Relationships between Fruit Weight and Diameter at 60 Days after Bloom and at Harvest for Three Apple Cultivars

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Abstract. Early-season fruit diameter measurements for ‘Gala’, ‘Fuji’, and ‘Honeycrisp’ apples in three orchards for 3 years were used to develop regression models to estimate fruit weight at harvest. Fruit weight at harvest was linearly related to fruit diameter 60 days after bloom, but intercepts and slopes were not homogeneous for all nine combinations of orchards and years for any of the cultivars. When the entire data set for a cultivar was used to develop a single predictive model, the model was biased and underpredicted fruit weight for small fruit and overpredicted fruit weight for large fruit. Adding the ratio of (fruit weight/fruit diameter) at 60 days after bloom to the model with fruit diameter at 60 days after bloom produced a less-biased model with improved coefficients of determination, and predicted values were more similar to the observed values. The (fruit weight/fruit diameter) ratio was positively related to cumulative growing degree days for the 60 days before the fruit were measured and tended to be lower in years when fruits were exposed to frosts. These multiple regression models can be used to develop tables with predicted fruit weights at harvest for varying combinations of fruit diameter and (fruit weight/fruit diameter) ratio 60 days after bloom.

Fruit size is a major factor determining apple prices. While developing marketing programs, wholesale customers often ask apple growers and packers to estimate the volume of different size fruit they expect to have available during the marketing season. Accurate estimates of fruit size are increasingly important for preharvest negotiations with buyers. In addition, growers may be able to use such information to modify cultural practices, such as hand fruit thinning or irrigation to obtain the desired fruit size. Davis and Davis (1948) were perhaps the

first to demonstrate a relationship between early-season fruit diameter (FD) and FD at harvest for several cling peach cultivars over 8 years. Batjer et al. (1957) used data from several orchards in Washington over 4 years to show that apple FD at 35 d after bloom was related to FD at harvest. They also developed tables of predicted box sizes for ‘Delicious’ and ‘Winesap’ fruit from FDs measured at various times during the season. Williams et al. (1969) developed a similar table for ‘Bartlett’ pears in Oregon. Forshey (1971) used early-season FD measurements to predict FD of ‘McIntosh’ at harvest in New York’s Hudson Valley. In general, these papers showed that correlation coefficients increased as fruits were measured later in the season but FD at harvest could be adequately predicted from FD measurements at 60 d after bloom.

Since apples are marketed on the basis of weight (number of fruit per 19.05 kg unit), rather than diameter, there is a need for

models to estimate fruit weight (FW) or box count from early-season FD measurements. In previous studies, initial FD measurements were recorded at 30 to 60 d after full bloom (DAFB). Cell division is nearly completed by 60 DAFB, and fruit growth during the remainder of the season is due primarily to cell expansion and is assumed to be consistent from year to year (Bain and Robertson, 1951). Early-season temperature affects apple fruit growth rate because the rate and duration of cell division is a function of temperature (Austin et al., 1999; Bergh, 1990; Blanpied and O’Kennedy, 1967; Warrington et al., 1999). Fruit shape of some cultivars also is sometimes influenced by early-season temperatures (Greenhalgh and Godley, 1976; McKenzie, 1971; Tukey, 1960). Therefore, it is likely that the relationship between FD and FW may not be consistent for a given cultivar grown under different environmental conditions, which vary with season and location. The objectives of this study were to evaluate the relationships between 1) fruit diameter at 60 DAFB (FD60) and fruit diameter at commercial harvest (FDh); and 2) FD60 and FW at harvest (FWh). These relationships were evaluated for ‘Honeycrisp’, ‘Buckeye Gala’, and ‘Aztec Fuji’ produced in three Pennsylvania orchards over 3 years.

