Using Simulation Modeling to Estimate the Relationship Between Date of Fruit Maturity and Yield Potential in Peach

M. E. Berman,[1] A. Rosati,[2] L. Pace,[3] Y. L. Grossman,[4] and T. M. DeJong[1]

Abstract

Fruit growth data for eight clingstone peach cultivars with dates of fruit maturity spanning eight weeks, were collected over two years and used with a peach fruit growth and crop yield simulation model to estimate the effect of date of fruit maturity on crop yield potential. Cultivars with early dates of fruit maturity were estimated to have substantially reduced dry weight yield potential compared to later maturing cultivars. However, fruit of earlier maturing cultivars had a higher water content than fruit of late maturing cultivars. These differences in water content offset some of the predicted loss in fruit dry weight yield potential related to early fruit maturity, when yields were calculated on a fresh weight basis. The estimated sacrifice in fresh crop yield potential related to advancing fruit maturity beyond the current earliest harvested commercial California clingstone peach cultivars was approximately 1.8 tons ha^{-1} day^{-1}. Within the parameters of this study, maximum yield potentials for peach are predicted to be achieved in cultivars maturing during early to mid-August.

Introduction

Peach crop yield is a function of fruit size and fruit number and commercial success depends on the ability to achieve high numbers of relatively large sized fruit. A major factor that determines fruit size is fruit growth potential, the maximum fruit size attainable under non-limiting conditions (10, 12). Growth potential is a genetically determined trait that varies between species and cultivars. Monitoring the growth of fruit on lightly cropped trees, where competition between fruits has been minimized, can be used to develop growth potential curves for fruits of specific cultivars. Growth potential curves provide a means to estimate fruit sink demand throughout fruit development (8). Grossman and DeJong (7) have developed a computer simulation model that uses such curves to predict fruit growth at varying crop loads.

The interaction of fruit growth potential with additional factors, including crop load and the length of the fruit growth period, determines the mean size of the fruit at harvest. Under commercial growing conditions, fruit rarely obtain their maximum potential size due to interfruit competition. Early and late in the peach fruit developmental period, the presence of numerous competing fruit sinks usually results in carbohydrate supply limitations to growth (5, 8). Peach trees generally set heavy crops and the strong effects of interfruit competition on fruit growth requires reduction of the crop load by thinning to attain fruit of the desired size. Heavy thinning ensures large fruit size, but represents a loss in yield as the number of fruit is reduced. Under-thinning results in many fruit of less than salable size.

Fruit size and crop yield are also affected by the length of the fruit growth period. Breeders have developed commercial, non-melting-flesh type clingstone peach cultivars with a range of ripening dates

[1]Department of Pomology, University of California, Davis, Davis, CA 95616.
[2] Istituto Sperimentale Orticoltura, Via di Cavalleggeri 25, 84098 Pontecagnano, Italy.
[3]Istituto di colture Legnose Agrarie e Forestali, Facolta di Agraria, Universita di Reggio Calabria, Piazza S. Francesco da Sales, Gallina, Reggio Calabria, Italy.
[4]Biology Department, Beloit, College, 700 College Street, Beloit, WI 53511, USA.

from early July to September. Late maturing peach cultivars have higher yields than early maturing cultivars (2, 3, 9) presumably because fruit have a longer amount of time in which to develop and accumulate carbohydrates. The peach industry is aware of this loss in yield in early maturing cultivars but there is an economic incentive to plant these cultivars because growers receive a premium price for early fruit. However, there have been no quantitative physiological studies that have documented theoretical differences in yield between early and late maturing cultivars.

The recent development of the PEACH crop growth simulation model (7) provides an opportunity to investigate theoretical differences in yield potential between peach cultivars with differing fruit development periods based on the fruit growth potential concept. The goal of this research was to quantify fruit growth potentials of eight commercially important California clingstone peach cultivars and to use the PEACH model (7) to quantify the functional relationship between potential crop yield and the length of the fruit development period.

