Predicting the Diameters and the Mass of Granny Smith Apple Fruits Using Growing Degree Days

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Abstract

A two-year study (2012 -2013) was performed in an apple orchard of Korca District, Albania, to develop predictive tables for size and mass of Granny Smith cultivar fruits. Five trees of same age and vigour were chosen, and in each tree forty fruits were randomly selected and tagged. Fruit diameters were measured on a weekly basis, starting from 40 Days After Full Bloom (DAFB) to harvest (159 DAFB). The accumulated Growing Degree Days (GDD) from 40 DAFB to harvest were used as independent variables in regression equations. It was found that fruit diameters at 40 DAFB were very decisive in final fruit size and mass, and air temperatures accumulated from full bloom to 40 DAFB play and important role in fruit size. Among three regression models: linear, quadratic and cubic compared, the quadratic equation resulted being the best in describing the relationship between each diameter's growth and the accumulated GDD, with the highest adjusted coefficient of determination (R^2 between 0.99 and 1.0) and the lowest residual standard deviation (R*SD* between 0.40 and 0.55). Multiple regression equations with equatorial and longitudinal diameters as independent variables provided high prediction accuracy in respect fruit mass, with a very high R^2 (from 0.977 to 0.999) and a low R*SD* (from 0.370 to 0.558).

KEYWORDS: apple, Granny Smith, prediction, diameter, mass.

INTRODUCTION

Production of fresh apples is becoming a very import income source for many farmers of north-eastern and south-eastern parts of Albania. The continuous increase in domestic apple production in the recent years has drastically cut down import, while since 2011, modest amounts of Albanian fresh apples have been exported and the growth trend for the next years is positive. Granny Smith is an important apple cultivar that accounts about 10% of trees planted in new orchards. It is a late ripening cultivar, which stands long after harvest even without refrigeration. Due to less sugar content than other cultivars, it is preferred by Albanian and foreign customers.

As for other fruits and vegetables, apple should comply with international standards. Among several requirements apple fruits' equatorial diameter and mass at harvest are two important ones, and apart from being biological characteristics of any cultivar, they also depend also a number of agro-technical and climate factors. Apple growers intending to have a sustainable business and enter profitable domestic and international markets should know well in advance the final size and mass of their produce. That can help them as a tool in taking early-season decisions regarding the general growing agro-techniques employed in orchards and particularly, the appropriate fruit thinning process. Size and mass prediction is also important in planning the packaging material orders and in signing well in advance produce-selling contracts, based on the percentage of saleable fruit, according to their size/mass groups.

Growth models in size and mass and expressed mathematically have been subjects of numerous works since decades ago. Several studies have shown that the growth in diameter has a sigmoidal shape but plots of mass data of fresh fruits versus time may also show a late-season decline in fruit growth rates, which is more evident in commercial apple orchards (Pratt, 1988). In that regard, it was showed that during the first 3 – 5 weeks, the fruit growth model is curve-linear, followed by linear growth until harvest, especially in trees with light fruit load (Blanpied, 1966; Assaf *et al.*, 1982). Other authors (Gourdiaan and Monteith, 1990) described the apple growth model as an expo-linear equation that shows an exponential increase of dry matter in the first 3 – 5 weeks after bloom, and is characterized by an intensive division of cells. The other period preceding harvest is followed by a linear growth, where cells don't divide anymore, but only expand (Bollard, 1970; Blanpied and Wilde 1968; Pratt 1988).

Several mathematical models, in the form of regression equations, have been used to express apple fruit growth, like the polynomial, the logistic and the logarithmic type (Bramardi *et al*., 1997; Garritz *et al.*, 1993; Bajter *et al*,. 1957; Ortega – Farias *et al*., 1997; 1998; Berg and Lötze, 2006).