Materials and Methods

Trees used for this study included ‘Aztec Fuji’, ‘Honeycrisp’, and ‘Buckeye Gala’ on M.9 NAKBT337 rootstock. All trees were 6 to 10 years old and trained to a vertical axis system, and information describing each orchard is presented in Table 1. All trees carried moderate crop loads after chemical and hand thinning except for Rock Springs in 2017 where a series of frosts during and following bloom reduced the crop load to about 10% for ‘Fuji’ and 80% for the other cultivars. About 60 DAFB, in 2015, 2016, and 2017, 10 fruits from around each of 10 trees per cultivar per orchard per year were tagged and FD (FD60) was measured with an electronic fruit size measurer (QA Supplies LLC, Norfolk, VA). Fruit at about 1.25 to 2.0 m aboveground were selected to represent a range of fruit sizes. On the same day, 50 fruits per cultivar per orchard were harvested and FD60 and FW (FW60) were recorded for each fruit to develop an early-season relationship between FD60 and FW60. At the time of commercial harvest in 2015, while still on the tree, the diameters of all tagged fruit were recorded. A sample of 50 fruit, representing a range of fruit sizes, was harvested to measure FDh and FW to determine the relationship between FDh and FW. In 2016 and 2017, all tagged ‘Fuji’ fruit were harvested and transported to the laboratory to measure FDh and FW. For ‘Gala’ and ‘Honeycrisp’, the tagged fruit were harvested for such measurements in only 2017. These data were used to evaluate relationships between FDh and FW, as well as FD60 vs. FDh and FD60 vs. FW.

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SAS's Proc GLIMMIX was used to perform analyses of variance by cultivar to test the effect of orchard and year on FD60. Since the interaction of orchard $\times$ year was significant, lsmeans within years were compared with the SLICEDIFF option. To evaluate relationships, SAS's PROC MIXED (Little et al., 2006) was used to perform analysis of covariance (Milliken and Johnson, 2002), where FDh or FWh were response variables, orchard and year were included in the model as indicator variables, and linear and quadratic terms for FD60 were included as regressor variables, along with all possible interactions. The interaction term with the largest nonsignificant P value was deleted and the model was rerun. This manual backward elimination process continued until only significant ($P < 0.05$) variables remained in the model. Scatter plots and plots of residuals and studentized residuals were used to determine whether a quadratic term for the regressor variable might improve the model. When interactions were significant, estimate statements were requested with PROC MIXED to make all pairwise comparisons of the nine slopes (3 orchards $\times$ 3 years). Since there were 36 pairwise comparisons, a comparison-wise error rate of 0.05 would have an experiment-wise error rate of 0.842 [$1 - (0.95)^{36}$] (Kemp, 1975), so a P value of 0.001 (experiment-wise error = 0.035) was used to compare slopes. PROC REG (Freund and Littell, 2000) was used to obtain coefficients of determination for models for combinations of orchard and year. Data sets with common slopes were pooled to develop common slopes models.

Results

General. The 50-fruit-samples collected at 60 DAFB and at harvest for the three orchards and years were combined for each cultivar to provide a wide range of fruit sizes and the relationship between FD and FW was curvilinear for all three cultivars (Fig. 1). Sometimes the interaction of orchard $\times$ FD or year $\times$ FD was significant, probably because the sample sizes were quite large ($n \approx 900$). Since the coefficients for the nine combinations of orchard and year were similar, a single model was fit for each cultivar. The coefficients of determination were all > 0.89 , so a single model developed with the pooled data set is probably adequate to estimate FW from FD measurements made at any time of the season from 60 DAFB until harvest.

'Gala'. Average FD60 tended to be lower in 2017 than for the previous 2 years, but the effect of orchard was not consistent for all 3 years (Table 2). Linear regression models for the nine combinations of year and orchard indicated a good relationship between FDh and FD60 for each of the nine combinations (Fig. 2), with R^2 values ranging from 0.70 to 0.99, except for the Fruit Research and Extension Center (FREC) in 2016 ($R^2 = 0.22$). Analysis of covariance using the entire data set showed that the three-way interaction of year $\times$ orchard $\times$ FD60 was significant, so

Table 1. Location and row orientation for three Pennsylvania orchards used for the 3-year study to predict apple fruit weight at harvest from fruit diameter measured 60 d after bloom.

