Journal of the American Pomological Society 72(4): 231-241 2018

The NC-140 Multi-Location Peach Physiology Trial: Relationships Between Peach Fruit Weight, Crop Density and Early Season Temperature

Richard P. Marini[1], Esmaeil Fallahi[2], Polina Francescatto[3,] Jaume Lordan[3], Michael J. Newell[4], David Ouellette[5], Gregory Reighard[5], Terrence L. Robinson[3], and Dwight Wolfe[6]

Additional index words: *Prunus persica*, growing degree days, days from bloom to harvest

Abstract

A multi-location trial was conducted to evaluate the individual and combined effects of crop density (CD) and early-season temperature on peach fruit weight (FW) at harvest. 'Redhaven' and 'Cresthaven' peach trees growing at five sites were hand-thinned each of four years to provide a range of CDs. For each site, cumulative growing degree days were calculated from minimum and maximum daily temperatures for the first 30 days after full bloom using 4°C as the base temperature ($CGDD_{30}$). The relationships between average FW and CD and $CGDD_{30}$ were fairly variable, but FW was generally negatively related to both CD and $CGDD_{30}$. There was a negative quadratic relationship between days from bloom to harvest and $CGDD_{30}$. Variability in the data likely resulted from differences in orchard practices at the different sites. The interaction of CD and $CGDD_{30}$ was rarely significant at an individual site, indicating that the two factors are independent and have an additive effect on FW and days from bloom to harvest.

During the past 40 years produce market brokers have increasingly demanded larger fruit. Therefore, growers and researchers have been motivated to enhance their understanding of individual and combined effects of orchard practices and environmental factors that influence fruit size. In commercial peach orchards, large fruit are obtained by hand thinning to a predetermined crop load that varies with cultivar. Johnson and Handley (1989) found that peach fruit size was negatively and linearly related to the number of fruits harvested per tree; the slopes for early-, mid- and late-season cultivars were similar, but the intercepts were different. Early-season crop load adjustment is important because fruit size improvement declines as the number of days after bloom to thinning increases (Havis, 1962). More recently researchers have reported that fruit size and days from bloom to harvest were related to early-season temperatures (Ben Mimoun and DeJong, 1999). Day et al. (2008) reported that peach and nectarine harvest dates could be predicted using growing degree hours accumulated during the first 30 days after bloom. Using four cultivars of peach and nectarines with different ripening dates, they found that the slopes for each type of fruit were similar, so a single model could be used to predict harvest dates for peaches and another model could be used for nectarines. Using data from different California orchards, Lopez and DeJong (2007) found that days from bloom to reference date (date when 80% of the fruits had hardened pits near their distal end, plus

[1] Department of Plant Science, The Pennsylvania State Univ., University Park, PA 16802 (rpm12@psu.edu)
[2] Dept. of Plant Sciences, Univ. of Idaho, Parma Res. and Ext. Centr., Parma, ID 83660
[3] School of Integrative Plant Science, Cornell Univ., NYAES, Geneva, NY 14456
[4] Univ. of Maryland, Wye Res. and Ed. Centre., Queenstown, MD 21658
[5] Plant & Environmental Sciences Dept., Clemson Univ., Clemson, SC 29634
[6] Univ. of Kentucky, Res. & Ed. Centre. Princeton, KY 42445

10 days) declined linearly with increasing growing degree hours during the first 30 days after bloom. When fruit size trends for three major cultivars were analyzed, days from full bloom to reference date was negatively related to cumulative growing degree hours during the 30 days post bloom, and fruit size was negatively related to days from full bloom to reference date (Lopez et al., 2007). Taken together, these data supported the hypothesis that trees exposed to high spring temperatures cannot supply assimilates adequately to support maximum early-season fruit growth rates. Working with data for a number of peach cultivars in two regions in South Carolina over several seasons, Kenealy et al. (2015) validated the concept that cumulative growing degree days during the first 30 days after bloom could be used to predict days from bloom to harvest.

Since early season temperatures and crop load can affect both days from bloom to harvest and fruit size at harvest, it is important to know if the effect of early season temperatures is independent of crop load. Therefore, the objective of this study was to determine the effects of crop density and early-season temperature, alone and in combination on days from bloom to harvest and on peach fruit size at harvest.

Materials and Methods

General. In spring 2009, under the auspices of the NC-140 multi-state project, a multi-location peach rootstock trial was established. Trees were planted 5 x 6 m and trained to the open vase form. Ten trees of 'Cresthaven', 'Redhaven' and 'Crimson Lady' were planted at 14 locations to study the effect of early-season temperature, solar radiation and precipitation on average fruit weight (FW) and fruit soluble solids concentration. All trees for a given cultivar were propagated by the same nursery. Cooperators from ID, KY, MD, NY, and SC participated for four years (2014 – 2017) to study the effects of crop density and early-season temperatures on fruit size. During the first 45 days after full bloom each year at each site, trees were hand-thinned to obtain a range of crop densities (CD). The target range for CD was 0.5 to 5.0 fruit per cm^2 trunk-cross-sectional area (TCA), but due to spring frost or poor fruit set, the maximum desired CDs were rarely achieved. Each year cooperators recorded TCA, the dates of full bloom and 50% fruit harvest, the number of fruit per tree and total yield (kg per tree). Days from bloom to 50% harvest date, CD and FW were estimated for each tree. Daily maximum and minimum temperatures were reported and used to calculate cumulative growing degree days (CGDD) for the 30, 45 and 60 days after bloom using both 4° and 7°C as the base temperature. 'Crimson Lady' had inadequate crop loads at most locations in most years, so data analyses were limited to 'Redhaven' and 'Cresthaven'.