In all these regression equations, either Days After Full Bloom (DAFB) or Growing Degree Days (GDD) have been used as the independent variable, while the fruit diameters the dependent ones. However, in some cases, the use of DAFB isn't highly accurate when climatic factors and growing season temperatures in particular have significant deviations from the average (Berg and Lötze, 2006). Instead, the use of GDD is more appropriate (Ortega – Farias *et al*., 1997; 1998). Meanwhile, to predict fruit mass, both equatorial and longitudinal diameters can serve as independent variables in multi-linear regression equations providing high accuracy (Ortega – Farias *et al*., 1997; 1998).

Taking into consideration that importance, a study was carried out in the area of Korça, Albania, during two consecutive growing seasons, 2012 and 2013. There were three objectives of this study:

a) to select the best fitting regression model that describes the relationship between the Granny Smith diameters' growth and accumulated GDD from 40 DAFB to harvest (159 GDD);

b) to prepare predictive tables of diameters values with respect to GDD accumulated for this cultivar;

c) to prepare predictive tables of apple fruit masses with respect to various equatorial and longitudinal Granny Smith diameter combinations.

MATERIAL AND METHODS

To fulfil the first three objectives of this study (a, b, c) in early May 2012, five Granny Smith apple trees of similar vigour, grafted on MM106 rootstock, were randomly selected in a 12-year old apple orchard in Drenova Commune, Korça District, Albania, with coordinates: latitude 40^{o} 35' 33" N, longitude 20^{o} 45' 53" E, and altitude 860 m above sea level. Trees to a density of 1250/ha were trained to a slender spindle form, hand thinned each year within 40 – 50 DAFB to have a density of 6 – 6.5 fruits/cm^2 of trunk cross-section area. During the growing season there was applied drip-irrigation and fertigation based on water and nutrition requirements, and plant protection followed as much as possible the Integrated Pest Management principles. No soil tillage was practiced against weeds, but herbicide used instead.

In year 2012 and 2013, at 40 DAFB, in each of five trees selected, 40 fruits were randomly selected and tagged at a 1-2 m height from soil, from outer to inner part of canopy, in each cardinal direction. The fruits' equatorial and longitudinal diameters were measured with an electronic calliper of 0.01 mm precision, and data were entered in an Excel spreadsheet. Each fruit was measured 18 times (once a week), starting from 40 DAFB until harvest (159 DAFB). In each autumn after fruit harvest, before proceeding with calculations, the rows of data in the Excel spreadsheet were rearranged in an increasing order regarding the equatorial diameter, but each equatorial diameter was always accompanied by its respective longitudinal diameter in the next column. To get more accurate calculations and predictions, the whole range of equatorial diameters values was split in four groups at 2-mm intervals: 27–29 mm, 29–31 mm, 31–33 mm and 33–35 mm.

The daily minimum and maximum air temperatures and rainfalls were collected from the meteorological station at the Centre of Agriculture Technology Transfer, situated at a distance of 3.1 km from the orchard. The calculation of GDD for each day from the full bloom up to harvest was made based on the following formulae:

$$GDD = (T_{min} + T_{max})/2 - 10$$

where:

T_{min} = Minimum daily temperature (in ^{O}C);

T_{max} = Maximum daily temperature (in ^{O}C);

10 = lower threshold temperature (10^{O}C).

All recorded data were processed with Minitab 16.1 Statistical Software, at a confidence level of 95%. The following represents methodologies used to fulfil the aim of the study: a; b; and c.

a) For selecting the best fitting regression model that describes the relationship between each group's growth and the accumulated GDD, three types of regression models were compared:
 - Linear, or first degree equation: $D = b_0 + b_1*GDD$
 - Quadratic, or second degree equation: $D = b_0 + b_1*GDD + b_2*GDD^2$
 - Cubic, or third degree equation: $D = b_0 + b_1*GDD + b_2*GDD^2 + b_3*GDD^3$

 where:

 D = apple fruit diameter (equatorial or longitudinal);

 b_0 = fruit diameter (equatorial or longitudinal) when the value of GDD is zero;

 GDD = Growing Degree Days;

 b_1, b_2, b_3 = coefficients that show the estimate change in fruit diameter (equatorial or longitudinal) mean when GDDs is increased by one unit (1^{O}C).

