Estimating Apple Diameter from Fruit Mass Measurements to Time Thinning Sprays

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ADDITIONAL INDEX WORDS. *Malus × domestica*, fruit size

SUMMARY. The relationship between fruit mass and fruit diameter for apple fruit 2 to 26 mm (0.08 to 1.04 inches) in diameter was evaluated for two cultivars sampled from several orchards for three years. A single regression model was appropriate for all combinations of year, cultivar, and orchard. The model was used to develop a chart to quickly estimate fruit diameter from fruit mass. These fruit diameter estimates can be used by commercial fruit growers to time chemical thinner sprays.

Chemical thinners are applied to apple trees to reduce the crop load and improve return bloom, pest control, and fruit quality. In many areas thinners are applied 2 to 3 weeks after full bloom (Greene and Autio, 1989), but in other areas fruit size is used to time thinning sprays (Byers et al., 1995; Pfeiffer, 1997). Luckwill (1953a, 1953b) suggested that susceptibility to thinning chemicals might vary with developmental changes in the fruit. Response to chemical thinners apparently is not always influenced by fruit size or days after bloom. Batjer et al. (1968) reported that thinning results did not vary when naphthalene-acetic acid (NAA) or carbaryl (Sevin 50 W) was applied at 8 to 21 d after bloom when fruit diameters averaged 5 to 16 mm (0.2 to 0.65 inches). Their mean separations indicated that the degree of

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Table 1. Strains of apples sampled from Virginia orchards 1991 and 1992.

Region	Orchard	Cultivar and strain	
		Delicious	Golden Delicious
Central Piedmont	Mt. Cove	Redchief	Smoothee
Roanoke Valley	Sprinkle	Redchief	Smoothee
Southern Piedmont	Ayers	Redchief	Smoothee
New River Valley	Virginia Tech	Redchief	Smoothee
		Red Prince	
		Starks Spur Supreme	
		Top Red	

thinning did not consistently differ for different treatment dates. However, there were trends in the means that may have been significant had data been analyzed by regression because there would have been more degrees of freedom in the error term. Donoho (1968) and Tukey (1965) found that the efficacy of thinners was related to fruit size. Marini (1996, 1997) found that sevin, oxamyl, and NAA thinned moderately at petal fall (mean fruit diameter = 4.5 mm), but were most effective at 10 to 14 mm, and were not effective at >18 mm; ethephon was most effective at >16 mm. Leuty (1973) found that optimum fruit size for thinning with NAA varied with cultivar. 'Delicious' was most sensitive at 6 to 8 mm, 'McIntosh' was most sensitive at 8 to 10 mm and 'Northern Spy' at 9 to 10 mm. However, benzyladenine thinned 'Empire' trees similarly when applied from 6 to 29 d after bloom (Elfving and Cline, 1993).

Many commercial apple growers in the mid-Atlantic region use fruit diameter to time thinning sprays. Because measuring individual fruit with calipers is expensive, a faster method to measure fruit size is needed. This study was undertaken to determine if fruit mass could be used to estimate the diameters of fruit from different orchards and cultivars for timing thinning sprays.

Materials and methods

Data for this study were collected in 1991 and 1992 for 'Smoothee Golden Delicious' and four strains of 'Delicious', and fruit were sampled from several orchards located in central and southern Virginia (Table 1). Each year trees of 'Smoothee' and 'Campbell Redchief Delicious', growing in two orchards (Ayers and Virginia Tech), were sampled three or four times to provide fruit diameters ranging from ≈ 4 (petal fall) to 26 mm (0.16 to 1.04 inches), and in 1992 fruit were sampled once from two additional commercial or-

chards. Four other strains of 'Delicious' were sampled once from the Virginia Tech orchard. These single sampling dates provided samples with fruit diameters ranging from about 6 to 16 mm. On each date two fruiting spurs, having one or more fruit, were harvested from each of 15 trees. Spurs were defoliated, sealed in zip-lock plastic bags, and transported on ice in coolers to the laboratory. The maximum diameter of each fruit was measured with calipers and each fruit, with pedicel attached, was weighed. About 50 fruit per sample, varying from the largest to the smallest fruit that appeared as if they would not abscise, were measured.