Data analysis. Various types of scatter plots were generated to evaluate relationships between variables, to identify suspicious observations, and to visualize potential sources of variation. Initially SAS's PROC MIXED (Littell et al., 2006) was used to perform analysis of covariance (ANCOVA), where site was included in the model as an indicator variable, and linear and quadratic terms for CD and CGDD were considered regressor variables along with all possible interaction terms. The response variables included FW and days from bloom to harvest. The most complex interaction term with the highest P-value was deleted from the model and the new model was run. This manual backward elimination continued until only significant (P=0.05) terms remained in the model (Milliken and Johnson, 2002). Interaction terms were rarely significant, but scatter plots and the analysis of covariance indicated that FW was often related to CGDD and CD in a quadratic manner. When the site x CD interaction was not significant, a single model was fit with data pooled over all sites. When site interacted with CD and/or CGDD, PROC REG (Freund and Littell, 2000) was used to fit polynomial regression models for each site.

Results

'Redhaven' fruit weight. Some descriptive statistics are presented in Table 1. Full bloom ranged from 12 March 2017 (Julian date = 71) in SC to 6 May 2017 (Julian date = 126) in NY. $CGDD_{30}$ varied from 241 in NY in 2017 to 439 in KY in 2016. Days from

Table 1. Descriptive statistics for 'Redhaven' and 'Cresthaven' peach crop density (CD), fruit weight (FW), date of 50% full bloom (FB) and days from full bloom to 50% harvest (Days) for four years at five sites.

			CD (fruit/cm2)			FW (g)				
Site	Year	$CGDD_{30}$	Min.	Mean	Max.	Min.	Mean	Max.	FB	Days
'Redhaven'										
KY	2014	397	0.56	2.20	3.88	92.7	125.7	154.6	100	98
	2015	369	0.66	1.45	2.46	136.5	160.9	193.9	97	99
	2016	439	0.59	2.40	4.00	112.2	148.7	185.0	91	105
	2017	368	0.33	2.12	5.99	108.5	163.5	226.7	83	110
SC	2014	291	0.92	1.89	3.21	195.2	246.2	287.3	80	101
	2015	387	0.88	2.69	5.23	156.8	203.1	272.3	79	96
	2016	347	0.66	1.69	3.05	174.4	211.2	255.9	81	96
	2017	350	0.82	1.89	3.49	163.5	199.6	237.6	71	98
MD	2014	328	0.42	1.08	1.57	181.8	205.3	221.5	106	100
	2015	399	0.57	1.65	2.84	167.9	195.6	247.9	108	98
	2017	358	0.79	1.94	3.52	133.9	170.4	216.8	90	104
NY	2015	402	0.29	1.92	2.76	101.5	123.2	152.0	126	92
	2017	241	0.08	0.48	0.76	125.0	176.5	211.5	109	108
ID	2014	244	0.11	1.24	2.75	215.6	261.1	365.4	101	120
	2015	219	0.19	1.02	1.70	161.7	190.1	216.7	90	126
	2016	296	0.40	1.76	2.97	141.5	204.5	324.3	96	121
'Cresthaven'										
KY	2014	406	0.83	1.86	4.21	90	143	177	104	114
	2015	393	0.01	0.09	0.19	150	194	229	104	108
	2016	483	0.63	1.50	2.44	97	155	197	95	120
	2017	385	0.64	2.02	4.07	102	158	222	91	121
SC	2014	291	0.78	2.22	4.25	220	269	329	80	129
	2015	386	1.04	2.61	3.98	157	223	288	79	123
	2016	347	0.52	1.46	2.54	236	277	332	81	127
	2017	392	0.78	2.19	3.68	146	212	279	76	120
MD	2014	328	0.39	1.04	1.39	255	280	330	106	120
	2015	399	0.58	1.40	2.43	224	262	312	108	124
	2017	358	1.00	2.23	3.82	166	197	240	90	130
NY	2015	402	0.10	1.26	2.74	126	139	154	126	134
ID	2014	244	0.23	1.52	3.01	229	315	378	101	143
	2015	223	0.32	1.22	2.24	188	253	304	90	147
	2016	294	0.52	1.26	2.03	180	251	310	96	146

bloom to harvest varied from 92 in NY in 2015 to 126 in ID in 2015. For most sites and years the minimum CDs were less than 0.9 fruit/cm². However, due to spring frost, the maximum CDs were sometimes less than 2.8 and maximum CDs greater than five fruit/cm² were obtained at only KY in 2017 and SC in 2015. Depending on location and year FW varied from 102g to 365g.

