Bioagro 36(3): 299-310. 2024 doi: http://www.doi.org/10.51372/bioagro363.5

GROWTH OF PEACHES AT THREE ALTITUDES IN THE SANTANDER MOUNTAINS OF NORTHEASTERN COLOMBIA

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ABSTRACT

A study was conducted in the high tropics in the province of Pamplona, Colombia, with the objective of evaluating the growth of peach, Jarillo variety, under three different altitudes (1670, 1870, and 2170 masl). A total of eight trees were sampled per altitude for the purposes of this study. Ten fruits were taken from the middle third, and their mass was measured as follows: fresh and dry from the fruit and fruit pulp, pulp-seed ratio, and the roundness index during the three stages of development after defoliation. A multivariate analysis of variance and a nested longitudinal mixed model were employed to analyze the total fresh mass from three altitudes. The simple effects of altitude and the phenological stages and their interaction were found to be significant when the nested structure of the random effects, fruits nested in trees, and trees in altitudes were incorporated. The effects of time and altitude demonstrated a significant interaction for all variables. In all cases, 1670 masl was the altitude which had the highest fresh mass and the pulp-seed relationship, which it allowed a higher percentage of pulp from harvested fruits for agro-industrial processes. The pattern of relationship between fruit-associated variables as a function of days after defoliation was explained using a second-order polynomial regression model.
Additional keywords: Fruit roundness index, mixed nested longitudinal model, *Prunus persica*

RESUMEN

Evaluación del crecimiento de duraznos en tres altitudes en las montañas de Santander del Noreste de Colombia

Se realizó un estudio en el trópico alto en la provincia de Pamplona, Colombia, con el objetivo de evaluar el crecimiento del durazno, variedad Jarillo, bajo tres diferentes altitudes (1670, 1870 y 2170 msnm). A efectos de este estudio, se tomaron muestras de un total de ocho árboles por altitud. Se tomaron diez frutos del tercio medio del árbol, y se midió la masa fresca y seca del fruto, pulpa del fruto, relación pulpa-semilla y el índice de redondez, durante las tres etapas de desarrollo después de la defoliación. Se empleó un análisis multivariado de la varianza y un modelo mixto longitudinal anidado para analizar la masa fresca total a partir de tres altitudes. Los efectos simples de la altitud y los estadios fenológicos y su interacción resultaron significativos cuando se incorporó la estructura anidada de los efectos aleatorios, frutos anidados en árboles y árboles en altitudes. Los efectos del tiempo y la altitud demostraron una interacción significativa para todas las variables. En todos los casos, 1670 msnm fue la altitud que presentó la mayor masa fresca y relación pulpa-semilla, lo que resultó en un mayor porcentaje de pulpa delos frutos cosechados para procesos agroindustriales. El patrón de relación entre las variables asociadas al fruto en función de los días después de la defoliación fue explicado mediante un modelo de regresión polinómica de segundo orden.
Palabras clave adicionales: Índice de redondez, modelo longitudinal anidado mixto, *Prunus persica*

Associated Editor: Dr. Georgina Vargas-Simón

INTRODUCTION

The peach (*Prunus persica* L. Batsch) is one of the 10 most produced fruits around the world (Hernández et al., 2017). In 2019, approximately 25.74 million tons of peaches were produced, mainly in temperate zones. Peach cultivation is currently spreading to non-traditional areas in subtropical and high tropical regions, where the climate differs from the fruit's natural habitat (Fadón et al., 2020), such as the Andes, since these regions have comparative advantages (soil, climate and the accumulation of cold hours) compared to those planted in temperate zones (Pinzón et al., 2014). In

Received: December 3, 2023 Accepted: Julio 1, 2024
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Colombia, the agronomic production of peach is concentrated in the Andean departments of Boyacá, Cundinamarca, North of Santander and Santander, located in the Eastern Cordillera of the Andes, a mountain range of sedimentary geological origin, and specifically in municipalities whose altitudinal range is between 1600 and 3332 masl (Carranza and Miranda, 2013).