 * = multiplication symbol

 In comparing these three regression models, the one which had the highest adjusted coefficient of determination (R^2) and the lowest residual standard deviation (R*SD*) was considered the best fit.

b) To prepare the predictive tables of equatorial and longitudinal diameters with respect to accumulated GDD, in each regression equation selected in part (a), the following GDD were used: from 100^{O}C to 1400^{O}C, in increasing 50^{O}C intervals. The value of GDD at 40 DAFB was considered 0^{O}C.

c) To prepare the predictive tables of apple fruit mass with respect to various equatorial and longitudinal diameter combinations, each fruit's mass at harvest (152 DAFB) was measured with an electronic scale of 0.1 g precision. Using the equatorial and longitudinal diameters as two independent variables and fruit mass as a dependent variable, a multiple regression equation was generated for each mean diameter of the five groups, in the following form:

$M = b_0 + b_1De + b_2Dl$

where:

M = the fruit mass (weight) in g;

b = constant coefficient of regression equation;

D*e* and D*l* = equatorial and longitudinal diameters, respectively

b_1 and b_2 = coefficients that show change of fruit mass when values of D*e* and D*l* are increased by one unit (1 mm).

RESULTS AND DISCUSSION

The first fruit measurements made at 40 DAFB showed that there was a difference between the fruit equatorial diameters in year 2012 and 2013 respectively despite the fact that each year had a normal bloom and similar flower loads per tree. Similar differences of fruit diameters in Golden Delicious and Red Chief cultivars were evidenced in the same orchard and same years (Papamihali, 2014[a-b]). The 200 fruits measured at 40 DAFB in 2012 had equatorial diameters that lied in three group sizes 27 – 29 mm and 29 – 31 mm, and 31 – 33 mm, while those of year 2013 in two groups 31 – 33 and 33 – 35 mm, as shown in Table 1.

Table 1. Equatorial diameter groups, number of fruits in group and their average diameters

Year	D*e* 27–29 mm		D*e* 29 -31 mm		D*e* 31-33 mm		D*e* 33-35 mm	
	No. of fruits	Avg. D*e*	No. of fruits	Avg. D*e*	No. of fruits	Avg. D*e*	No. of fruits	Avg. D*e*
2012	88	28.37	92	29.89	20	31.28	-	-
2013	-	-	-	-	132	32.20	68	33.77

Differences in longitudinal diameters between fruits measured at 40 DAFB in 2012 and same point in time in 2013 were also evidenced, and they are shown in Table 2.

Table 2. Longitudinal diameter groups, number of fruits in group and their average diameters

Year	D*l* 27 – 30 mm		D*l* 30 – 32 mm		D*l* 31 – 34 mm		D*l* 33 – 36 mm	
	No. of fruits	Avg. D*l*	No. of fruits	Avg. D*l*	No. of fruits	Avg. D*l*	No. of fruits	Avg. D*l*
2012	88	28.80	92	30.23	20	31.92	-	-
2013	-	-	-	-	132	32.82	68	34.45

The above-mentioned differences in both fruit diameters between years at 40 DAFB can be explained by the significant gap of GDD accumulated each year from the day of full bloom (DFB) to 40 DAFB. This temperature gap in monthly basis is shown in Table 3.

Table 3. Growing Degree Days from date 1 April to 11 October (2012 and 2013)

Year	April	May	June	July	Aug.	Sept.	Oct.	Amount
2012	7.9	110.2	258.0	459.2	420.4	248.7	68.0	1572.4
2013	47.8	199.4	287.8	380.9	415.2	234.7	28.5	1594.3

In year 2012 from 5 May (DFB) to 14 June (40 DAFB) were accumulated 160.3 GDD, while in 2103 (DFB on 29 April and DAFB on 7 June) were 264.8 GDD, or 104.5^{o}C plus. The role of early season temperatures in apple growth and maturity has been clearly evidenced by Berg (1990) and Warrington *et al.*, (1999).

a) Selection of the best-fitting regression model that describes the relationship between the diameters' growth and accumulated GDD from 40 DAFB to harvest (159 GDD).