Site characteristic	Orchard name, location, county		
	Bedford	Fruit Research and Extension Center (FREC)	Russell E. Larson Agricultural Research Center (Rock Springs)
	Fishtown, Bedford	Biglerville, Adams	Rock Springs, Center
Elevation (m)	540	160	400
Longitude	78°31' 37"	77°15' 25"	77°57' 12"
Latitude	40°7' 40"	39°56' 22"	40°42' 34"
Row orientation	NW – SE	NE – SW	NW – SE
In-row tree spacing (m)	0.91	0.91	1.5
Between-row spacing (m)	3.7	3.7	2.75
Irrigation	None	Trickle	Overhead in 2016

the nine slopes were compared with estimate statements. The slope for FREC in 2016 was 0.62 and was significantly different from all other slopes except for Bedford in 2017 (slope = 0.99, Fig. 2). The highest slope values were for the 3 years at Rock Springs (1.30, 1.28, and 1.16, respectively, in 2015, 2016, and 2017). Except for FREC in 2016 and the 3 years at Rock Springs, the other five slopes ranged from 0.97 to 1.1. A reduced data set was used to develop an equal slopes model with data from the five combinations of years and orchards with similar slopes and the predictive model was still fairly poor: $FDh = 53.95 + (0.352 \times FD60)$, $R^2 = 0.249$. Surprisingly, the model developed with the entire data set with all nine combinations of year and orchards fit the data better than when the reduced data set was used and the estimates for intercept and slope were similar [$FDh = 52.96 + (0.375 \times FD60)$, $R^2 = 0.338$]. Only in 2017 were tagged 'Gala' fruit harvested to record FWh. The relationship between FWh and FD60 varied slightly for the three orchards (Fig. 3), but a common slopes model for 2017 fit the data quite well ($R^2 = 0.79$).

While measuring fruit in 2017, we felt that fruit shape varied with orchard, possibly due to frost during or soon after bloom. In the absence of fruit length data, an index of fruit shape was obtained by dividing FW60 by FD60 for each fruit in the 50-fruit sample from each orchard. The average ratio ranged from 0.80 at Rock Springs in 2017, a year with severe frost when fruit were about 10 mm in diameter, to 1.49 at Rock Springs in 2015 (Table 2). A multiple linear regression model was used to estimate FDh using linear terms for FD60 and FW60/FD60, and both terms were significant ($R^2 = 0.63$). Estimated FDh, using the simple linear model with data from all nine combinations of year and orchard, were plotted against the values for the observed FDh (Fig. 4). If predicted values were equal to observed values, the symbols would fall on the 45° line of unity. However, the model overestimated FDh for observed values less than 68 mm, and it underestimated FDh for observed values greater than 75 mm. To account for differences in fruit shape, values estimated with the multiple linear regression model were plotted against the observed values, and predicted

Fig. 1. The relationship between fruit weight and fruit diameter for three apple cultivars sampled from three Pennsylvania orchards in 3 years: (A) 'Gala', (B) 'Fuji', and (C) 'Honeycrisp.' Fruit were sampled at 60 d after bloom and at harvest to obtain a wide range of fruit sizes. Symbols represent a single fruit; the solid line is the predicted value from polynomial regression. Broken lines are the upper and lower 99% confidence limits for individual predicted values.

values were more similar to observed values (Fig. 4).

'Fuji'. Simple linear regression by year and site indicated that for all combinations of year and orchard, FW60 was highly

Table 2. Average apple fruit diameter and ratio of fruit weight/fruit diameter for fruit sampled from three orchards in three seasons at 60 d after full bloom. The year $\times$ orchard interaction was always significant at the 5% level. Cumulative growing degree days, 10 °C base temperature for the 60 d (CGDD60) before early-season fruit diameter was measured were obtained from nearby weather stations.