The department of Boyacá is the largest producer and contributes 45.65 % of the national production in Colombia. According to AGRONET (2024), the department of North of Santander ranks second, with a production of 12,544 t and yields of 14.71 t·ha-1, with crops of the Jarillo variety of Venezuelan origin (Campos, 2013). In the year 2022, the planted area was 40 hectares, and the yield was 10.00 t·ha-1 in the Province of Pamplona. The cultivation of peaches is an important economic activity, it being source of income for producers in this region (Cancino et al., 2019). In these agroecological scenarios, the agronomic yield is low compared to the world average of 16.85 t·ha-1 (FAOSTAT, 2021).

Average temperatures between 14 °C and 20°C favor the continuous production of deciduous trees in Colombia, where it has been found that a temperature of around 18 °C is suitable for the growth, flowering, and development of the fruit in deciduous crops. The peach exhibits low requirements for cold temperatures (Jana, 2021). The increase in altitude exerts profound effects upon the physiology of the plant through the increase in radiation (especially ultraviolet) and wind, while the temperature decreases by 0.6 °C for every 100 m of altitude, and the partial pressure of gases (CO2, O2, N2, H2O) and precipitation decrease (Bajpai et al., 2015). In this context, it is important to indicate that the physicochemical characteristics of the fruits are influenced by the climatic conditions of the production area (Romeu et al., 2015) and that they vary according to altitude, as found in other perennial species (Sarmiento et al., 2020).

The phenological stages of fruit crops represent different periodic biological processes that occur during plant growth and development (Ding and Nilsson, 2016) and are the result of environmental conditions. The proper development of Jarillo peach plants is a combination of growth and differentiation processes that lead to the accumulation of dry matter (De La Bruna and Moreto, 2011). These morpho-physiological changes can be determined using a specific coding system for characterizing the entire developmental cycle of the plant as indicated by Fadón et al. (2015).

The primary factors responsible for the development of the peach are the differentiation and growth of the ovary walls after fertilization. The fruit-growth curve exhibits stages I, II, and III. Prior to the onset of stage II, the fruits usually undergo a thinning performed by the grower. The increase of dry matter in the seed, as observed in the Jarillo variety, occurs during stage III, which persists until the fruit reaches its ripening stage (Martínez et al., 2017).

In relation to peach fruit, the primary determinants of quality can be classified as visible quality, which encompasses exocarp size and appearance; flavor quality, which is typically quantified by soluble solids concentration and malic acid content; and texture quality, which includes firmness and juiciness (Reig et al., 2023). In the yield of Jarillo peaches for fresh consumption, the size of the fruit is one of the determining factors of quality, since it is a fundamental requirement of consumers (Morais et al., 2017). The estimation of the size of the peaches based on the diameters and the weight of the fruit is important for agronomic yield (Septar et al., 2021). The shape of a fruit is an important external characteristic that consumers use to select preferred varieties (Guo et al., 2018). The shape of the peach can be classified as round or flat, with flat or oblate peaches being more popular than round peaches (Aular and Cásares, 2019; Tan et al., 2019).

The timing of phenophases in fruit trees has important economic implications, as it directly affects fruit production (Lisandru et al., 2017). These processes allow growers to create agronomic management calendars that are used to regulate the timing of various cultural practices.

It is therefore of great importance to gain an understanding of the behavioral responses of plants to variations in environmental conditions in order to implement measures that enhance yield and fruit quality. Consequently, the objective of this study was to analyze the growth of Jarillo peaches and their relationship with different altitudes.

MATERIALS AND METHODS

Plant material and study area. The Jarillo variety of this research has the following agronomic characteristics: yellow exocarp and pulp, small size, rounded shape, highly prolific production and susceptibility to post-harvest handling. This peach has established itself in small areas with a good adaptation to the study area. The plants are large due to the established planting distance of 6-7 m between plants and rows, distributed according to homogeneous conditions of slope and agronomic management, forming plots with peach trees in full production from sexual seed and with an age of fourteen years (Campos, 2013).