A comparison of the three models showed that the quadratic regression equation was the best model in describing the relationship between each equatorial and longitudinal diameter group growth and the accumulated GDD. For each of the five equatorial diameters groups referenced in Table 1 and the respective longitudinal groups referenced in Table 2, at a confidence level of 95%, ($p<0.05$), the quadratic model provided the highest adjusted coefficient of determination R^2 (0.99 to 1.0) and for equatorial and the lowest residuals of standard deviation (R*SD* = 0.40 to 0.55), compared to the linear and the cubic models. On the other hand, when each final diameter (equatorial or longitudinal) at harvest was regressed (using the quadratic model) against the diameters at any of 18 measurements, the difference was always less than 1.2 mm, which shows that the equations were highly accurate. Similar accuracy of quadratic model (with difference less than 1 mm) has been evidenced in the same orchard and study years with Golden Delicious and Red Chief cultivars (Papamihal, 2014[a-b]). The quadratic regression equations for each group of diameters are shown in Table 4.

Table 4: Regression equation of equatorial diameters (D*e*) and longitudinal (D*l*) diameters

Fruit group	D*e* in mm (40 DAFB)	D*e* regression equations	D*l* in mm (40 DAFB)	D*l* regression equations
1	28.37 (27 – 29)	D*e* = 28.37 + 0.05246*GDD - 0.000011*GDD^2	28.80 (27 – 30)	D*l* = 28.18 +0.04394*GDD – 0.000009*GDD^2
2	29.89 (29 – 31)	D*e* = 29.82 + 0.05542*GDD - 0.000012*GDD^2	30.23 (30 – 32)	D*l* = 29.60 +0.04626*GDD – 0.00009*GDD^2
3	31.28 (29 – 31)	D*e* = 31.28 + 0.05782*GDD - 0.000013*GDD^2	31.92 (31 – 34)	D*l* = 31.19 +0.04890*GDD – 0.000010*GDD^2
4	32.20 (31 – 33)	D*e* = 32.81 + 0.06751*GDD - 0.000019*GDD^2	32.82 (31 – 34)	D*l* = 32.12 +0.05630*GDD – 0.000015*GDD^2
5	33.77 (33 – 35)	D*e* = 34.41 + 0.07069*GDD - 0.000020*GDD^2	34.45 (33 – 36)	D*l* = 33.63 +0.05928*GDD – 0.000016*GDD^2

b) Preparation of predictive tables for equatorial and longitudinal diameters growth with respect to accumulated GDD