Materials and Methods
Fruit Growth Measurements

Fruit growth was measured on 10-year old clingstone peach trees, trained to an open vase, at the U.C. Davis Wolfskill Experimental Orchard in Winters, CA. Eight commercially important clingstone peach cultivars ('Loadel,' 'Carson,' 'Andross,' 'Ross,' 'Dr. Davis,' 'Halford,' 'Hesse' and 'Corona') with a range of ripening dates from early July to September were studied. Trees were growing in adjacent rows. In early April of 1995, trees were thinned to very light crop loads with one fruit per shoot and fruit was subsequently sampled at four-week intervals. In 1996, the trees were thinned on March 30 (approximately two weeks after full bloom), to the same level as in 1995. In 1996 fruit were sampled every 10 - 14 days to improve resolution of the fruit growth curves. Ten-fruit samples were collected from five trees of each cultivar, fresh weight was measured, and then samples were dried at 65°C and dry weight was recorded. Final samples were collected when fruit had reached full maturity.

Generation of Potential Growth Curves

For each cultivar, the natural logarithm (ln) of individual fruit dry weight was plotted against degree-day date (degree-days for Winters were calculated using the U.C. Integrated Pest Management computer system). The resulting curves were hyperbolic in shape. Cubic spline equations with a single knot at about one-third of the way through the fruit development period were fit to the data for each cultivar. Extrapolated points were added beyond the range of the observed data to force the fitted curves through the final data point and to avoid unrealistic inflections at the end of the curve. The resulting functions estimated potential individual fruit dry weight through the season. Seasonal patterns of fruit relative growth rate (RGR) were calculated by taking the first derivative of the natural logarithm-based dry weight curve. Seasonal patterns of absolute growth rate (AGR) were calculated by taking the first derivative of the dry weight curve.

Crop Simulation Model

Potential growth curve equations were entered into the PEACH crop yield and tree growth simulation model developed by Grossman and DeJong (7). This model uses environmental data and tree organ growth potentials to estimate photosynthesis, organ respiration and organ growth on a whole-tree basis. The model predicts dry weight growth of fruit, leaves, stems, trunk and roots using site-specific weather data and supply and demand relationships derived from previous studies on peach trees.

Model simulations were performed using similar vegetative growth and light interception parameters for each cultivar so that the differences in potential yield were due primarily to differences in fruit growth parameters and not vegetative
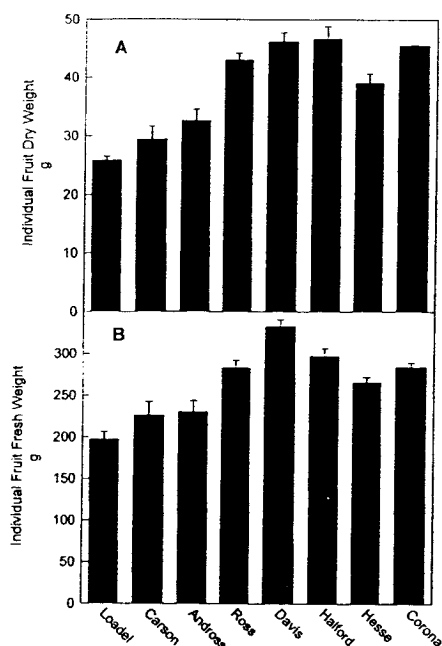
Figure 1. Mean dry (A) and fresh (B) weights of individual fruits at harvest on heavily thinned trees from eight clingstone peach cultivars. Each bar represents the mean ± SE fruit weight of five ten-fruit subsamples.

characteristics of the cultivars. Growth was simulated on mature perpendicular-V trees in a high density planting (4) since research has documented that this system is commercially feasible and has higher yield potential than the low density open vase system (6). Simulated initial fruit set was 1500 fruit per tree and fruit thinning was simulated to achieve variable crop loads (50, 100, 200, 400 and 600 fruit/tree) six weeks after bloom. Daily temperature, degree-days and solar radiation data from the Winters, CA, CIMIS (the California Irrigation Management Information System) weather station for 1991-1995 were used to calculate five-year average daily weather values for the model simulations. Fruit growth simulation with a crop load of 50 fruit per tree on high density perpendicular V trees gave estimates of fruit growth and was within 3% of the experimentally observed poten-

tial fruit size for each respective cultivar in the low density open vase orchard.

Individual fruit dry weight and total crop dry weight predictions were simulated for each cultivar at crop loads of 100, 200, 400 and 600 fruit/tree. Fruit dry weight predictions were plotted against crop load and the length of the growing season to determine the effects of ripening date and crop load on fruit size. Fruit dry weight:fresh weight ratio data were available from 1995 and 1996 and the average dry:fresh ratio was regressed against date of harvest. Using the above regressions, the crop load which would result in an average fruit fresh weight of 150 g, was calculated for a range of maturity dates.