When FW was plotted against all six combinations of CGDD (30, 45, and 60 days after bloom) and base temperature (4° and 7°C), FW was best related to CGDD for 30 DAFB with a base temperature of 4°C and will be referred to as $CGDD_{30}$ (Fig. 1). Analysis of covariance, where each combination of base temperature and days after bloom were included in the model as covariates, confirmed interpretation of the scatter plots: both FW and days from bloom to harvest were best related to $CGDD_{30}$. Scatter plots show that a quadratic relationship between FW and CGDD deteriorated as CGDD was calculated with temperatures for 45, and 60 days after bloom and for the base temperature of 7°C compared to base temperature of 4°C for 30 days after bloom (Fig. 1).

A scatter plot of FW against CD shows a general negative linear relationship between FW and CD. FW was highest in SC and ID and lowest in NY and KY (Fig. 2). There was also a negative relationship between FW and $CGDD_{30}$ and again FW was highest for SC and sometimes for ID, but the highest $CGDD_{30}$ was recorded in KY (Table 1). FW was low for NY in 2017 and ID in 2015 despite low early-season temperatures and low CD and if those data are ignored, there was a

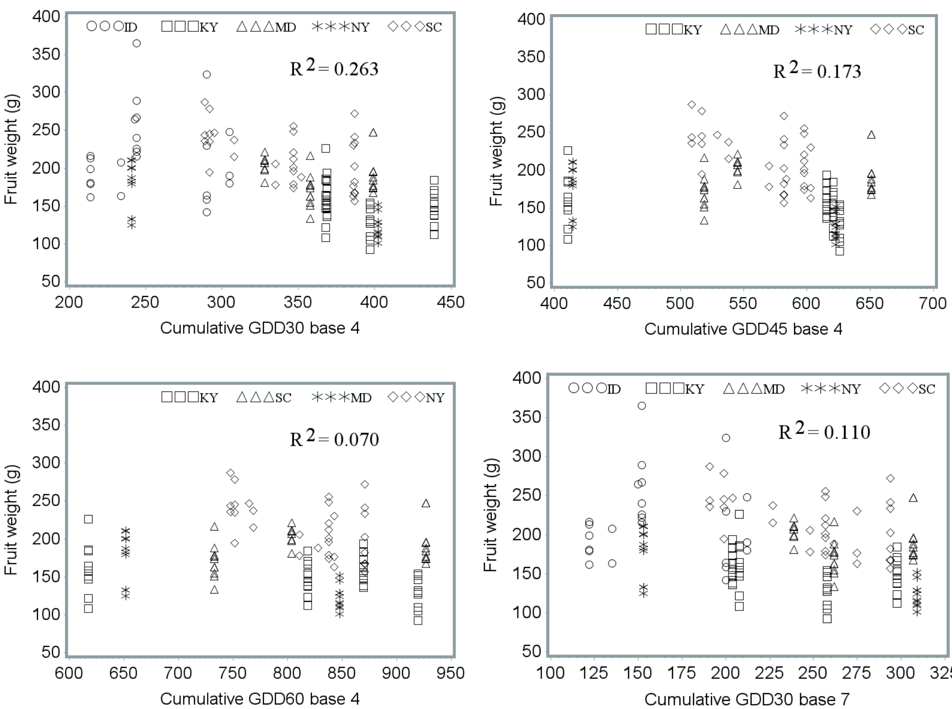

Figure 1. Relationship between fruit weight and cumulative growing degree days for 30, 45 and 60 days after bloom with base temperature of 4°C (CGDD) and 30 days after bloom with base temperature 7°C (CGDD30) for 'Redhaven' peach trees at five sites over four years.

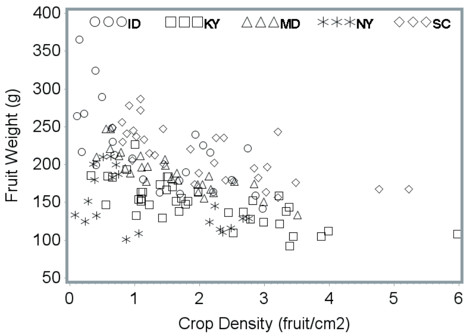

Figure 2. Relationship between fruit weight and crop density for 'Redhaven' peach trees at five sites over four years.

general negative linear relationship between FW and $CGDD_{30}$ base temperature 4° but not for base temperature 7°C (Fig. 1).

ANCOVA performed on the entire data set indicated that the site x CD x $CGDD_{30}$ interaction was significant (P =0.011), so multiple regression was performed by site with Proc Reg, where the model contained linear and quadratic terms for CD and $CGDD_{30}$ plus interactions. There were data for only two years from NY, so those data were deleted from the data set. Manual backward elimination was used to delete nonsignificant terms from the model and final models containing only significant terms are shown in Table 2. The final models for each site had R^2 values greater than 0.69, but the model for SC had linear and quadratic terms for both CD and $CGDD_{30}$, whereas models for KY, ID and MD contained only linear terms for CD plus linear and quadratic terms for $CGDD_{30}$.