The research was conducted in the Santander mountains, which constitute the central portion of the Andean Eastern Cordillera in the department of North of Santander, at elevations ranging from 1600 to 2300 masl. In Pamplona, two sites were chosen: First, "Las Delicias" farm, Chíchira vereda (7°22'43" N, 72°37'41" W), was studied. It has an altitude of 2170 masl, a mean temperature of 16 °C, precipitation of 933 mm, a bimodal regime and soils belonging to the Inceptisol order. Second, in Chitagá, "El Recuerdo" farm, Carrillo vereda (7° 11' 15" N and 72° 39' 07" W) was studied. It has an altitude of 1870 masl, with an average temperature of 18 ºC, precipitation of 879.5 mm, a unimodal regime and soils of the Inceptisol order (IGAC, 2011).

Finally, in Pamplonita, "Bella vista" farm, Batagá vereda (7° 26' 18" N and 72° 38' 9" W), was studied. It has an altitude of 1670 masl, an average temperature of 20 °C, frequent and accumulated annual rainfall that exceed 1200 mm, a bimodal regime, and soils belonging to the Inceptisol order (IGAC, 2011).

Sampling methods. Samples were collected over the course of one year in an altitudinal strip situated between 1670 and 2170 masl. The samples were collected at the three following phenological stages: a) stage which corresponded to the green ovary surrounded by a crown of dying sepals; b) stage when the fruit was approximately half the size of the final stage; and c) stage which corresponded to fruits ripe for harvest (Fadón et al., 2015).

For the tree sampling at each altitude, conditional Latin hypercube sampling was employed (Minasny et al., 2012), using a rigid network in which 48 trees were identified (6 rows and 8 columns) involving the area of the foliar involvement, approximately elliptical in shape, as an auxiliary variable, so that it approximated the relationship associated with πab where a is related to the semi-major axis (length; meters) and b is related to the semi-minor axis (width; meters). The sampling by altitude was predetermined, and with the assistance of the R software library, a sample of eight altitude trees was generated. Ten fruits were randomly selected from the middle third of each tree and subjected to mass measurement. The mass was recorded for both the fresh and dry states of the fruit and fruit pulp, as well as for the relationship between the pulp and seed within the same fruit. Additionally, the roundness index was calculated. The samples were organized into a matrix of 240 observations, with altitude serving as the discriminating factor in the mixed-model analysis. In contrast, the multivariate analysis and polynomial regression employed a matrix of 30 observations, with altitude serving as the discriminating factor in each case.

Variable response and factors. The response variable was associated with the measurement of the fresh mass from 80 fruits of the Jarillo variety from three growth stages, for a total of 240 fruits: the beginning of growth, 33 days after defoliation, during the hardening of the fruit; 72 days after defoliation; and harvest, 170 days after defoliation (Lisandru et al., 2017). Dry mass was measured after the fruits were dried using a Mettler Toledo dry hot air forced circulation drying oven. The mass was measured by means of a two-digit electronic balance (Lexus) with a measuring range of 3600 g and precision of 0.01 g. The ratio longitudinal diameter/equatorial diameter of the fruit was used to calculate the roundness index.

The factors involved were altitude, with three levels related to the three main productive areas of the Jarillo peach in Pamplona at 2170 masl, Chitagá 1870 masl, Pamplonita 1670 masl, and phenological stages (fixed effects). The 10 trees were selected by conditional hyper-cube sampling (random effect nested at altitude) and the 3 randomly selected fruits (random effect nested in trees).

Statistical analysis. Before proceeding with the statistical analysis, an exploratory data analysis was applied, and the assumptions required by the statistical methods applied were checked. The first analysis included box plots to describe the fresh mass variable by altitude and days after defoliation.

To process the data of the variables associated with the fruit, a multivariate analysis of variance (Manova) was carried out. A multivariate MLG procedure was developed by SPSS 23.0 (Armonk, New York) that provided an analysis of variance for multiple dependent variables, based on a factorial distribution of factors with fixed levels, using, as a source of variation, altitude, as well as phenological stages.

