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PREDICTING THE DIAMETERS AND THE MASS OF RED CHIEF 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 Red Chief 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 (152 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, because small fruits did not catch up later to become large fruits. Among three regression models 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 (0.98 to 1.0) and the lowest residual standard deviation (0.045 to 0.32). Equatorial and longitudinal diameters used in multiple regressions provided high accuracy predictions of fruit mass.

KEYWORDS: Apple**,** Red Chief**,** Prediction, Diameter, Mass, Growing Degree Days

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. Red Chief is an important apple cultivar, which accounts for more than 40% of trees planted in new orchards. It is highly preferred by Albanian customers and has a higher price than other cultivars.

However, foreign markets, as well as local ones, are in demand of apples which comply with international standards. Apple fruits’ equatorial diameter and mass at harvest are two important standard requirements, which in addition to being biological characteristics of any cultivar, depend also on a number of agro-technical and climate factors. Apple growers intending to enter profitable domestic and international markets should know well in advance the final size and mass of their produce. That is considered a useful management tool for them in taking early-season decisions regarding the general growing agro-techniques employed in orchards and the appropriate fruit thinning process in particular. 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.

Since decades ago, horticulture scientists have tried to determine if growth models in size and mass can be mathematically expressed and predicted. It was found 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; Faust, 1989). However, 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 at 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, the use of DAFB isn't highly accurate when climatic factors and growing season temperatures in particular have significant deviations from the average.[8]Instead, the use of GDD is more appropriate (Berg and Lötze, 2006). On the other hand, to predict fruit mass, both equatorial and longitudinal diameters can serve as independent variables in multi-linear regression equations (Ortega – Farias et al., 1997; 1998). Although the production of apple fruits comprises an important portion of Albanian agricultural output and with an obvious trend of increasing in the long run, information on these matters is very limited.

Taking into consideration that importance, a study of Red Chief apples in the area of Korca was carried out, during two consecutive growing seasons, 2012 and 2013. The manifold aim of this study was:

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

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

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

MATERIALS AND METHODS

The study was performed with 12-year old Red Chief apple trees grafted on MM106 rootstock, at a density of 1250 trees/ha, in an orchard in Drenova Commune, Korca District, Albania, with coordinates: latitude 40^o 35' 33" N, longitude 20^o 45' 53" E, and altitude 860 m above sea level. Trees were trained to a slender spindle form, hand thinned within 40 – 50 DAFB to have a density of 9 – 9.2 fruits/cm^2 of trunk cross-sectional area, drip-irrigated and fertigated based on water and nutrition requirements, while plant protection in accordance with the Integrated Pest Management principles and no soil tillage practiced against weeds, with herbicide used instead.

To make the measurements of fruit diameters, five apple trees were randomly selected in early May 2012, having a very similar vigour to each other. The same trees were used for measurements of 2013 fruits as well. At 40 DAFB, in each tree, at a 1-2 m height from soil, 40 fruits were randomly selected and tagged, 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 17 times (once a week), starting from 40 DAFB until harvest (152 DAFB). 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 = (Tmin + Tmax)/2 – 10

where:

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

Tmax = 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 (RSD) was considered the best fit.

1. 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 1350^{O}C, in increasing 50^{O}C intervals. The value of GDD at 40 DAFB was considered 0^{O}C.
2. 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;

De and Dl = equatorial and longitudinal diameters, respectively

b_1 and b_2 = coefficients that show change of fruit mass when values of De and Dl are increased by one unit (1 mm)

RESULTS AND DISCUSSIONS

The first fruit measurements made at 40 DAFB showed that there was a significant 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. The 200 fruits measured at 40 DAFB in 2012 had equatorial diameters that lied in two group sizes 27 – 29 mm and 29 – 31 mm, while those of 2013 lied in three groups: 29 – 31 mm; 31 – 33 mm and 33 – 35 mm, as shown in Table 1.