Although site interacted with the two covariates, it was desirable to simplify the model and develop a single model for all sites. Therefore data from KY, ID, MD and SC were combined and the following multiple regression model was selected: $FW = 158.7 – 41.22(CD) + 4.51(CD^2) + 0.86(CGDD_{30}) – 0.002(CGDD_{30}^2)$, $R^2 = 0.51$, P = 0.0001, N = 124. Three dimensional plots are difficult to interpret, so predicted FW for four levels of CD were plotted against $CGDD_{30}$ (Fig. 3). The four curves decline with increasing $CGDD_{30}$, but the curves tend to converge as CD increases. When predicted values for FW were plotted against observed values the model slightly over-predicted FW for large fruit (Fig. 4). Discrepancies for large fruit were caused by data for two trees with very large fruit in ID. The bias for large fruit may reflect the fact that the model did not account for the influence of orchard practices that were not consistent for all sites.

'Cresthaven' fruit weight. Date of 'Cresthaven' bloom varied from 20 March 2017 in SC to 6 May 2015 in NY (Julian date 76 and

Table 2. Regression models describing the relationship between FW (g) with CD (fruit/cm^2 TCA) and $CGDD_{30}$ for 'Redhaven' and 'Cresthaven' peach trees at four sites. All models are significant (P = 0.0001).

Cultivar and site	Regression Model	R2
'Redhaven'		
KY	$FW = -1047.35 – 15.78(CD) + 7.46(CGDD_{30}) – 0.011(CGDD_{30}^2)$	0.706
SC	$FW = 883.66 – 52.63(CD) + 6.52(CD)^2 – 3.19(CGDD_{30}) + 0.0041(CGDD_{30})^2$	0.751
MD	$FW = 1753.00 – 26.17(CD) – 8.50(CGDD_{30}) + 0.012(CGDD_{30})^2$	0.808
ID	$FW = -1906.65 – 43.24(CD) + 16.75(CGDD_{30}) – 0.032(CGDD_{30})^2$	0.694
'Cresthaven'		
KY	$FW= -139.27 + 2.09CGDD_{30} – 0.0032(CGDD_{30})^2 – 31.76(CD) + 2.56(CD)^2$	0.597
SC	$FW = 500.09 - 1.80(CGDD_{30}) + 0.003(CGDD_{30})^2 + 26.94(CD) + 7.57(CD)^2 – 0.214(CD*CGDD_{30})$	0.360
MD	$FW = 4072.69 – 21.03(CGDD_{30}) + 0.029(CGDD_{30})^2 – 24.33(CD)$	0.463
ID	$FW = -2483.38 – 53.22(CD) + 22.73(CGDD_{30}) – 0.044(CGDD_{30})^2$	0.696

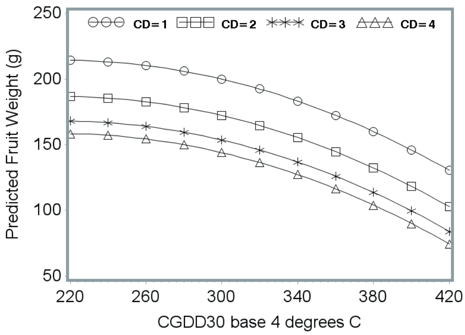

Figure 3. Plots of predicted values for 'Redhaven' fruit weight against cumulative growing degree days for 30 days after bloom ($CGDD_{30}$) for four levels of crop density (CD) averaged over four sites and four years (KY, ID, MD and SC).

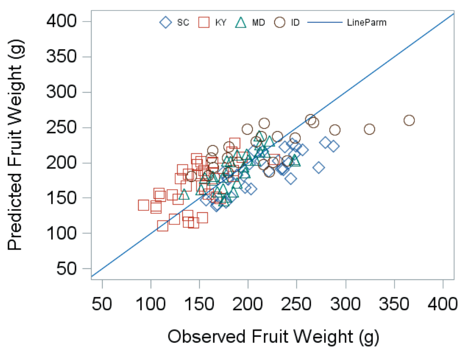

Figure 4. Plot of predicted fruit weight vs. observed fruit weight for 'Redhaven' using a pooled data set for KY, ID, MD and SC and the model included linear and quadratic terms for CD and $CGDD_{30}$. LineParm is parameterization line, or the line of unity, where points fall when predicted values equal observed values.

126, respectively). CGDD30 varied from 223 in ID in 2014 to 444 in SC in 2016 (Table 1). Due to spring frost in KY, CD ranged from only 0.01 to 0.19 fruit/cm^2 in 2015, but for all other locations the minimum CD was at least 0.1 and the maximum CD varied from 2.4 to 4.25 fruit/cm^2 (Table 1). The scatter plot of FW against CD indicates that over the range of CD, FW was higher in ID, MD and SC than in KY and NY, and FW generally declined linearly with increasing CD (Fig. 5). The scatterplot of FW against $CGDD_{30}$ also shows a general decline in FW as $CGDD_{30}$ increased (Fig. 6). Similar to the model for 'Redhaven', the model for 'Cresthaven' included a significant term for the site x CD x $CGDD_{30}$ interaction. The models for each location are shown in Table 2 and R^2 – values ranged from only 0.36 to 0.67. In an attempt to simplify the model, the entire data set was used to develop a multiple regression model using data from all sites with linear, quadratic and interaction terms for CD and $CGDD_{30}$. The linear term for CD and linear and quadratic terms for $CGDD_{30}$ were significant. The model was: $FW = 1765.2 – 16.62(CD) – 8.34(CGDD_{30}) + 0.011(CGDD_{30})^2$, $R^2 = 0.28$, $P = 0.0001$, $N = 117$. The low R^2 likely resulted from failure to include location in the model.