Yr	Orchard	Fruit diam (mm)	FW60/FD60 (g/mm)	N	CGDD60
<i>Buckeye Gala</i>					
2015	Bedford	52.05 b ^z	1.290 b	40	1052
	FREC	47.32 a	1.035 a	47	955
	Rock Springs	58.62 c	1.486 c	29	1134
2016	Bedford	52.26 b	1.260 b	50	1018
	FREC	45.53 a	0.992 a	47	918
	Rock Springs	54.39 c	1.262 b	49	1184
2017	Bedford	41.69 a	0.868 ab	39	772
	FREC	43.69 b	0.930 b	43	863
	Rock Springs	40.68 a	0.800 a	40	742
<i>Honeycrisp</i>					
2015	Bedford	56.02 a	1.312 a	40	
	FREC	57.84 b	1.401 ab	43	
	Rock Springs	61.26 c	1.478 b	34	
2016	Bedford	60.76 b	1.490 b	50	
	FREC	49.86 a	1.059 a	50	
	Rock Springs	64.62 c	1.693 b	50	
2017	Bedford	40.06 a	0.780 a	50	
	FREC	44.30 b	0.916 b	50	
	Rock Springs	44.56 b	0.843 ab	52	
<i>Aztec Fuji</i>					
2015	Bedford	51.20 b	1.224 a	40	
	FREC	47.77 a	1.064 a	47	
	Rock Springs	56.65 c	1.306 a	20	
2016	Bedford	51.54 b	1.131 a	50	
	FREC	47.08 a	0.999 a	50	
	Rock Springs	54.31 c	1.469 b	49	
2017	Bedford	40.06 a	0.780 a	50	
	FREC	44.30 c	0.917 a	50	
	Rock Springs	41.96 b	0.820 a	49	

^zMeans within cultivar and year followed by common letters do not differ at the 5% level of significance, by SLICEDIFF using PROC GLIMMIX. FW60 = fruit diameter at 60 d after full bloom; FD60 = fruit diameter at 60 d after full bloom; FREC = Fruit Research and Extension Center.

Fig. 2. Scatter plot showing the relationship between fruit diameter at harvest vs. fruit diameter at 60 d after full bloom, along with predicted regression lines for 'Gala' at three orchards and 3 years.

correlated with FD60 with $R^2 > 0.91$ (Table 3). When data for the entire data set were subjected to analysis of covariance, the three-way interaction of orchard $\times$ year $\times$ FD60 was significant ($P = 0.003$), verifying the scatter plot with predicted lines (Fig. 5). In general, slopes separated into three groups; slope coefficients were highest in 2015, lowest in 2017, and intermediate in 2016 (Table 3). FDh was fairly well related to FD60 with R^2 values ranging from 0.58 to 0.76, and the slope for Rock Springs in 2017 was higher than the other eight slopes (Table 3). Therefore, data for Rock Springs in 2017 were deleted and the covariance model was fit to data for the remaining eight combinations of orchards and years. Signif-

Fig. 3. Scatter plot, along with regression lines for the relationship between fruit diameter 60 d after bloom and fruit weight at harvest for 'Gala' in 2017. Slopes are not significantly different and the common slopes regression model is: $FW_h = -169.09 + (8.19 \times FD60)$, $R^2 = 0.792$, $P = 0.0001$, $n = 213$.

icant terms included orchard, year, orchard $\times$ year, and FD60. Since FD60 did not interact with the indicator variables, a common slopes model was fit, and the resulting predictive model was $FD_h = 71.46 + (0.129 \times FD60)$, $R^2 = 0.013$, $P = 0.002$, $n = 721$. Although slopes were similar, for unknown reasons the intercepts ranged from 11.6 to 33.8 (Table 3; Fig. 6). Since the common slopes model was a poor predictor of FDh, the data from this study cannot be used to develop a single simple linear regression model to estimate FDh from FD60 for 'Fuji'.