For modeling, the fresh mass of the fruits was considered as the response variable and the altitude as the factor of fixed effects, while the trees and their fruits were considered as random effects, with a nested structure, that is, with fruits nested in trees. This consideration is convenient, above all, because fruit sampling is destructive, and although this method incorporates greater variability into the data for each tree, it does not do so for all the trees within the altitudes, since the same trees are always evaluated. Since this study involved taking measurements from the same tree, longitudinal mixed models in three stages were considered (De La Bruna and Moreto, 2011).

For the study of altitudinal level, the fruits were separated into three groups, according to the sampled population per farm (altitude 1, Pamplona; altitude 2, Chitagá; altitude 3, Pamplonita). The test procedures for the multivariate analysis were as follows Wilks Lambda (Friendly and Sigal, 2020). In addition, polynomial regression was used to represent the growth of the fruits by altitude.

The research implemented a mixed linear model for longitudinal data using the fresh mass of the Jarillo peach as the variable. Consequently, the random effects in the research were those associated with the groups (trees, fruits) and with the units of analysis nested within these groups (fruits within trees and trees at altitude) to consider the grouped structure of the data and the correlation of residuals due to time.

For the purposes of the inferential statistical analysis, the analysis of variance was used for a mixed linear model associated with the design in repeated measurements with unevenly spaced by phenological stage, for which the Markov covariance structure (spatial power) was required to consider the effect that it had on the correlation with the unequally spaced measurements of the fruit mass by phenological stage. The fixed effects were the altitude, and the phenological stages and the random effects were the fruits nested in the trees and the trees nested at the altitudes in order to obtain the grouped structure of the data and consider the correlation of the residuals over time. To predict the relative quality of the statistical models the Akaike index (AIC) was computed**.**

RESULTS AND DISCUSSION

In the analysis carried out on the results obtained, differences were noted among the variables associated with the fruit (effect of altitude) and, in addition, effects of the interaction between the altitude and the number days after defoliation (daf) (Table 1).

The inter-subject-effects test showed that there were significant differences ($P \leq 0.05$) between altitudes with respect to the six parameters associated with the fruit in the interaction of altitude with daf (Table 1). It was shown that there were significant differences between the morpho-physiological variables associated with the fruit attributed to the effect of altitude and the daf. In the MANOVA analysis of these variables, the four statisticians showed significance once the absence of interaction between mixed factors was detected. Therefore, when comparing the three vectors of means corresponding to the altitudes and the twelve vectors of the daf, at least one vector of means was different. There were significant differences among the altitudes for the morpho-physiological variables studied.

Table 2a shows the results of the longitudinal mixed model analysis of variance after model adjustment. For the random-effects analysis, the need to include the level associated with the fruits in the trees was reviewed (Zhao et al., 2013). The present study allowed a comparison of the complete model with the reduced model with the effect of the fruits in the trees (Table 2b), including the effects between the factors. The reduce model was the best for having the lowest AIC value.

The effects of time and altitude demonstrated a significant interaction for all variables (Table 1), as illustrated in Figure 1a, which depicts that in the initial stages of the evaluation, the fresh mass of the fruits exhibited comparable values. However, the highest value was observed at an altitude of 1670 masl (Pamplonita), with the highest discrepancy observed at 170 daf. This is in agreement with the findings of Quevedo et al. (2017b)

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Table 1. Tests of the morpho-physiological variable inter-subject effects of the fruit