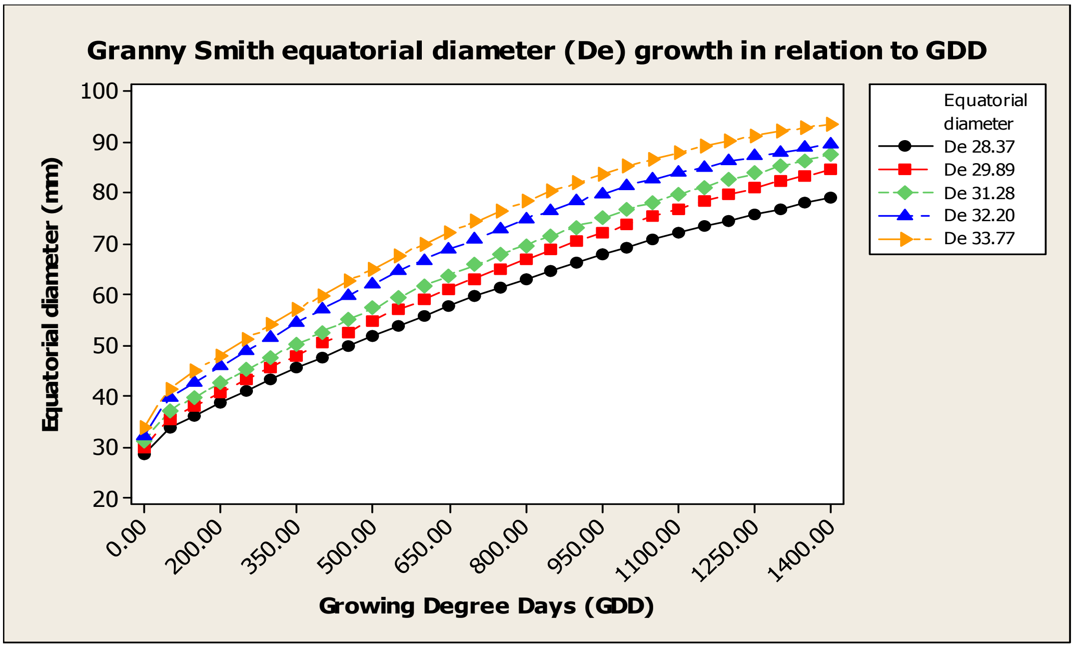
Using the contents of Table 4 (the average diameters for each group and the regression equations) a predictive table for the diameters' growth was prepared using different accumulated GDD during a growing season as independent variables. Table 5 shows these predictions. At 40 DAFB the GDD value was considered 0.00, and from that moment to the rest of season was cumulated up to 1400.0 GDD at 165 DAFB in 2012, but in year 2013, at 166 DAFB was amounted no more than 1310 GDD.

In a 5-year survey (2009 -2013) the average accumulated GDD from 40 DAFB to 159 DAFB were 1288. In the warmest growing season (2012), 1368 GDD were accumulated during that period, while in 2013, a value of 1280, which is very close to the average. This implies that in years with normal seasonal temperatures, the diameters‘ growth from 40 DAFB to harvest would be very similar, in contrast to hotter ones, when growth may slow down to a certain extent (Berg and Lotze, 2006). In that context, in orchards where are employed each year regular agro-technical measures, including fruit thinning to have same number of fruit per trunk cross-section area, diameters at 40 DAFB are the ones that have a very significant impact on final fruit sizes and consequently to their mass.

Table 5. Predictive table for equatorial and longitudinal diameters growth (2012 & 2013)