Results

In 1996, maturity dates ranged from July 12, for 'Loadel' and 'Carson,' to September 5 for 'Corona,' a period of eight weeks. Dry weight growth potential ranged from 26 g in Loadel to 46 g in the late cultivars (Figure 1a). With the exception of the 'Hesse' cultivar, dry weight growth potential increased with later harvest dates (Figure 2). Fruit dry weight potential at fruit maturity increased until early August, reaching an apparent asymptote at ~46 g.

'Dr. Davis' had the highest fresh weight growth potential, with fruit aver-
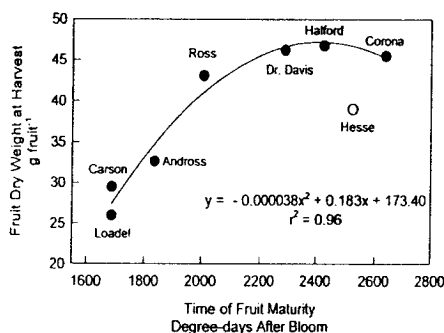

Figure 2. Individual fruit dry weight vs. time of fruit maturity on heavily-thinned trees of eight cling peach cultivars. A quadratic regression equation was calculated to fit seven of the points (closed symbols). 'Hesse' fruit (the open symbol) were excluded from the regression.
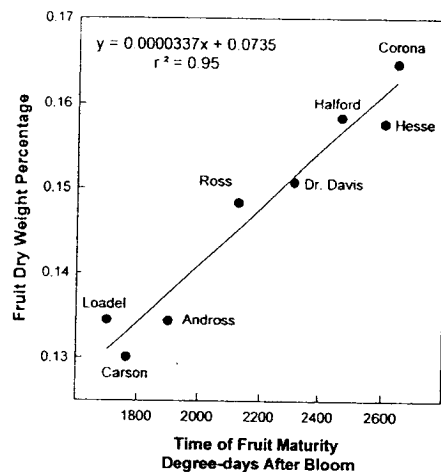
Figure 3. Fruit dry weight percentage vs. the time of fruit maturity. Dry weight percentage is the ratio of fruit dry weight to fruit fresh weight x 100. Each value represents the mean value of dry weight percentage at the mean harvest date from 1995 and 1996.

aging 332 g (Figure 1b). Fruit dry weight percentage, the ratio of dry weight to fresh weight, increased throughout the season (Figure 3) with the latest cultivar, 'Corona,' having over 20% greater dry weight percentage than the earliest cultivars. This increase in dry weight percentage reduced the fresh weight differences between early and late cultivars. For example, 'Corona' fruit dry weight was 75% greater than that of 'Loadel,' but due to different dry weight percentages, the fresh weight of 'Corona' was only 43% greater than that of 'Loadel.'

For seven cultivars, seasonal potential growth data were used to generate potential fruit relative growth rate curves. Data from 'Hesse' were not included, as small potential fruit size in this cultivar suggests that it is not similar to the other cultivars in its growth capacity (Figure 2). Potential relative growth rate curves were incorporated into the PEACH crop growth simulation model and the model was used to estimate fruit size at a range of crop loads. An example of the data and model output is presented in Figure 4 for 'Halford.' Predicted final fruit weight was strongly re-

lated to crop load (Figure 5a) and date of fruit maturity (Figure 5b). The effect of crop load and date of maturity on simulated fruit dry weight was examined with multiple linear regression. The results of this regression analysis are presented in Figure 6, a surface plot showing the positive effect of lengthening the fruit growth period and the negative effect of increasing crop load on fruit size at maturity. Near the end of the season, simulated fruit weight declined with increasing date of fruit maturity. This negative slope, late in the season, is probably an artifact of the binomial function used to fit the data (Figure 2 or Figure 5b).