Origin	Dependent variable	df	F	Sig.
cm	Roundness index	46	137.91	0.000
	Fresh pulp mass (g)	46	216.08	0.000
	FPM/FSM	46	173.56	0.000
	Total fresh mass (g)	46	202.08	0.000
	Pulp dry mass (g)	46	178.42	0.000
	Total dry mass (g)	46	170.39	0.000
Int	Roundness index	1	54450.34	0.000
	Fresh pulp mass (g)	1	13208.24	0.000
	FPM/FSM	1	16322.06	0.000
	Total fresh mass (g)	1	16487.17	0.000
	Pulp dry mass (g)	1	10160.20	0.000
	Total dry mass (g)	1	16865.96	0.000
alt	Roundness index	2	47.04	0.000
	Fresh pulp mass (g)	2	72.57	0.000
	FPM/FSM	2	15.98	0.000
	Total fresh mass (g)	2	73.97	0.000
	Pulp dry mass (g)	2	118.96	0.000
	Total dry mass (g)	2	114.34	0.000
daf	Roundness index	43	124.92	0.000
	Fresh pulp mass (g)	43	197.25	0.000
	FPM/FSM	43	167.82	0.000
	Total fresh mass (g)	43	181.72	0.000
	Pulp dry mass (g)	43	145.64	0.000
	Total dry mass (g)	43	139.95	0.000
alt * daf	Roundness index	1	24.02	0.000
	Pulp fresh mass (g)	1	53956	0.000
	FPM/FSM	1	21689	0.000
	Total fresh mass (g)	1	49876	0.000
	Pulp dry mass (g)	1	82012	0.000
	Total dry mass (g)	1	56616	0.000
Error	Roundness index	423		
	Pulp fresh mass (g)	423		
	FPM/FSM	423		
	Total fresh mass (g)	423		
	Pulp dry mass (g)	423		
	Total dry mass (g)	423		

cm: corrected model, Int: intersection, alt: altitude, daf: days after defoliation, FPM: fresh pulp mass, FPS: fresh seed mass

For the 170 daf, the differentiation among the altitudes was evident, with the greatest variation occurring between 1670 and 2170 masl, which is located within the Catatumbo basin, and the altitude of 1870 masl, which is situated within the Orinoco basin (Figure 1a). The last stage of the growth curve coincided with the highest growth rate, which is known as fruit filling. The aforementioned characteristics may vary according to the specific variety, environmental conditions, and other factors, such as the fruit's location (Wu et al., 2005).

The analysis of variance in the reduced model was like that of statistical significance, where, again, the significant interaction between the altitude and the evaluation time remained. The significant interaction between the altitudes and the evaluation time is a common phenomenon in growth models (Quevedo et al., 2017a). Following 100 daf, the fruit mass exhibited a notable rise, occurring after the hardening of the stage II. This corresponded to stage III of the growth and to the second part of the double sigmoid (stage II) of the fruit (thinning was performed). Finally, the fruit growth was resumed in accordance with the proposal of Martínez et al. (2017).

Figure 1b repeats Figure 1a by pooling the different altitudes to better show the steep increase of the variance as the evaluation time increased. Therefore, it was appropriate to test whether there was a significant change in the variance over time when the variability within the altitudes was visualized for the daf. In this case, an increase in variability with the evaluation of time was more clearly noted; however, descriptively, the two end times were similar. Additionally, a smoothing of the fresh-mass profiles for the fruits was observed for each altitude (Figure 1c). The interquartile range was higher at 1670 compared to 1870 masl due to the greater variability observed in the fresh matter; however, the median was higher at 1870. While fresh matter at 2170 showed a lower median and higher variability, or interquartile range (Figure 1c). The microclimate generated by the altitude of the area exerts profound effects on plant physiology, as noted by Bajpai et al. (2015).

Table 2. Models and analysis of variance employed in the investigation

(a)

Variation Source	Degrees of freedom denominator	F value	P value
Intercept	474	1,551.60	<0.0001
Time (daf)	474	1823.32	<0.0001
Altitude	21	8.12	<0.01
Altitude: daf	474	18.07	<0.0001

(b)

Model	Degrees offreedom	AIC	Test I Vs II	P value
Full (I)	17	4138.05		0.0645
Reduced (II)	16	4134.90	1823.32	<0.0001

(a) Analysis of variance for the fixed effect associated with altitude and the longitudinal factor corresponding to the evaluation time. (b) Comparison of the complete three-level model (I) with the two-level model (II). AIC: Akaike index

Another interesting result was the effects of the interaction between the daf and the altitudes on the expected outcomes (Figure 2). The highest) average was observed at an altitude of 1670 masl (Pamplonita), a pattern that was also evident when the daf and altitudes were considered together (Figure 2).