'Redhaven' days from bloom to harvest. Scatter plots indicated little relationship between days from bloom to harvest and CD (data not shown), but days from bloom to harvest declined with increasing $CGDD_{30}$ (Fig. 7). When the entire data set, excluding NY, was used to fit the model, the significant terms included site and the linear and quadratic terms for $CGDD_{30}$ (R^2= 0.052, P=0.028). The percentage of model Type III sum of squares (partial SS) explained by site, $CGDD_{30}$ and $(CGDD_{30})^2$ was 38, 29, and 33% respectively, and all three variables were significant at the

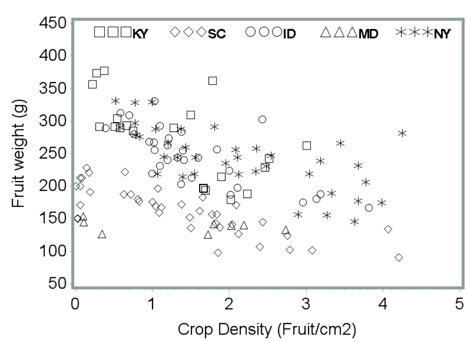

Figure. 5. Scatter plot showing the relationship between fruit weight and crop density for 'Cresthaven' trees at five sites over four years.

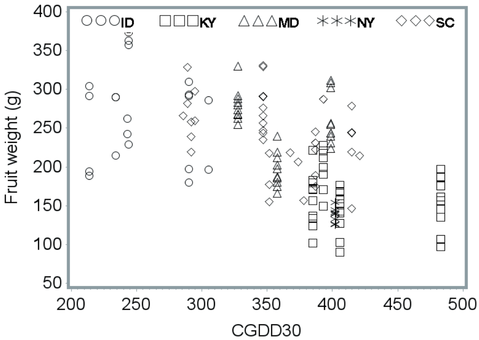

Figure 6. Relationship between fruit weight and cumulative growing degree days for 30 days after bloom with base temperature of 4°C ($CGDD_{30}$) for 'Cresthaven' peach trees at five sites over four years.

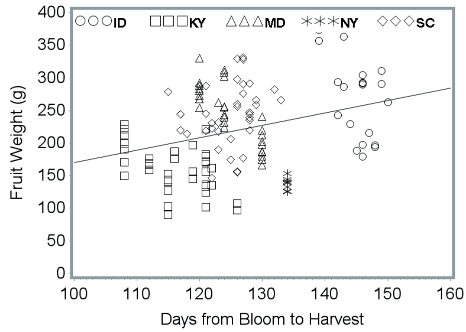

Figure 7. Scatter plot showing the relationship between fruit weight and days to harvest for 'Cresthaven' at five sites over four years. Regression model: FW = 19.17 + 1.89Days, R^2 = 0.098, P = 0.0002.

0.05 level. Although site did not interact with the other variables, multiple regression models were fit for each site using manual backward elimination of nonsignificant terms until only significant terms remained in the model and these models are presented in Table 3. The R^2 values varied from 0.012 in MD to 0.477 in ID. The only sites where regression models were significant was KY, where days from bloom to harvest was linearly related to $CGDD_{30}$ and ID where the linear term for CD and the quadratic term for $CGDD_{30}$ were significant (Table 3).

'Cresthaven' days from bloom to harvest. Scatter plots revealed poor relationships between days from bloom to harvest and CD and $CGDD_{30}$ (data not presented). When a multiple regression model was fit with the entire data set, the significant variables included CD, CD^2, $CGDD_{30}$ and $CD*CGDD_{30}$, but the adjusted R^2 was only 0.229. When an unequal slopes model was fit, the 3-way interaction of site x CD x $CGDD_{30}$ was significant, so models were developed for each site

Table 3. Regression models describing the relationship between days from bloom to harvest (Days) with CD (fruit/cm^2 TCA) and $CGDD_{30}$ for 'Redhaven' and 'Cresthaven' peach trees at four sites.

Cultivar and site	Regression Model	R^2	Model P-value
'Redhaven'			
KY	Days = 73.79 + 0.088($CGDD_{30}$)	0.139	0.001
SC	Days = 109.01 + 1.58(CD)	0.016	0.293
MD	Days = 110.51 + 1.68(CD)	0.012	0.421
ID	Days = 261.77 + 2.37(CD) – 1.06($CGDD_{30}$) + 0.0019$(CGDD_{30})^2$	0.477	0.004
'Cresthaven'			
KY	Days = -371.51 + 5.14(CD) + 2.78($CGDD_{30}$) – 0.899$(CD)^2$ – 0.0039$(CGDD)^2$	0.789	0.001
SC	Days = 83.20 + 55.95(CD) + 0.47($CGDD_{30}$) – 0.203($CD*CGDD_{30}$)	0.279	0.001
MD	Days = 4072.69 – 21.03($CGDD_{30}$) – 24.33(CD) + 0.029$(CGDD_{30})^2$	0.463	0.001
ID	Days = 120.08 + 1.59(CD)	0.128	0.087

(Table 3). The R^2 values varied from 0.28 for SC to 0.79 for KY; no two of the four models contained the same terms and CD interacted with $CGDD_{30}$ in SC.