A fruit having a fresh weight of 150 g has an average diameter of 64-mm (data not shown) and represents a desirable size for the canning industry. Using the dry weight percentage equation in Figure 3, the dry weight required to obtain a 150-g fresh weight fruit was calculated. The resultant dry weight and the regression represented in Figure 6, were subsequently used to calculate the crop load that would yield 150 g fruit for the harvest date of each cultivar. This resulted in a prediction
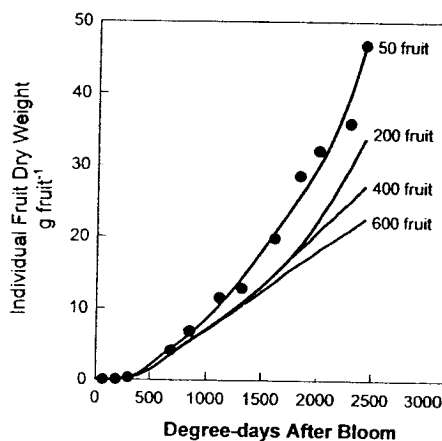

Figure 4. Simulated course of individual fruit dry weight for 'Halford.' Fruit dry weight (symbols) was measured over the course of the season on heavily-thinned trees. Growth potential curves were fitted to these data and used in the PEACH crop simulation model to simulate individual fruit growth at crop loads of 50, 200, 400 and 600 fruit (lines).
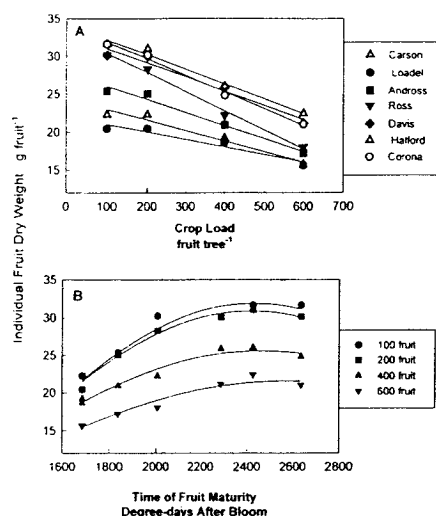
Figure 5. Modeled predictions of individual fruit dry weight at harvest for seven cultivars at crop loads of 100, 200, 400 and 600 fruit. In figure 5A, the dry weight predictions are plotted against crop load. In figure 5B the dry weight predictions are plotted against time of fruit maturity.

of yield over the range of represented ripening dates (Figure 7A). Fixing dry weight percentage at the median value between 'Loadel' and 'Corona' gave a slightly different predicted yield curve over the season compared to using a variable dry weight percentage (Figure 7A). At the earliest dates of fruit maturity (around 1700 degree-days after bloom) the predicted change in yield in response to date of harvest was 0.1 tons per degree-day. The average summer day in Winters, CA, accumulated ~18 degree days. Thus, during the early part of the season, a day's delay in the date of maturity increased the predicted yield potential by approximately 1.8 tons per hectare (Figure 7B). The relative yield advantage in delaying the date of fruit maturity declined rapidly over the following days until early August. After this point, delays in maturity had a minimal effect on predicted yield. The predicted decline in yield potential in late August was probably partially an artifact of the binomial curve fit, and partially due to changes in dry weight percent-

age (Figure 7) since later maturing fruit gain less fresh weight for each unit of dry weight.

Discussion

Dry weight growth potential increased by a factor of nearly two from July to September (Figure 2). This is in agreement with most horticultural situations, where a longer growth period translates into higher yields. The maximum dry fruit weight, in this experiment, was ~46 g and suggests that a maximum potential dry weight near this value may exist for peach. It is difficult to compare these values with previous studies because there has been very little research on peach dry weight growth or on heavily thinned trees. The value of 46 g is greater than that of ~41 g previously reported for the late maturing, melting-flesh, freestone peach cultivar 'Cal Red' (8, 11).

Deviation from the growth potential vs. time curves in Figure 2 may have important consequences for yield potential. For example, in 1996, 'Loadel' and 'Carson' had the same bloom date and harvest date, but fruit growth potential of 'Carson' was ~14 percent higher than that of 'Loadel.'
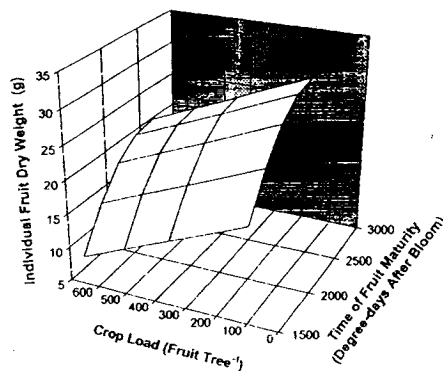