The last stage of the growth curve coincided with the highest growth rate and what is known as fruit filling, which it can vary (Wu et al., 2005). In stage III, between 100 and 150 daf, as showed in figure 2d y 2f, the peach fruits grew attributed to cell expansion in the last weeks (or months) before harvest, accumulating water, sugars, organic acids and mineral elements in the cell vacuole (Huang et al., 2021). Whereas subsequent growth is solely dependent on cell elongation, extending up to 170 daf, as illustrated in Figure 2 and corroborated by Sutton et al. (2020).

In all measurements, the means of fresh fruit mass were higher at 1670 masl (Pamplonita), followed by 2170 masl at each time and secondary stage of development (Figure 2). This suggests that if the initial measurement is truncated, it is possible to find parallel profiles.

The values of fruit-associated variables (Figure 2) improved in the climatic conditions at the lowest altitude evaluated (1670 masl, Pamplonita), as noted by Ding and Nilsson (2016). However, the improvements in variable expression were different at 1870 and 2170 masl (Chitagá and Pamplona, respectively). The sole exception to this observation was the ratio of pulp fresh weight to seed fresh weight. At an altitude of 2170 masl, a ratio of 12.28 to 188 daf was obtained, while at 1870 masl the ratio was 10.48 to 208 daf (Figure 2c), in accordance with the values predicted by the polynomial model utilized. This indicated that the environmental conditions and the period of growth and development of the fruit between the stages of 33 and 170 daf was important for the expression of these morpho-physiological variables, which allowed us to conclude that the interactions at the lowest altitude were better for obtaining a higher pulp-seed ratio of the fruit than at the other altitudes