'Redhaven' FW vs. day from bloom to harvest. A scatter plot for the entire data set showed a general negative relationship between FW and days from bloom to harvest (Fig. 6). When Proc Mixed was used to fit an ANCOVA model with location as an indicator variable, linear and quadratic terms for days from bloom to harvest, plus interactions, the only significant variables were linear and quadratic terms for days from bloom to harvest. Proc Reg was then used to fit polynomial models for the entire data set with no indicator variable in the model, and only the linear term was significant (R^2=0.12, P=0.0005, n=100). To obtain SS, Proc GLM was used to fit the model with site and linear and quadratic terms, and the SS explained by site, days, and $days^2$ were 86, 7, and 7%, respectively, indicating that days from bloom to harvest explained much less variation than site. When quadratic models were fit by location, only the linear term was significant for MD and ID (R^2 = 0.28 and 0.44, respectively) and the models for the other two locations were not significant.

'Cresthaven' FW vs. day from bloom to harvest. 'Cresthaven' FW generally increased as days from bloom to harvest increased, and the nature of the relationship differed by site (Fig. 7). For KY and MD the relationship appeared negative and little relationship was apparent for SC (Fig.7). Polynomial regression models, with days from bloom to harvest as the regressor variable, were fit for each location because the location x days from bloom to harvest interaction was significant (Table 4). FW was linearly related in a negative manner to days from bloom to harvest for KY, ID and MD, but the relationship was not significant for SC (Table 4). Days from bloom to harvest also declined linearly with increasing $CGDD_{30}$ (Fig. 8).

Discussion

For both cultivars, FW was higher in ID, MD and SC than in KY and NY. The reasons for these differences are not obvious, but may be related to water status of the trees, date of fruit thinning, pruning severity, and low temperature injury that does not kill flowers but adversely affects fruit growth. Some, but not all sites provided irrigation. Peach FW was reduced by water stress and the effect of water stress increased with increasing crop load (Berman and DeJong, 1996; Morris et al., 1962). If trees were thinned earlier in ID, SC and MD, FW would likely be higher because thinning date can influence fruit size

Table 4. Regression models describing the relationship between FW and days from bloom to harvest (DAYS) for 'Redhaven' and 'Cresthaven' grown at four sites.

Cultivar and sites	Regression Model	R^2	Model P-value
'Redhaven'			
KY	FW = 64.19 + 0.83(Days)	0.0275	0.3067
SC	FW = 420.94 – 2.11(Days)	0.0351	0.3046
MD	FW = 693.56 – 5.01(Days)	0.2833	0.0036
ID	FW = 1264.34 – 8.56(Days)	0.437	0.0004
'Cresthaven'			
KY	FW= 524.27 – 3.13(Days)	0.245	0.0012
SC	FW= -2.37 + 1.98(Days)	0.032	0.0681
MD	FW= 1340.51 – 8.77(Days)	0.658	0.0001
ID	FW = 1724.59 – 10.00(Days)	0.229	0.0282

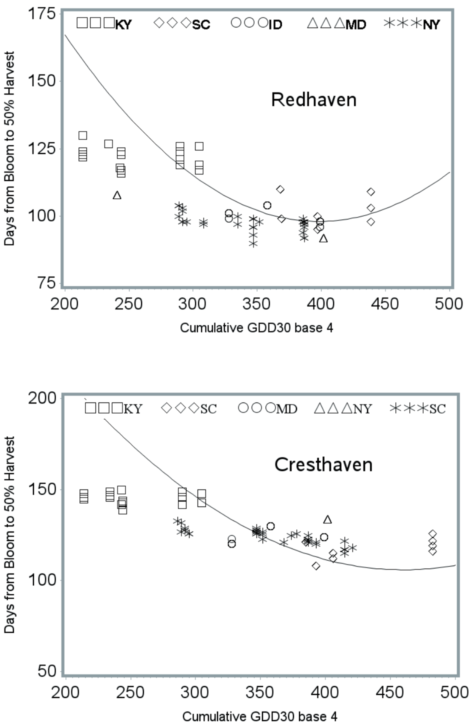

Figure 8. Scatter plot showing the relationship plus regression curves for Days from bloom to 50% harvest at five sites over four years. Regression models for 'Redhaven': Days=211.1 – 0.56CGDD + 0.00071x$CGDD_{30}^2$, R^2 = 0.536, P = 0.0001; 'Cresthaven': Days = 228.8 – 0.48$CGDD_{30}$ + 0.000x52C-GDD_{30}^2, R^2 = 0.571, P= 0.0001.