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

Year	De 27–29 mm		De 29 -31 mm		De 31-33 mm		De 33-35 mm	
	No. of fruits	Avg. De	No. of fruits	Avg. De	No. of fruits	Avg. De	No. of fruits	Avg. De
2012	127	28.23	73	29.73	-	-	-	-
2013	-	-	15	30.84	137	32.06	48	33.67

Similar 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	Dl 28 – 31 mm		Dl 30 – 33 mm		Dl 32 – 35 mm		Dl 34 – 36 mm	
	No. of fruits	Avg. Dl	No. of fruits	Avg. Dl	No. of fruits	Avg. Dl	No. of fruits	Avg. Dl
2012	127	29.73	73	31.24	-	-	-	-
2013	-	-	15	32.23	137	33.62	48	35.14

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. In year 2012 during that period were accumulated 158.15 GDD, while in 2103 were 264.7 GDD, or 106.55^0C plus. The role of early season temperatures in apple growth and maturity was earlier documented (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.

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 ($R^2 = 0.98$ to 1.0) and the lowest residuals of standard deviation (RSD = 0.045 to 0.32), 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 17 measurements, the difference was always less than 1 mm, which shows that the equations were highly accurate.

The quadratic regression equations for each group of diameters are shown in Table 3.

Table 3: Regression equation of equatorial diameters (De) and longitudinal (Dl) diameters

Fruit group	De in mm (40 DAFB)	De regression equations	Dlin mm (40 DAFB)	Dl regression equations
1	28.23 (27 – 29)	De = 28.70 + 0.06026*GDD - 0.000018*GDD^2	29.73 (28 – 31)	Dl = 30.04 +0.05442*GDD – 0.000019*GDD^2
2	29.73 (29 – 31)	De = 30.10 + 0.06350*GDD - 0.000019*GDD^2	31.24 (30 – 33)	Dl = 31.58 +0.05697*GDD – 0.000020*GDD^2
3	30.84 (29 – 31)	De = 30.59 + 0.06646*GDD - 0.000020*GDD^2	32.23 (32 – 36)	Dl = 32.54 +0.06161*GDD – 0.000022*GDD^2
4	32.06 (31 – 33)	De = 32.02 + 0.06920*GDD - 0.000020*GDD^2	33.62 (33 – 37)	Dl = 34.23 +0.06572*GDD – 0.000023*GDD^2
5	33.67 (33 – 35)	De = 33.47 + 0.07322*GDD - 0.000022*GDD^2	35.14 (35 – 38)	Dl = 35.78 +0.06867*GDD – 0.000024*GDD^2

Table 4. Predictive table for equatorial and longitudinal diameters growth (years 2012 & 2013)

GDD (^{0}C)	Fruit groups growth in respect to GDD									
	Group 1		Group 2		Group 3		Group 4		Group 5	
	De	Dl	De	Dl	De	Dl	De	Dl	De	Dl
0.0	28.23	29.73	29.73	31.24	30.84	32.23	32.06	33.62	33.67	35.14
100.0	34.55	35.29	36.26	37.08	37.04	38.85	38.74	40.57	40.57	42.41
150.0	37.33	37.78	39.20	39.68	40.11	41.57	41.95	43.57	43.96	45.54
200.0	40.03	40.16	42.04	42.17	43.08	44.19	45.06	46.45	47.23	48.55
250.0	42.64	42.46	44.79	44.57	45.95	46.70	48.07	49.22	50.40	51.45
300.0	45.16	44.66	47.44	46.87	48.73	49.11	50.98	51.88	53.46	54.22
350.0	47.59	46.76	50.00	49.07	51.40	51.41	53.79	54.41	56.40	56.87
400.0	49.92	48.77	52.46	51.17	53.97	53.61	56.50	56.84	59.24	59.41
450.0	52.17	50.68	54.83	53.17	56.45	55.71	59.11	59.15	61.96	61.82
500.0	54.33	52.50	57.10	55.07	58.82	57.69	61.62	61.34	64.58	64.12
550.0	56.40	54.22	59.28	56.86	61.09	59.58	64.03	63.42	67.09	66.29
600.0	58.38	55.85	61.36	58.56	63.27	61.36	66.34	65.38	69.48	68.34
650.0	60.26	57.39	63.35	60.16	65.34	63.03	68.55	67.23	71.77	70.28
700.0	62.06	58.82	65.24	61.66	67.31	64.60	70.66	68.96	73.94	72.09
750.0	63.77	60.17	67.04	63.06	69.19	66.07	72.67	70.58	76.01	73.78