Tagged fruit were harvested in 2016 and 2017 to record FW_h and assess the relation-

ship between FW_h and FD60. When the relationship between FW_h and FD60 was assessed for all six combinations of years and orchards, the R^2 values ranged from 0.54 to 0.72 (Table 3). Results from analysis of covariance showed that the three-way interaction of orchard $\times$ year $\times$ FD60 was significant. Based on a multiple comparison of the six slopes, the slope coefficient for Bedford in 2016 was significantly lower than all slopes in 2017, whereas the slopes for FREC and Rock Springs in 2016 were intermediate (Table 3). Using FD60 as the regressor variable, a common slopes model was fit to the pooled data set for the six combinations of orchards and years and the model fit the data poorly: $FW_h = 85.82 + (3.378 \times FD60)$, $R^2 = 0.141$, $P = 0.001$, $n = 493$. After deleting data for Bedford in 2016, a similar model fit only slightly better: $FW_h = 54.76 + (4.285 \times FD60)$, $R^2 = 0.224$. Although slopes were similar, the reason for the poor R^2 is likely due to the intercepts being quite different (Fig. 6). The different intercepts may have been caused by varying fruit shapes because when a multiple linear regression model was fit to the data using FD60 plus FW60/FD60 as regressor variables, the resulting model was an improvement: $FW60 = 114.21 + (10.444 \times FD60) - (358.473 \times FW60/FD60)$, $R^2 = 0.538$, $P = 0.001$, $n = 493$. When estimated values were plotted against observed values, the model containing only FD60 overpredicted at low values of observed FW_h and underpredicted at high values of observed FW_h. Values estimated with the multiple

Fig. 4. Plots of predicted vs. observed 'Gala' fruit diameter at harvest estimated with a simple linear regression model (A) $FD_h = 52.96 + (0.375 \times FD_{60})$, $R^2 = 0.338$, and a multiple linear regression model to adjust fruit diameter at 60 d after bloom for fruit shape (B) $FD_h = 85.39 + (0.241 \times FD_{60}) - [52.955 \times (FW_{60}/FD_{60})] + \{0.586 \times (FD_{60} \times [FW_{60}/FD_{60}])\}$, $R^2 = 0.627$. The 45° lines are the lines of unity, where points fall when the predicted value is equal to the observed value.

linear regression model fell much closer to the line of unity (Fig. 7).

'Honeycrisp'. Similar to the other cultivars, the relationship between FD_h and FD_{60} was linear for all combinations of year and orchard. However, the R^2 values ranged from 0.14 to 0.88 and slope coefficients ranged from 0.73 to 1.15 (Fig. 8). To determine whether a common slopes model would adequately fit the data, analysis of covariance was performed. The three-way interaction of year $\times$ orchard $\times$ FD_{60} was significant ($P = 0.037$), so a single model is not appropriate for estimating 'Honeycrisp' FD_h with data from different orchards in different seasons.

Tagged fruit were harvested for recording FW_h in only 2017. From an analysis of covariance the orchard, but not the orchard $\times$ FD_{60} interaction, was significant, indicating that the slopes, but not the intercepts, were homogeneous (Fig. 9). Since slopes were not different, a common slopes model was fit with the entire data set from 2017. The low R^2 of 0.34 was likely because the intercepts were quite different, possibly due to differences in fruit shape. Multiple linear regression with FD_{60} plus FW_{60}/FD_{60} as the regressor terms had a R^2 of 0.48. Plots of estimated vs. observed values of FW_{60} show that estimated values from the multiple regression model were less biased than those from the simple linear regression model containing only FD_{60} (Fig. 10).

Table 3. Linear regression models used to evaluate relationships between fruit diameter at 60 d after bloom (FD_{60}), fruit weight at 60 d after bloom (FW_{60}), fruit diameter at harvest (FD_h), and fruit weight at harvest (FW_h) for 'Fuji' apples grown at three orchard locations in three seasons.