GDD (^{0}C)	Fruit groups growth in respect to GDD									
	Group 1		Group 2		Group 3		Group 4		Group 5	
	D*e*	D*l*	D*e*	D*l*	D*e*	D*l*	D*e*	D*l*	D*e*	D*l*
0.0	28.37	28.80	29.89	30.23	31.28	31.92	32.20	32.82	33.77	34.45
100.0	33.51	32.48	35.24	34.14	36.93	35.98	39.37	37.60	41.28	39.40
150.0	35.99	34.57	37.86	36.34	39.66	38.30	42.51	40.23	44.56	42.16
200.0	38.42	36.61	40.42	38.49	42.32	40.57	45.55	42.78	47.75	44.85
250.0	40.80	38.60	42.93	40.60	44.92	42.79	48.50	45.26	50.83	47.45
300.0	43.12	40.55	45.37	42.67	47.46	44.96	51.35	47.66	53.82	49.97
350.0	45.38	42.46	47.75	44.69	49.92	47.08	54.11	49.99	56.70	52.42
400.0	47.59	44.32	50.07	46.66	52.33	49.15	56.77	52.24	59.49	54.78
450.0	49.75	46.13	52.33	48.59	54.67	51.17	59.34	54.42	62.17	57.07
500.0	51.85	47.90	54.53	50.48	56.94	53.14	61.82	56.52	64.76	59.27
550.0	53.90	49.62	56.67	52.32	59.15	55.06	64.19	58.55	67.24	61.39
600.0	55.89	51.30	58.75	54.12	61.29	56.93	66.48	60.50	69.62	63.44
650.0	57.82	52.94	60.77	55.87	63.37	58.75	68.66	62.38	71.91	65.40
700.0	59.70	54.53	62.73	57.57	65.38	60.52	70.76	64.18	74.09	67.29
750.0	61.53	56.07	64.64	59.23	67.33	62.24	72.76	65.91	76.18	69.09
800.0	63.30	57.57	66.48	60.85	69.22	63.91	74.66	67.56	78.16	70.81
850.0	65.01	59.03	68.26	62.42	71.03	65.53	76.47	69.14	80.05	72.46
900.0	66.67	60.44	69.98	63.94	72.79	67.10	78.18	70.64	81.83	74.02
950.0	68.28	61.80	71.64	65.42	74.48	68.62	79.80	72.07	83.52	75.51
1000.0	69.83	63.12	73.24	66.86	76.10	70.09	81.32	73.42	85.10	76.91
1050.0	71.33	64.39	74.78	68.25	77.66	71.51	82.75	74.70	86.58	78.23
1100.0	72.77	65.62	76.26	69.60	79.15	72.88	84.08	75.90	87.97	79.48
1150.0	74.15	66.81	77.68	70.90	80.58	74.20	85.32	77.03	89.25	80.64
1200.0	75.48	67.95	79.04	72.15	81.94	75.47	86.46	78.08	90.44	81.73
1250.0	76.76	69.04	80.35	73.36	83.24	76.69	87.51	79.06	91.52	82.73
1300.0	77.98	70.09	81.59	74.53	84.48	77.86	88.46	79.96	92.51	83.65
1350.0	79.14	71.10	82.77	75.65	85.64	78.98	89.32	80.79	93.39	84.50
1400.0	80.25	72.06	83.89	76.72	86.75	80.05	90.08	81.54	94.18	85.26

Figures from Table 5 show that fruits of smaller diameter groups grew less than the bigger ones. The gap between average equatorial diameter of the first and fifth group widens from 5.40 mm at 0.0 GDD (40 DAFB) to 13.93 mm at 1400.0 GDD. Graph 1 depicted the abovementioned widening of the gap. Similarly, the gap between the average longitudinal diameters of the first to the fifth group widened from 5.65 mm to 13.20 mm in the same timeframe.



Graph 1. Widening gap of equatorial diameter from 40 DAFB to harvest (159 DAFB)

In practice, this means that larger fruits have higher growth rates than smaller fruits, and that is in same direction with the conclusion reached by Lakso *et al.* (1995), and Lakso and Goffinet (2013). They showed that small fruits in a tree at 40 DAFB, can never catch up later to become large fruits. When they measured cell numbers per fruit, they found that the difference in growth rate was directly controlled by cell numbers, as each cell grew the same amount per day in all fruits. Since cell numbers are set in only the first few weeks after bloom, that is a critical time for the whole season.

c) Preparation of a predictive table of apple fruit mass with respect to each equatorial and longitudinal diameter group

In both years, at 159 DAFB all tagged fruits were harvested and measured for the last time, recording their diameters size and mass. From the initial total of 200 fruits at 40 DAFB, at harvest there were 177 of them remaining in 2012 and 182 in 2013. The rest had previously fallen for different reasons. The correlation between fruit diameters and mass was expressed by the multiple regression equation for each of the five fruit groups and provided a very high accuracy, with an absolute error of less than 0.7 g/fruit. In all five equations, the adjusted coefficient of determination (R^2) had large values, ranging from 0.977 to 0.999, while the residual standard deviations (R*SD*) from 0.370 – 0.558 (Table 6). These equations can be used to predict the final mass for any fruit within each group. The average fruit mass at 159 DAFB show a very big difference between groups, as fruits of fifth group had a mass 1.48 times higher than those of first one (315.0 / 213.2 g).

Based on weekly fruit diameters recorded during 18 measurements in both years and each fruit group mass at harvest, a predicative table of fruit mass at 138, 145 and 152 DAFB for each group was calculated, using the multiple regression equations (Table 7).