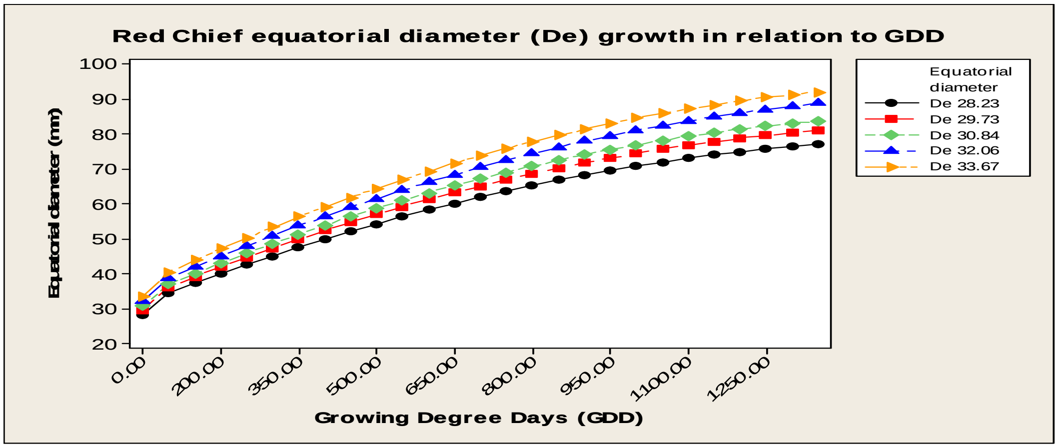
800.0	65.39	61.42	68.74	64.36	70.96	67.43	74.58	72.09	77.97	75.36
850.0	66.92	62.57	70.35	65.55	72.63	68.69	76.39	73.47	79.81	76.81
900.0	68.35	63.63	71.86	66.65	74.20	69.84	78.10	74.75	81.55	78.14
950.0	69.70	64.59	73.28	67.65	75.68	70.88	79.71	75.91	83.17	79.36
1000.0	70.96	65.46	74.60	68.55	77.05	71.82	81.22	76.95	84.69	80.45
1050.0	72.13	66.23	75.83	69.35	78.32	72.66	82.63	77.88	86.10	81.42
1100.0	73.21	66.91	76.96	70.05	79.50	73.39	83.94	78.69	87.39	82.28
1150.0	74.19	67.50	78.00	70.65	80.57	74.02	85.15	79.39	88.58	83.01
1200.0	75.09	67.98	78.94	71.14	81.54	74.54	86.26	79.97	89.65	83.62
1250.0	75.90	68.38	79.79	71.54	82.42	74.96	87.27	80.44	90.62	84.12
1300.0	76.62	68.68	80.54	71.84	83.19	75.27	88.18	80.80	91.47	84.49
1350.0	77.25	68.88	81.20	72.04	83.86	75.48	88.99	81.03	92.22	84.74

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

Using the contents of Table 3 (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 4 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 1350.0 GDD, which was scored at 155 DAFB in 2012 and at 165 DAFB in 2013.

In a 5-year survey (2009 -2013) the average accumulated GDD from 40 DAFB to 152 DAFB were 1275. In the warmest growing season(2012), 1334 GDD were accumulated during that period, while in 2013, a value of 1267, 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). However, despite the climatic situation, diameters at 40 DAFB are the ones that have a very significant impact on final fruit size and mass.

Figures from Table 4 show that fruits of smaller diameter groups grew less than the bigger ones. The gap between each average equatorial diameter group widens from 1.11 – 1.61 mm at 0.0 GDD (40 DAFB) to 2.66 – 5.13 mm at 1350.0 GDD. Graph 1 depicted the abovementioned widening of the gap. Similarly, the gap between each average longitudinal diameter group widened from 0.99 – 1.52mm to 3.16 – 5.55 mm in the same timeframe.