Yr	Orchard location	Regression model	R^2
<i>Model to predict FW_{60} from FD_{60}</i>			
15	Bedford	$FW_{60} = -124.76 + 3.67FD_{60}$ ab ^z	0.934
	FREC	$FW_{60} = -92.15 + 3.00FD_{60}$ bc	0.944
	Rock Springs	$FW_{60} = -148.42 + 3.94FD_{60}$ a	0.962
16	Bedford	$FW_{60} = -91.17 + 2.91FD_{60}$ c	0.933
	FREC	$FW_{60} = -75.67 + 2.63FD_{60}$ c	0.976
	Rock Springs	$FW_{60} = -108.05 + 3.26FD_{60}$ c	0.917
17	Bedford	$FW_{60} = -52.73 + 2.10FD_{60}$ d	0.945
	FREC	$FW_{60} = -62.22 + 2.35FD_{60}$ d	0.956
	Rock Springs	$FW_{60} = -51.97 + 2.07FD_{60}$ d	0.918
<i>Model to predict FD_h from FD_{60}</i>			
15	Bedford	$FD_h = 24.75 + 0.88FD_{60}$ a	0.619
	FREC	$FD_h = 16.28 + 1.10FD_{60}$ a	0.701
	Rock Springs	$FD_h = 11.62 + 1.04FD_{60}$ a	0.759
16	Bedford	$FD_h = 26.61 + 1.03FD_{60}$ a	0.576
	FREC	$FD_h = 25.43 + 1.20FD_{60}$ a	0.695
	Rock Springs	$FD_h = 14.25 + 1.27FD_{60}$ a	0.644
17	Bedford	$FD_h = 30.95 + 1.22FD_{60}$ a	0.585
	FREC	$FD_h = 33.83 + 1.15FD_{60}$ a	0.572
	Rock Springs	$FD_h = 1.73 + 1.92FD_{60}$ b	0.657
<i>Model to predict FW_h from FD_h</i>			
16	Bedford	$FW_h = -375.19 + 7.40FD_h$ b	0.896
	FREC	$FW_h = -438.08 + 8.38FD_h$ b	0.926
	Rock Springs	$FW_h = -375.55 + 7.44FD_h$ b	0.929
17	Bedford	$FW_h = -401.68 + 7.93FD_h$ b	0.861
	FREC	$FW_h = -563.31 + 9.98FD_h$ a	0.944
	Rock Springs	$FW_h = -327.22 + 6.96FD_h$ c	0.828
<i>Model to predict FW_h from FD_{60}</i>			
16	Bedford	$FW_h = -222.28 + 8.47(FD_{60})$ b	0.639
	FREC	$FW_h = -253.01 + 10.68(FD_{60})$ ab	0.722
	Rock Springs	$FW_h = -297.40 + 9.96(FD_{60})$ ab	0.664
17	Bedford	$FW_h = -238.37 + 11.77(FD_{60})$ a	0.714
	FREC	$FW_h = -238.00 + 11.79(FD_{60})$ a	0.566
	Rock Springs	$FW_h = -307.25 + 13.14(FD_{60})$ a	0.542

^zSlopes within types of predictive models followed by common letters do not differ at the 0.035% experiment-wise error rate, using estimate statements in PROC MIXED.

Discussion

In previous studies, early-season apple diameters were used to predict FD or box size at harvest. We expected that using FD_{60} to predict FW_h would be less accurate than predicting FD_h . Initially we planned to use the tagged fruit to estimate FD_h from FD_{60} , then use the relationship between FW_h vs. the predicted FD_h to estimate FW_h . It was not until 'Gala' and 'Honeycrisp' had been harvested in 2016 that we realized that by harvesting the tagged fruit we could evaluate the relationship between FW_h vs. FD_{60} directly. In either case, the ability to accurately estimate FW at harvest from early-season FD measurements for all three cultivars was influenced by year and orchard.