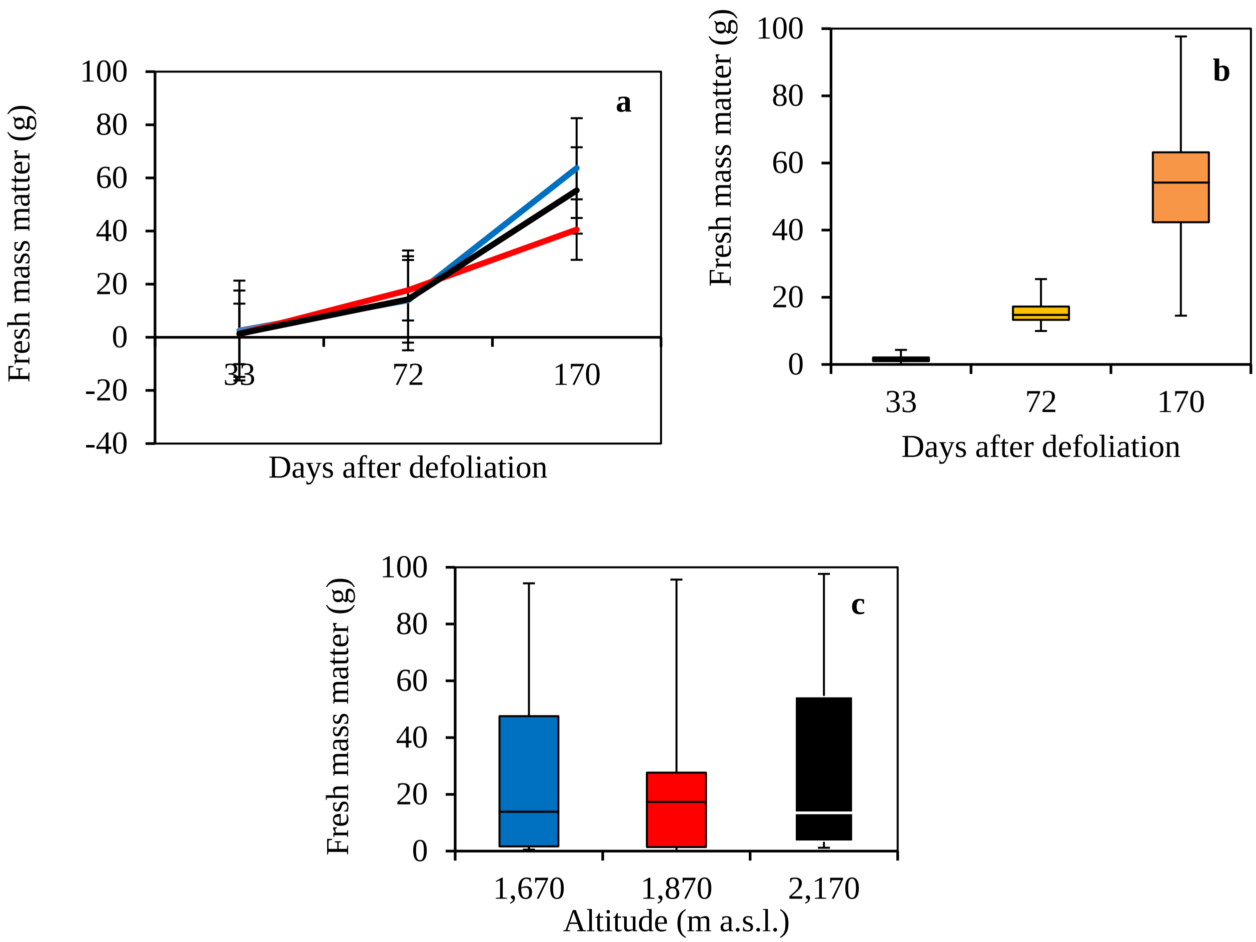

Figure 1. a) Box plot for fruit fresh mass measured on different days after defoliation at different altitudes. b) Box plot for fruit fresh mass measured on different days after defoliation (1b). c) Box plot for fresh mass measured at the different altitudes. Blue: 1670 masl; Red: 1870 masl; Black: 2170 masl

As a result, at the agronomic level, the fresh seed mass was higher at the lowest altitude, located in Pamplonita, at 1670 masl (Figure 2), with 12.56 g, a value that, when compared to eight varieties grown in Brazil was higher than five of them and lower than those grown in Bonão (Nogueira et al., 2017). Therefore, the environmental conditions at this altitude are adequate to grow Jarillo peaches with a higher pulp production for the development of agribusiness. This confirms that these altitudes influenced the results of this variable in association with a fruit crop of agronomic importance (Nogueira et al., 2017)