Graph 1. Widening gap of equatorial diameter from 40 DAFB to harvest (152 DAFB)

In practice, this means that larger fruits have higher growth rates than smaller fruits, in agreement with the conclusion reached by Lakso and Goffinet, (2013) who 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 152 DAFB all tagged fruits were harvested and measured for the last time, recording their size and mass. From the initial total of 200 fruits at 40 DAFB, at harvest there were 189 of them remaining in 2012 and 186 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 0.5 g/fruit. In all five equations, the adjusted coefficient of determination (R^2) had large values, ranging from 0.971 to 0.999, while the residual standard deviations (RSD) from 0.334 – 0.387 (Table 5). These equations can be used to predict the final mass for any fruit within each group. The average fruit mass at 152 DAFB show a very significant difference between groups, as fruits of fifth group had a mass 1.51times higher than those of first one(301.0 / 199.4 g).

Table 5. Fruit mass with respect to each diameter group at 152 DAFB

Fruit group	Avg. De & Dl (mm) at 152 DAFB		Mass (M) regression equation for average diameter groups at 152 DAFB	R^2	RSD	Avg. fruit mass (g) at 152 DAFB
	De	Dl				
1	76.86	69.26	M = - 318 + 4.26*De + 2.74*Dl	0.998	0.387	199.4 ±0.1
2	80.64	72.95	M = - 320 + 4.29*De + 2.00*Dl	0.999	0.358	225.6 ±0.1
3	82.58	75.91	M = - 302 + 3.73*De + 3.04*Dl	0.971	0.334	241.8±0.2
4	87.26	80.28	M = - 300 + 3.10*De + 3.63*Dl	0.998	0.371	273.7±0.1
5	91.35	83.89	M = - 302 + 3.13*De + 3.62*Dl	0.998	0.363	301.0 ±0.3

Based on weekly fruit diameters recorded during 17 measurements in both years and each fruit group mass at harvest, a predicative table of fruit mass at 131, 138 and 145 DAFB for each group was calculated using the multiple regression equations (Table 6). Figures from Table 5 and 6 shown that for the period 131 – 152 DAFB fruits of each group had gained:16.5 g or 0.79 g/day the first group; 13.5 g or 0.64 g/day the second group;16.3 g or 0.78 g/day the third group;18.6 g or 0.89 g/day the fourth group and 20.4 g or 0.97 g/day the fifth group. Fruit mass in each four prediction dates (131, 138,145 and 152 DAFB) can assist growers in deciding the harvest days for their produce. That is important to find a better balance for their profits in regard to fruit maturity and mass on one side and market demand and prices to the other.

Table 6. Fruit mass prediction for each diameter group at 131, 138 and 145 DAFB

Fruit group	Avg. De & Dl (mm) and Mass (g) at 131 DAFB			Avg. De & Dl (mm) and Mass (g) at 138 DAFB			Avg. De & Dl (mm) and Mass (g) at 145 DAFB		
	De	Dl	Mass	De	Dl	Mass	De	Dl	Mass
1	67.18	61.77	182.9 ±0.3	75.44	68.50	190.9 ±0.2	75.82	68.85	193.5 ±0.2
2	78.36	71.45	211.5 ± 0.1	79.07	71.98	216.0 ±0.2	79.97	72.35	220.7 ±0.2
3	79.86	74.11	225.5 ± 0.1	81.05	75.16	233.4 ±0.1	82.32	75.34	239.1 ±0.2
4	84.04	78.38	255.1 ±0.3	85.21	79.49	263.1 ± 0.3	86.41	79.68	268.5 ±0.3
5	87.76	81.90	280.6 ± 0.3	89.69	83.06	219.8 ± 0.3	90.32	83.26	295.0 ± 0.2

CONCLUSION

The results of this two-year study indicated that between three models used to describe the Red Chief 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. A high correlation between the diameter of apples and the accumulated GDD was found, with an adjusted coefficient of determination (R^2) ranging from 0.98 to 1.0 and with residuals of standard deviation (RSD) from 0.045 to 0.32. 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 (0.971 to 0.999) and a low RSD (0.234 to 0.387). The fruit diameters at 40 DAFB were very decisive in final fruit size and mass, because small fruits can never catch up later to become large fruits.

The results of this two year study suggest that it is possible to construct prediction tables of apple size and mass, which can assist growers to make their decisions in respect to agricultural services, fruit thinning and harvest dates an generate more incomes. However, these tables should be taken as a general guide and must be adjusted to the specific conditions of accumulated GDD, soil, climate, agro-technical measures, fruit load, cultivar and any other specific conditions related to the orchard.

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