Fruit size at harvest has been predicted from early-season fruit measurements for several tree fruit species. Davis and Davis (1948) recorded FD s for three cling peach cultivars 10 d after the tip of the pit hardened and then again at harvest. Depending on the cultivar and year, correlation coefficients ranged from 0.46 to 0.82 and for 19 of the 24 cultivar/year combinations r values > 0.6 . Batjer et al. (1957) extended this concept to 'Winesap' and 'Delicious' apples by correlating FD measured at different times of the season with diameter measurements at harvest for 4 years. Correlation coefficients

Fig. 5. Scatter plot with linear regression lines showing the relationship between fruit diameter at harvest and 60 d after full bloom for 'Fuji' apples from three orchards and three seasons. Linear regression models for each combination of orchard and year are presented in Table 3.

improved from an average of 0.76 at 35 DAFB to 0.84 at 75 DAFB. From these data, tables were developed for each cultivar relating average FD at various times following bloom to box size at harvest, based on FD . Williams et al. (1969) performed a similar study with 'Bartlett' pear in WA and reported correlation coefficients > 0.87 for a 7-year study. As with apple, fruit size predictions improved as FD was measured later in the season. FD could be estimated to within 3.2 mm 83% of the time from measurements

Fig. 6. Scatter plot with regression lines showing the relationship between fruit weight at harvest and fruit diameter 60 d after bloom for 'Fuji' apples from three orchards and three seasons. Linear regression models for each combination of orchard and year are presented in Table 3.

Fig. 7. Scatter plots of predicted vs. observed 'Fuji' fruit weight at harvest estimated with a simple linear regression model (A) $FWh = 85.82 + (3.378 \times FD60)$, $R^2 = 0.146$, and a multiple linear regression model to adjust fruit diameter at 60 d after bloom for fruit shape (B) $FWh = 114.21 + (10.444 \times FD60) - [358.473 \times (FW60/FD60)]$, $R^2 = 0.538$. The 45° lines are the lines of unity, where points fall when the predicted value is equal to the observed value.

made at 60 DAFB. Forshey (1971) measured 'McIntosh' fruit at different times during the season in six Hudson Valley orchards for 6 years and obtained results similar to those reported for Washington orchards. Correlation coefficients ranged from 0.63 when fruit were measured on 1 July and improved to 0.98 when measured on 1 Sept., which was about 20 d before the average commercial harvest date. Depending on the year, the 1 July measurement date was 42 to 60 DAFB. When measured on 1 July, 88% of the fruit grew to within 6.5 mm of the predicted diameter (Forshey, 1971). None of these

Fig. 8. Scatter plot with regression lines showing the relationship between fruit diameter at harvest and fruit diameter at 60 d after bloom for three 'Honeycrisp' orchards in 3 years.

Fig. 9. The relationship between fruit weight at harvest and fruit diameter measured 60 d after bloom for 'Honeycrisp' apples at three orchards in 2017. Common slopes Regression model: $FWh = -34.39 + (5.907 \times FD60)$, $R^2 = 0.339$, $P = 0.0001$, $n = 200$.

authors showed scatter plots of their data or reported regression equations, and none compared slopes for the different years, probably because analysis of covariance was difficult to perform until statistical software and computers with adequate speed and memory became available. However, if slopes were considerably different for different years and orchards, the authors would likely have noticed and reported those differences, so we assume that the regression equations were fairly consistent.

In this study predicting the FW of all three cultivars at harvest using FD60 required adjusting the FD60 data for fruit shape. Most of the previous research on predicting fruit size was limited to the western United States, where orchard-to-orchard and year-to-year variation in fruit shape is likely less than in Pennsylvania. Forshey (1971) worked with 'McIntosh', which is a round apple and fruit shape may be less variable than for the more conically shaped cultivars in the present study. Variable fruit shape in the current study was likely related to early-season temperatures. Shaw (1911) reported that the same individual 'Ben Davis' trees seemed to have more elongated fruit in most years. The upper south regions of the canopy, which were probably the warmest sections of the trees, had the flattest fruit. Cool early-season temperatures during the first 25 d after bloom also produced elongated fruit (Shaw, 1911). More recently other researchers have re-