(Havis, 1962). Pruning severity influences initial crop load and early-season fruit size (Marini, 2003; Morris et al., 1962), so variability in the number of shoots per tree retained after pruning may explain some of the site differences in FW at harvest. The effect of non-lethal winter injury is poorly studied but may have been a factor in the small FW in NY and fluctuating winter temperatures in KY may also have affected FW. In previous studies, FW always decreased linearly with increasing CD (Johnson and Handley, 1989) and $CGDH_{30}$ (Lopez et al, 2007; Lopez and DeJong, 2017; Day et al., 2008). However, in the present study when CD and $CGDD_{30}$ were both included in the model, FW decreased in a curvilinear manner with increasing CD in three of the eight location-year combinations and the relationship was quadratic for all eight location-years for $CGDD_{30}$. The interaction of CD and $CGDD_{30}$ was usually not significant (Table 2). These unexpected results may be due to the confounding of CD and $CGDD_{30}$. Bubble plots generated to help visualize the three-dimensional relationship in two-dimensions, showed that in some locations the lowest CDs occurred only in cool years (Fig. 9). The curved relationships may have been caused by this confounding of CD and $CGDD_{30}$. For example, in MD 2014 was the coolest season and all trees had CDs less than 2.0. In NY, 2017 was the coolest season and all trees had CDs less than 1.0. In KY, CD ranged from 0.5 to 4.0 in both 2014 and 2016, but 2014 was the cooler year and FW was consistently lower than in 2016; FW was relatively high in 2017 which was the coolest year. The relationship between FW and CD in SC appeared curvilinear and at a given CD, FW was high in 2014 which was a cool year (Fig. 5). Data from ID somewhat contradicted data from the other sites. FW declined curvilinearly with increasing CD, and at a given CD, FW was lowest in the cool season of 2015 and CD was also relatively low (Fig. 9).

Coefficients of determination obtained with the combined data set in the current study are lower than in most previous reports (Day et al., 2008; Johnson et al., 2011; Lopez and DeJong, 2017; Lopez et al., 2007). This may be partially explained by the fact that previous studies often used FW averaged over several trees or blocks of trees as the response variable, whereas in the current study data for individual trees were used for the analyses. Tree-to-tree variation is typically high for peach (Marini, 1985) and likely explains why relationships in this study appear relatively poor. Additionally, in previous studies crop load was reduced to commercial standards (Day et al., 2008; Kenealy et al., 2015; Lopez et al, 2007; Lopez and DeJong,

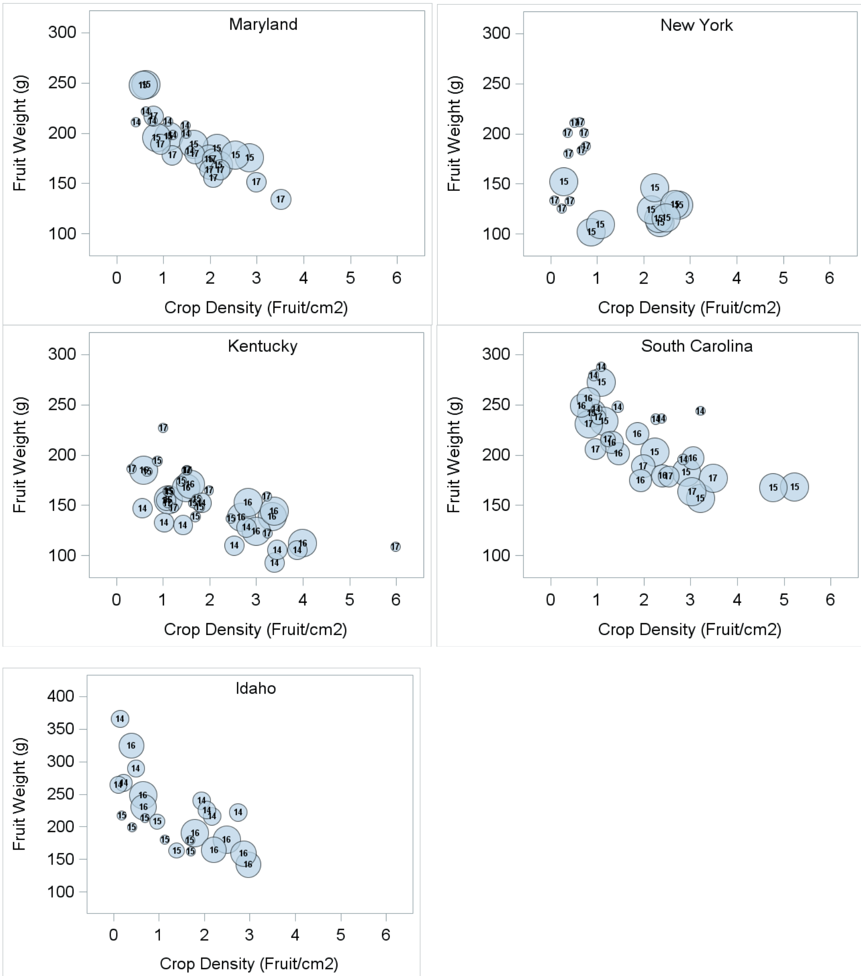

Figure 9. Bubble plots showing the three dimensional relationship between 'Redhaven' fruit weight and crop density and cumulative growing degree days for 30 days after bloom ($CGDD_{30}$) for four locations over four years. The size of the circles is proportional to the $CGDD_{30}$ and the numbers in the circles indicate the year (2014, 2015, 2016, and 2017).

2017) or to levels below a commercial crop (Johnson et al., 2011). By varying two factors in the present study (CD and $CGDD_{30}$), we would expect increased variation.