MODEL BUILDING. The relationship between fruit diameter (FD) and fruit mass (FM) for 'Redchief Delicious' was evaluated by fitting various polynomial regression models with the REG Procedure of SAS (Freund and Littell, 1991). Fruit diameter was the dependent variable and the independent variables were FM, $FM^{-1/2}$, $FM^{-1/3}$, and $FM^{-1/4}$. All 14 possible combinations of these four variables were evaluated with the Rsquare option of the REG Procedure. Criteria used to select the best model included the coefficient of determination (R^2), adjusted R^2 , Mallow's conceptual predictive criteria (Cp), mean square error (MSE) and the prediction sum of squares (PRESS). Residuals were analyzed to check for the presence of outliers, nonconstant error variance and omission of important predictor variables. The best model was $FD = FM - FM^{-1/3}$. Analysis of covariance was then performed with the GLM Procedure of SAS (Littell et al., 1991) to test equality of models for different orchards, strains, and years. One of the categorical variables (orchard, strain, or year) was included as the indicator or dummy variable and FM, the continuous variable, was included as the covariate. Type III sums of squares were used to evaluate the significance of the indicator variable and interaction terms in-

volving the indicator variable (for example, location $\times$ FM and location $\times$ $FM^{-1/3}$). Because the indicator variables (orchard, strain, and year) and the two interaction terms containing indicator variables were not significant ($p > 0.05$) for each indicator variable, all 'Delicious' data were pooled to develop a single model to estimate FD from FM. The same approach resulted in a single model for 'Smoothee'. Analysis of covariance also indicated that models for 'Delicious' and 'Smoothee' did not differ significantly ($p > 0.05$). Therefore, data from all locations and strains for 1991 and 1992 were pooled (referred to as the estimation data set) to develop a single model that will be referred to as the estimation model.

MODEL VALIDATION. To validate the estimation model, 120 'Smoothee' and 60 'Campbell Redchief Delicious' fruit were collected from the Virginia Tech orchard in 1997 to develop a new data set (validation data set). Two techniques were then used to validate the fitting model. 1) The validation data set was used to produce a validation model by reestimating the model parameters using the all-possible regressions approach used to develop the estimation model and the two models were compared for consistency. 2) The regression parameter estimates from the estimation model were then used to predict outcomes for observations in the validation data set (Montgomery and Peck, 1992). Because both techniques indicated that predictive performance of the estimation model appeared reasonably good, the final estimation of parameters was accomplished by pooling data from all three years (referred to as the entire data set) to develop the entire model (Myers, 1990).

Results and discussion

Regression models for several combinations of year, location, and strain are presented in Table 2 to provide

Table 2. Regression models relating fruit diameter (FD) to fruit mass (FM) for several strains of 'Delicious' apple sampled from several apple orchards during 2 years.

Year	Strain ^y	Orchard ^x	Coefficient (SE of estimate)			Model ^z	
			Intercept	FM	FM ^{-1/3}	N	R ²
1991	RC	A	18.76 (1.31)	1.23 (0.32)	-8.88 (0.96)	140	0.92
		M	7.07 (3.34)	5.69 (2.40)	-2.00 (1.73)	50	0.84
		S	36.25 (3.64)	0.32 (0.14)	-31.61 (4.98)	50	0.95
		V	9.99 (2.61)	3.65 (0.99)	-3.26 (1.69)	28	0.93
1992	RC	A	14.35 (0.21)	1.94 (0.05)	-5.99 (0.13)	300	0.99
		M	7.94 (3.42)	5.61 (3.11)	-2.90 (1.64)	36	0.80
		V	17.72 (0.48)	1.46 (0.06)	-8.59 (0.42)	177	0.98
	RP	V	17.58 (1.52)	1.48 (0.33)	-8.35 (1.16)	50	0.96
	SS	V	15.43 (1.01)	1.71 (0.23)	-6.82 (0.75)	50	0.97
	TR	V	20.32 (1.96)	0.84 (0.44)	-10.67 (1.51)	50	0.94

^zAll models are significant ($P < 0.0001$).

^yRC = Redchief; RP = Red Prince; SS = Starks Spur Supreme; TR = Top Red.

^xM = Mt. Cove, S = Sprinkle, A = Ayers, V = Virginia Tech.

readers with the opportunity to evaluate the similarity of the models. For eight of the 10 models, the $R^2 > 0.9$ and, except for 'Redchief Delicious' sampled from Sprinkle Orchard in 1991, parameter estimates and standard errors of the estimates were similar. No explanation can be offered as to why data from Sprinkle Orchard differ from data from other orchards.

Parameter estimates and statistics from SAS output are presented for the estimation, validation, and entire models (Table 3). The parameter estimates and R^2 values are similar for the estimation and validation models, providing some assurance about the applicability of the estimation model to data beyond those on which the model is based (Neter et al., 1996).