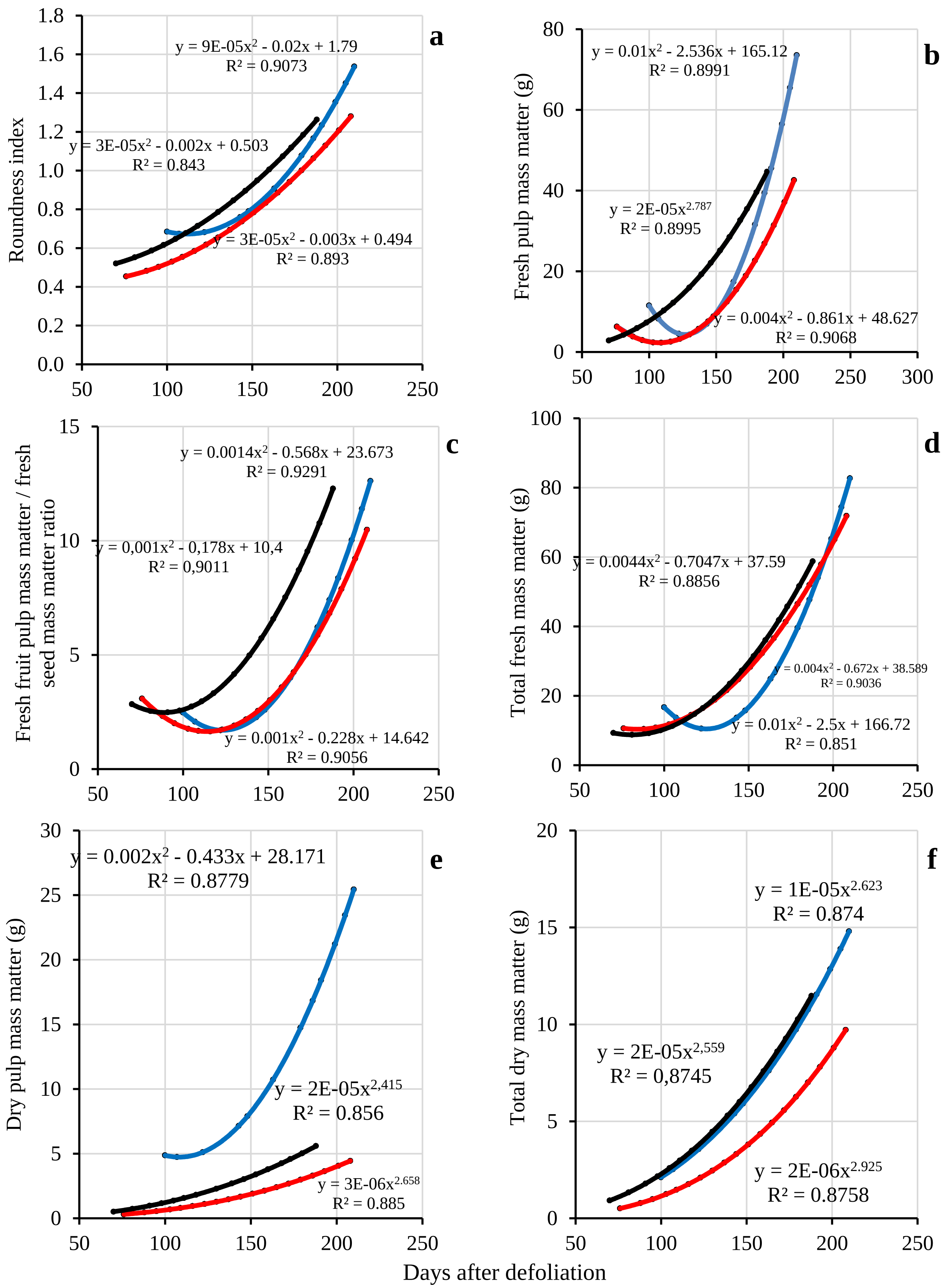

Figure 2. Estimates of the second degree polynomial regression models for the variables associated with the fruit as a function of the days after defoliation. Blue: 1670 masl. Red: 1870 masl. Black: 2170 masl

Figures 2a–f showed the reason for the variability of the fruit mass and their parts among the different growth stages during the evaluation days for each altitude. They also demonstrated the superiority of the effects of the altitude of 1670 (Pamplonita) on the fruit mass and their parts, as well as the relationships of agronomic interest from the beginning of the evaluation to the beginning of 33 daf. The greatest difference was observed at 170 daf, which aligns with the findings of Quevedo et al. (2017b), who employed a discriminant analysis.

The lowest fruit mass observed during the productive cycle under study was recorded at an altitude of 1870 masl (Chitagá in the Orinoco basin), in contrast to the lowest altitude (1670 masl, Pamplonita) where the highest value of fruit mass was recorded (Figure 2).

In the case of the fresh mass of the fruits and the time measurement, it is clear that the altitudes of 1670 and 2170 masl (Catatumbo basin) had the highest fresh-fruit mass and they were slightly higher than those found at lower altitudes (1670 masl, Pamplonita), and according to Silva et al. (2016).

The fresh mass is an important quantitative hereditary factor determining the yield, the quality and the acceptability of the fruit to the consumer (Matias et al., 2017). The mass in this study was probably due to environmental influences on the physiology of Jarillo peach from the thermal zones located at 1670 and 2170 masl, belonging to Catatumbo (Pamplonita and Pamplona

CONCLUSIONS

The effects of time after defoliation and altitude demonstrated a significant interaction for all variables evaluated in this study.

The altitude with the highest fresh-fruit-pulp mass/fresh-seed-mass ratio was 1670 masl (Pamplonita), which it allowed a higher percentage of pulp from harvested fruits for agro-industrial processes.

The pattern of relationship between fruit-associated variables as a function of days after defoliation was explained using a second-order polynomial regression model.

ACKNOWLEDGEMENTS

Financial support was provided by the University of Pamplona, Colombia, and the deciduous fruit producers Carlos Alberto Portilla and William Eduardo Flórez.

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