therefore, cucumber cultivation in spring is more suitable than cultivation in summer. Winter cultivation can be carried out in protected cultivation, since the crop is sensitive to frost.

The ideal temperatures for the growth and development of cucumbers should be mild to hot, varying between 20 to 30° C (Carvalho et al., 2013). In the present study, temperatures remained within the average for most of the crop cycle, however there were some days when the temperature was below ideal, a factor that may have caused productivity drops, mainly because they occurred in the reproductive phase.

Growth models are an efficient alternative to assess the behavior of the crop production cycle, having advantages for increasing the inferences in the interpretation of the results, and the parameters and critical points with biological interpretations allow more robust conclusions about the treatments (Diel et al., 2020; 2019; Sari et al., 2019). We can see that when analyzing this experiment with the use of anova and complementary analyzes we lost several interpretations regarding the culture production cycle, in addition, the assumptions of the anova are violated. Heteroscedastic residues are very common in vegetable experiments due to uneven fruit ripening and should be taken into account when analyzing the data.

The use of nonlinear models as an alternative to anova was suggested by Sari et al. (2019b), because due to the maturation of the fruits being staggered, there is a violation of the assumptions of the anova models. Diel et al. (2020b) found that using the adjustment of a linear model it was only possible to conclude about the total production for *Capsicum chinense* fruits, while when adjusting nonlinear models inferences about the crop cycle can be made. Thus, nonlinear models are promising alternatives for analyzing crops from multiple harvests, allowing to compare the total production in addition to increasing inferences about the productive behavior of multiple harvests over time (Sari et al., 2019).

For the results of the models to be reliable, some requirements must be met, such as meeting the assumptions of the mathematical model (normality, homogeneity and error independence), and low values for the results of intrinsic and parametric nonlinearity, and measures of c^{θ} < 1 and c^{i} < 0.3 are ideal (Bates & Watts, 1988; Sari et al., 2018; Zeviani et al., 2012).

The logistic model was indicated as being the best to model the crop cycle of multiple harvests, especially vegetables, because it has the model parameters with linear behavior (Diel et al., 2019; Sari et al., 2018). In these studies, the nonlinearity was tested, being a preferable measure of selection of nonlinear models to the Akaike Information criterion (AIC) and Bayesian criterion (BIC).

The parameters and critical points of the adjusted model have biological interpretations (Mischan et al., 2011b; Sari et al., 2018; 2019), and when analyzed together, they allow the interpretation of several factors of the production cycle, such as precocity, production rate and production concentration in each evaluated treatment (Sari et al., 2018). In addition, the use of confidence intervals estimated by bootstrap allows the comparison of treatments. This alternative, in addition to circumventing the model's assumption problems, allows one to compare treatments through the confidence intervals estimated for each of the model's parameters and their critical points. You can see that the 'Fuyu' cultivar was the most productive (bigger β_1) and this was already expected since the three cultivars are from different groups, with 'Fuyu' being of the Japanese (Carvalho et al., 2013). In addition, most of the Japanese cucumber hybrids are parthenocarpic, while the redneck type do not have parthenocarpy and need to be pollinated (Filgueira, 2003), causing differences in the amount of fruit. There were no significant differences between the cultivars 'Atlantico' and 'Caipira'.

The cultivar 'Fuyu' was also earlier and had a higher production rate (smaller β_3) compared to the cultivars 'Atlantico' and 'Caipira', in addition to showing maximum increments at the beginning of production (smaller MAP). These differences are mainly attributed to the genotype which respond differently to the environment, reflecting the growth and development of plants (Oszlányi et al., 2020), in addition hybrid cultivars, have characteristics of being earlier (Cardoso, 2002). The crop in general has a short production cycle, with approximately 1027.45 °C day^{-1} accumulated.

The cultivars 'Atlantico' and 'Caipira' decreased production well before the cultivar 'Fuyu', that showed a higher concentration of production, remaining longer in fruit production, which is due to the differences between the cultivars, and they respond differently, for example to amount of water and nutrients used (Oszlányi et al., 2020). All cultivars studied in the present work can be used in the off-season (summer) in regions of subtropical climate, even having the ideal season for spring, as it presents characteristics of temperature and light ideal for its growth and development (Carvalho et al., 2013). The choice of cultivar will depend on the purpose of production, with each group having different characteristics and consumer preference.

Conclusions

The analysis of data in crops of multiple harvests by analysis of variance and complementary tests have less inferences about the crop cycle than when they are analyzed by nonlinear models, the latter allows to identify the production, precocity and production rate of cucumber cultivars evaluated.

The cultivar 'Fuyu', a hybrid of the Japanese type, has higher productivity compared to the cultivars 'Atlantico' and 'Caipira' (salad and 'Caipira' group respectively), however the choice of the ideal cultivar should be based on the objective of the producer based on consumer preferences.

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