Analysis of residuals is an important technique for evaluating the fit of

regression models. The residual for a given observation is defined as the difference between the observed and fitted value. When plotted against the observed values of a response variable, the residuals for a good model are distributed randomly and normally in a horizontal band centered around zero (Neter et al., 1996). These residuals are measures of quality of how a model fits the data that were used to develop it, but they do not assess quality of future prediction. A model that fits the data well may not be good for predicting future observations. The least squares procedure is designed to produce properties in the regression function that will result in residuals that are smaller than true prediction errors and do not generally indicate how the regression model will predict (Myers, 1990). Because the model developed in this study will be

used to predict fruit diameter from fruit mass, it is critical to investigate the model's predictive performance. For validation, the estimation regression model was used to predict outcomes for an independent set of data; data that were not used to estimate the model parameters (validation data set) (Montgomery and Peck, 1992; Myers, 1990; Neter et al., 1996). If the model is a good predictor, the prediction errors (the difference between the observed and predicted values) should be similar in magnitude and distribution to the residuals for the data (estimation data) used to estimate the model parameters. This was the case for the validation data set (Fig. 1). Additionally, the predicted values for fruit diameter from the validation data set were similar to the observed values (Fig. 2).

A means of measuring the actual

Table 3. Statistics and parameters estimated from regression models developed from three data sets. The estimation model was developed using fruit of several strains of 'Delicious' and 'Golden Delicious' collected from several locations in 1991 and 1992. The validation model was developed from 'Delicious' and 'Smoother' fruit sampled in 1997. The complete model was developed by combining the estimation and validation data sets.

Statistic or parameter estimate ^z	Estimation model	Validation model	Entire model
Intercept estimate	16.791	19.1258	17.1964
Standard error of intercept	0.1086	0.5548	0.1051
Regression coefficient for FM	1.457	1.1171	1.3572
Standard error for FM	0.0194	0.0522	0.0166
Regression coefficient for FM ^{-1/3}	-7.579	-9.3643	-7.8247
Standard error for FM ^{-1/3}	0.0754	0.4886	0.0751
Error sums of squares	653.645	169.9560	860.1743
Prediction sum of squares	659.008	---	865.300
Mean square error	0.4639	0.9602	0.5413
Mean of the squared prediction errors	---	1.2724	---
Coefficient of determination	0.9796	0.9677	0.9788
Total degrees of freedom	1411	179	1590

^zFM = fruit mass (g).

Fig. 1. Comparison of regression residuals and predicted errors from validation of the estimation model. (A) Data are from the estimation data set. The regression residual was defined as the actual value minus the fitted value. (B) Data are from the validation data set. Outcomes were predicted using parameter estimates obtained from the estimation data set. Prediction error was defined as the actual value minus the predicted outcome.

Fig. 2. Performance of the model parameter estimates obtained from the estimation data set to predict fruit diameter from the validation data set.

predictive capability of the estimation regression model is to use this model to predict each case in the validation data set and then to calculate the mean of the squared prediction errors (MSPR). If the MSPR is fairly close to the MSE based on the regression fit to the estimation data set, then the MSE for the selected regression model is not seriously biased and gives an appropriate

indication of the predictive ability of the model. In this case, the MSPR from the validation data set (1.27) does not differ too greatly from the MSE of the estimation data set (0.46). This implies that the MSE based on the estimation data set is a reasonably valid indicator of the predictive ability of the estimation regression model (Neter et al., 1996).

The PRESS criterion is a measure of how well the use of the fitted values for a subset model can predict the observed values of the response

variable Y_i . The error sum of squares (SSE) is also such a measure. The PRESS measure differs from SSE in that each fitted value for the PRESS criterion is obtained by deleting the i^{th} case from the data set. The regression function is estimated for the subset model from the remaining $n-1$ cases, and then the fitted regression function is used to obtain the predicted value of Y for the i^{th} case. PRESS was calculated for the models developed from the estimation data and

the entire data set by summing the squared prediction errors (the difference between the observed and predicted fruit diameter when one observation is deleted). Some evidence of the internal validity of the fitted model is to compare PRESS and SSE. The PRESS value is always larger than SSE because the regression fit for the i^{th}

case when this case is deleted in fitting can never be as good as that when the i^{th} case is included. A PRESS value reasonably close to SSE, as here (for the estimation model PRESS = 659.0, SSE = 653.6; for the entire model PRESS = 865.3, SSE = 860.2), supports the validity of the fitted regression models and of the MSEs as an indicator of the predictive capability of these models (Neter et al., 1996).