Table 6. Fruit mass with respect to each diameter group at 159 DAFB

Fruit group	Avg. D*e* & D*l* (mm) at 159 DAFB		Mass (M) regression equation for average diameter groups at 159 DAFB	R^2	R*SD*	Avg. fruit mass (g) at 159 DAFB
	D*e*	D*l*				
1	78.40	71.13	M = - 373 + 4.85*D*e* + 2.90*D*l*	0.998	0.409	213.2 ±0.1
2	82.59	74.76	M = - 378 + 5.08*D*e* + 2.71*D*l*	0.999	0.396	243.9 ±0.1
3	86.34	78.73	M = - 390 + 4.93*D*e* + 3.02*D*l*	0.977	0.558	273.6 ±0.2
4	87.58	79.58	M = - 389 + 4.99*D*e* + 2.95*D*l*	0.999	0.370	282.1 ±0.1
5	91.85	83.53	M = - 389 + 5.02*D*e* + 2.92*D*l*	0.998	0.440	315.0 ±0.1

Table 7. Fruit mass prediction for each diameter group at 138, 145 and 152 DAFB

Fruit group	Avg. D*e* & D*l* (mm) and Mass (g) at 138 DAFB			Avg. D*e* & D*l* (mm) and Mass (g) at 145 DAFB			Avg. D*e* & D*l* (mm) and Mass (g) at 152 DAFB		
	D*e*	D*l*	Mass	D*e*	D*l*	Mass	D*e*	D*l*	Mass
1	76.10	69.15	196.1 ± 0.2	77.05	69.91	202.9 ± 0.2	77.88	70.59	209.0 ± 0.1
2	80.17	72.48	225.3 ± 0.2	81.17	73.38	232.8 ± 0.1	82.04	74.09	239.2 ± 0.1
3	83.83	76.64	253.9 ± 0.2	84.87	77.48	261.8 ± 0.2	85.77	78.14	268.5 ± 0.5
4	85.05	77.68	263.7 ± 0.1	86.10	78.51	271.5 ± 0.2	87.28	79.44	280.2 ± 0.1
5	89.19	81.53	295.3 ± 0.1	90.3	82.41	303.6 ± 0.2	91.53	83.38	312.8 ± 0.2

Figures from Table 6 and Table 7 showed that for the 21-day period (138 – 159 DAFB) fruits of each group had gained: 17.1 g or 0.81 g/day the first group; 18.6 g or 0.89 g/day the second group; 19.7 g or 0.94 g/day the third group; 18.4 g or 0.88 g/day the fourth group and 19.7 g or 0.94 g/day the fifth group.

CONCLUSIONS

The results of this two-year study indicated that in comparison among three models used to describe the Granny Smith fruits' diameter growth, the quadratic regression equation was the best fit, expressing most accurately the relationship between each equatorial and longitudinal diameter group at 40 DAFB and the accumulated GDD to harvest (159 DAFB). A high correlation between the diameter of apples and the accumulated GDD was found, with an adjusted coefficient of determination (R^2) ranging from 0.99 to 1.0 and with residuals of standard deviation (R*SD*) from 0.40 to 0.55. Multiple regression equations with equatorial and longitudinal diameters as independent variables provided high prediction accuracy in respect fruit mass, with a very high R^2 (0.977 to 0.999) and a low R*SD* (0.370 to 0.558). The fruit diameters at 40 DAFB were very decisive in final fruit size and mass.

The results of this two year study suggest that predictive tables of apple size and mass are possible to be constructed. These can assist growers to make their decisions in respect to agricultural services, fruit thinning and harvest dates, and generate more incomes. However, the predictive tables of this study should be taken as a general guide because they refer to a particular orchard and technical management. Tables for other orchards can be compiled taking into account the specific conditions regarding accumulated GDD, soil fertility, climate, agro-technical measures, fruit load, cultivar and any other specific conditions related to the orchard.

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