In the present study, unlike in previous reports (Day et al., 2008; Kenealy et al., 2015), days from bloom to harvest was not well related to $CGDD_{30}$ or CD, and FW was not well related to days from bloom to harvest. One reason for these unexpected results is likely due to our inability to obtain a wide range of CDs each year. In a similar multi-location trial with apples cooperators had difficulty achieving target CDs because fruit are difficult to see early in the season, and bloom density and fruit set vary from year-to-year for a number of reasons (Marini et al., 2012). Non-uniform orchard practices, such as pruning severity, date of fruit thinning, and availability of irrigation also likely influenced the relationships between FW, CD, and days from bloom to harvest. Weather conditions not recorded in this study may have influenced FW and days from bloom to harvest because Johnson et al. (2011) reported that FW on lightly cropped 'Cresthaven' trees increased linearly with increasing days from bloom to harvest, FW decreased linearly with increasing early-season solar radiation, and soluble solids concentration declined with total rainfall for 40 days before harvest.

The poor relationship between FW and CD when combining data for all six locations in the same analysis may be due to the method of measuring CD using trunk-cross-sectional area (TCA). TCA is a poor reflection of canopy size after trees have filled their allotted space and are pruned to contain tree size. Reginato et al. (2007) showed that expressing CD based on light interception resulted in a common relationship between FW and CD across several north-south locations in Chile. CD based on light interception is more physiologically sound than when based on TCA. In future trials with mature trees, consideration should be given to using light interception as a covariate.

Conclusions

Although the relationships were more variable than expected, these results generally agree with previous reports where FW declined as $CGDD_{30}$ and CD increased. The primary reason to evaluate both $CGDD_{30}$ and CD was to determine if the response to $CGDD_{30}$ depended on CD. Because the interaction was not very important we can conclude that the negative relationship between FW and $CGDD_{30}$ reported for California is valid across North America, but the slopes may vary with site.

Literature Cited

Ben Mimoun, M. and T.M. DeJong. 1999. Using the relation between growing degree hours and harvest date to estimate run-time for PEACH: a tree growth and yield simulation model. Acta Hort. 499:107-114.

Berman, M.E. and T.M. DeJong. 1996. Water stress and crop load effects on fruit fresh and dry weights in peach (Prunus persica). Tree Physiol. 16:859-864.

Day, K., G. Lopez, and T. DeJong. 2008. Using growing degree hours accumulated thirty days after bloom to predict peach and nectarine harvest date. Acta Hort. 803: 163-166.

Freund, R.J. and R. C.Littell. 2000. SAS® system for regression. 3rd ed. SAS Institute Inc. Cary, NC.

Havis, A. L. 1962. Effect of time of fruit thinning of 'Redhaven' peach. Proc. Amer. Soc. Hort. Sci. 80:172-176.

Johnson, R.S. and D.F. Handley. 1989. Thinning response of early, mid-, and late-season peaches. J. Amer. Soc. Hort. Sci. 114:852-855.

Johnson, S., M.J. Newell, G.L. Reighard, T.L. Robinson, K. Taylor, and D. Ward. 2011. Weather conditions affect fruit weight, harvest date and soluble solids content of 'Cresthaven' peaches. Acta Hort. 903:1063-1068. DOI: 10.17660/ActaHortic.2011.903.148.

Kenealy, L., G. Reighard, B. Rauh and W. Bridges, Jr. 2015. Predicting peach maturity dates in South Carolina with a growing degree day model. Acta Hort. 1084:749-752.

Littell, R.C., G.A. Millien, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. SAS® for mixed models. 2nd ed. SAS Institute Inc. Cary, NC.

Lopez, G. and T.M. DeJong. 2017. Spring temperatures have a major effect on early stages of peach fruit growth. J. Hort. Sci. and Biotech. 82:507-512.

Lopez, G., R.S. Johnson and T.M. DeJong. 2007. High spring temperatures decrease peach fruit size. California Agr. 61(1):31-34.

Marini, R.P. 1985. Sample size estimates for peach tree growth and yield experiments. J. Amer. Soc. Hort. Sci. 110:604-608.

Marini, R.P. 2003. Peach fruit weight, yield, and crop value are affected by number of fruiting shoots per tree. HortScience 38:512-514.

Marini, R.P., W.R. Autio, B. Black, J.A. Cline, w. Cowgill, Jr., R. Crassweller, P. Domoto, C. Hampson, R. Moran, R.A. Parra-Quezada, T. Robinson, M. Stasiak, D.L. Ward, and D. Wolf, 2012. Summary of the NC-140 apple physiology trial: the relationship between 'Golden Delicious' fruit weight and crop density at 12 locations as influenced by three dwarfing rootstocks. J. Amer. Pomol. Soc. 66:78-90.

Milliken, G.A. and D.E. Johnson. 2002. Analysis of messy data. Vol. III: Analysis of covariance. Chapman and Hall, London.

Morris, J.R., A.A. Kattan and E.H. Arrington. 1962. Response of Elberta peaches to the interactive effects of irrigation, pruning, and thinning. Proc. Amer. Soc. Hort. Sci. 80:177-189.

Reginato, G.H., V. García de Cortázar, J. Varela and T. L. Robinson. 2007. Crop load expressed in terms of intercepted PAR can be used as a covariate to compare peach tree performance. J. Hort. Sci. and Biotechnol. 82:715-720.