Fig. 10. Scatter plots of predicted vs. observed 'Honeycrisp' fruit weight at harvest in 2017 estimated with a simple linear regression model (A) $FWh = -4.393 + (5.907 \times FD60)$, $R^2 = 0.339$, and a multiple linear regression model to adjust fruit diameter at 60 d after bloom for fruit shape (B) $FWh = 308.71 + (9.069 \times FD60) - [583.252 \times (FW60/FD60)]$, $R^2 = 0.476$. The 45° lines are the lines of unity, where points fall when the predicted value is equal to the observed value

ported that shape of 'Golden Delicious' (Noè and Eccher, 1996) and 'Red Delicious' (Greenhalgh and Godley, 1976; McKenzie, 1971) fruit was influenced by early-season temperatures. To evaluate the influence of early-season temperatures on shape of the three cultivars, cumulative growing degree days (CGDD, base 10 °C) were obtained from the Network for Environment and Weather Applications web site (<http://newa.cornell.edu/>) from weather stations located close to the orchards used for this study. Analysis of covariance was performed, where FW60/FD60 was the response variable, cultivar was the indicator variable, and the regressor variables included the linear and quadratic terms for CGDD for the 60 d before fruits were measured (CGDD60). Cultivar and the linear term for CGDD60 were both significant ($P = 0.01$), but the interaction was not significant ($P = 0.105$, Fig. 11). The FW60/FD60 ratio increased linearly with increasing CGDD60. Therefore, fruits became more elongated as early-season temperatures increased, which conflicts with previous reports (Shaw, 1911). Variation in fruit shape was likely one of the factors responsible for the different intercepts we obtained and when the FW60/FD60 ratio was included in the predictive models the R^2 values were greatly improved. In 2017 all three orchards experienced multiple frosts during and after bloom, and at Rock Springs crop load was reduced to less than 20 fruit per tree. Rock Springs also had a frost during bloom in 2016.

Fig. 11. Relationship between the ratio of FW60/FD60 and cumulative growing degree days for three apple cultivars using a base temperature of 10 °C over three seasons. Regression models: 'Fuji': $FW60/FD60 = -0.337 + (0.0015 \times CGDD60)$, $R^2 = 0.974$; 'Gala': $FW60/FD60 = -0.239 + (0.0014 \times CGDD60)$, $R^2 = 0.856$; 'Honeycrisp': $FW60/FD60 = -0.713 + (0.0020 \times CGDD60)$, $R^2 = 0.880$. FW60 = fruit diameter at 60 d after full bloom; FD60 = fruit diameter at 60 d after full bloom; CGDD = cumulative growing degree days.

The FW60/FD60 ratio tended to be lowest in the four situations in which orchards experienced frost. Frost injury may have prevented fruit from elongating normally and may explain why fruit were most elongated in the warmer seasons, which conflicts with previous reports (Shaw, 1911; Tukey, 1960).

Results from this study indicate that FW at harvest cannot be accurately predicted from early-season FD measurements alone because fruit shape varies from year to year. However, early-season FD measurements can be used to estimate harvest FW if the model also accounts for fruit shape. After accounting for fruit shape, the models we developed to predict FD at harvest explained

similar proportions of variation to those previously reported. Correlation coefficients ranged from 0.73 to 0.88 ($R^2 = 0.53$ to 0.77) for 'Winesap' in Washington (Batjer et al., 1957), 0.51 to 0.92 ($R^2 = 0.26$ to 0.85) for peach in California (Davis and Davis, 1948), 0.89 to 0.99 ($R^2 = 0.79$ to 0.98) for 'Bartlett' pear in Washington (Williams et al., 1969), and 0.73 ($R^2 = 0.53$) for 'McIntosh' in New York (Forshey, 1971). We expected that predicting FW would be less accurate than predicting FD, but coefficients of determination were still similar to values previously reported for predicting FD. The models presented in this paper can be used to develop tables similar to those reported by Batjer et al. (1957) and Williams et al. (1969), where FW or box sizes can be estimated for various combinations of FD60 and FW60/FD60.

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