The PRESS residuals can be used to generate another R^2 -like statistic that reflects prediction capabilities (Myers, 1990). For the model developed from the entire data set, this statistic is calcu-

lated as $R^2_{\text{pred}} = 1 - (\text{PRESS} / \text{total sums of squares}) = 1 - (865.3 / 40657.8) = 0.9787$. Thus we might expect the model developed from the entire data set to explain $\approx 97.9\%$ of the variability explained by the least squares fit to the estimation data set. The loss in R^2 (0.9788 vs. 0.9787) is very small, so there is reasonably strong evidence that the least squares model will be a satisfactory predictor.

Results from model validation indicate that the model developed from the entire data set is a good predictive model to predict fruit diameter from fruit mass for 'Golden Delicious' and 'Delicious' strains grown in commercial orchards in Virginia. The predicted line from the regression model developed from the entire data set (Fig. 3) was used to develop a chart to be used by fruit growers to estimate FD from a sample of 100 fruit (Table 4). Most commercial growers do not have equipment to accurately weigh individual fruit, but most should be able to accurately weigh a sample of 50 to 100 fruit. Fruit mass values in Table 4 are reported in grams, ounces, and pounds because this table is intended to be used by growers, many of whom use English units.

Efficacy of thinning chemicals may be related to the distribution of fruit sizes on the tree (unpublished data) as well as the mean fruit size. Unfortu-

Fig. 3. Scatter plot and predicted line with the 95% prediction interval for a single observation showing the relationship between apple fruit mass (FM) and fruit diameter (FD). Data include 'Smoother Golden Delicious' and four strains of 'Delicious' sampled from four orchards during 1991, 1992, and 1997 (entire data set). Regression model: $FD = 17.2 + 1.36 FM - 7.82 FM^{-1/3}$; $n = 1593$, $R^2 = 0.979$, model $p < 0.0001$.

Table 4. Apple diameter estimated from apple mass.

Single fruit mass		100 Fruit mass			Mean fruit diam
(g)	(oz.)	(g)	(oz.)	(lb)	(mm)
0.15	0.005	15	0.530	0.033	2.67
0.2	0.007	20	0.706	0.044	4.09
0.25	0.009	25	0.883	0.055	5.12
0.3	0.011	30	1.059	0.066	5.92
0.4	0.014	40	1.412	0.088	7.12
0.5	0.018	50	1.765	0.110	8.02
0.7	0.025	70	2.471	0.154	9.33
0.9	0.032	90	3.177	0.199	10.31
1.1	0.039	110	3.883	0.243	11.11
1.3	0.046	130	4.589	0.287	11.79
1.6	0.056	160	5.648	0.353	12.68
2	0.071	200	7.060	0.441	13.70
2.4	0.085	240	8.472	0.530	14.61
2.8	0.099	280	9.884	0.618	15.44
3.3	0.116	330	11.649	0.728	16.42
3.9	0.138	390	13.767	0.860	17.52
4.5	0.159	450	15.885	0.993	18.56
5.2	0.184	520	18.356	1.147	19.74
5.9	0.208	590	20.827	1.302	20.87
6.8	0.240	680	24.004	1.500	22.29
7.7	0.272	770	27.181	1.699	23.68
8.7	0.307	870	30.711	1.919	25.20
9.7	0.318	900	31.770	1.986	25.65
10.7	0.378	1070	37.771	2.361	28.17

nately, weighing a sample of fruit and using Table 4 will provide no information concerning the distribution of fruit sizes.

Because fruit shape (length to diameter ratio) is influenced by temperature (Westwood, 1993) and the application of growth regulators (Bukovac and Nakagawa, 1968), this model may not be adequate for all situations in Virginia. However, because there is a fairly large window within which thinning treatments are effective (Donoho, 1968; Marini, 1996), the model may be robust enough to provide FD estimates with acceptable accuracy for commercial fruit growers. Fruit shape also varies with cultivar. Different models will likely need to be developed for nonconic cultivars. Observations that susceptibility to thinning chemicals varies with fruit development, along with the assumption that fruit size better estimates fruit development than days after bloom, led to the practice of using fruit size to time thinning sprays (Tukey, 1965). Cultural practices or growing conditions may influence fruit shape more than fruit development. Therefore, FM may actually be the better measure of fruit development. Unfortunately, many researchers report mean FD at the time of thinning application,

but few report FM. To develop a data base, and to test the validity of using FM to time thinning sprays, it would be beneficial if in the future researchers would report days after full bloom, as well as FD and FM at the time of thinner application.

Fruit size is only one component of thinning efficiency. Cultivar, choice of surfactant and environmental conditions for several days after treatment also can influence thinning. More research is needed to understand these other factors and the possible interactions of these factors with fruit size.

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