Figure 6. A regression of predicted dry weight vs. crop load and time of maturity yielded a significant effect of crop load and time of fruit maturity: $y = -0.02438x + 0.0706z - 0.000014z^2 - 49.95$, where y = predicted individual fruit dry weight, x = crop load and z = time of fruit maturity. This figure shows a surface plot of the predicted response over a range of crop loads and fruit maturity dates.
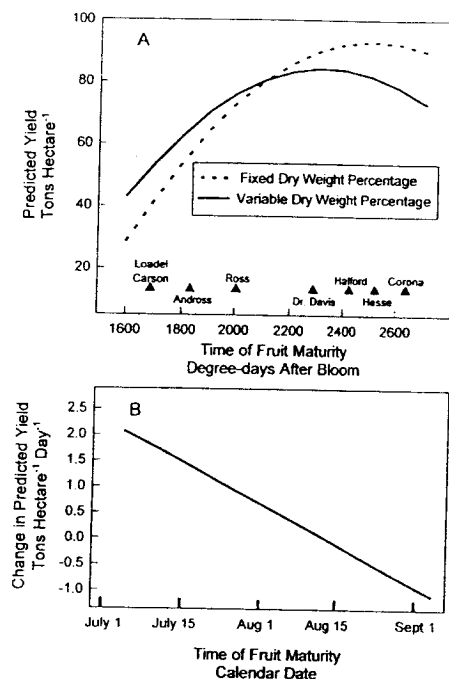
Figure 7. Plot A shows the predicted yield of 150 g (fresh weight) fruits vs. the time of fruit maturity. Predictions were made using the variable dry weight percentage observed in Figure 3 (solid line) and a fixed dry weight percentage at the median value (dotted line). Labeled symbols indicate the 1996 harvest date of each cultivar. Plot B depicts the change in yield predicted for extending the maturity date one day beyond the respective date on the X-axis. This line depicts the change in slope of the prediction line in plot A which was calculated using the variable dry weight percentage. The change in yield and the time scales have been converted into days by dividing the degree day date by 17.9, the average number of degree-days per day during the harvest period in Winters, CA, 1996.

As a result, the PEACH crop simulation model predicts higher yields for Carson at all crop loads (Figure 5a). Hesse had an unusually low fruit growth potential and is clearly below the other late varieties in its fruit growth capacity (Figure 2). A close examination of fruit growth potential and harvest date could help breeders to select cultivars with high fruit size and yield potential.

The results indicate that there are differences among cultivars in percent water content of fruit, with a general tendency for lower percent water content at later harvest dates. Small differences in dry weight percentage mean large differences in fresh weight because each g dry weight translates into 6-8 g of fresh weight. The importance of this ratio is demonstrated in Figure 7 by contrasting the curve generated using the median dry weight percentage with that of the variable dry weight percentage. Greater percent water content of fruits ripening in the early part of the season compensates for lower dry weight growth and increases fresh yield potential. Late season peaches appear to increase dry weight without proportional increases in water gain, resulting in less fresh yield per gram of dry weight. The differences in dry weight percentage may be related to the concentration of soluble solids (1).

The predicted yields in Figure 7 exceed industry averages for each cultivar by 30-100 percent. For example, we predicted a yield for 'Ross' of approximately 68 tons per hectare, while the industry average is about 48 tons per hectare. This discrepancy is to be expected, as the model predictions are an estimate of the theoretical production for a uniform crop where fruit set was not limiting. However, the range of theoretical yields is not unrealistic. In a thinning study on clingstone peach cultivars, yields of 56.7, 59.4, 69.3 and 80.7 tons per hectare were obtained, for the 'Loadel,' 'Carson,' 'Andross' and 'Ross' cultivars respectively (3).

It is important to note that the modeling work in this paper was conducted using tree growth and light interception parameters that were measured in a single orchard with no adjustment for cultivar. In other words, this work is based on the assumption that the canopy characteristics did not change with cultivar. We realize that this may not be a realistic assumption, but there is evidence from previous research in freestone peaches that trees with greatly differing times of fruit maturity differ very little in other aspects of physi-

ology, such as vegetative growth potential or photosynthesis (2, 8, 9).

It is also important to note that our theoretical yield estimates are not theoretical *maximum* yield estimates because they are based on actual tree growth, light interception and environmental data measured in the field. If the model had been run using optimal data for all these parameters theoretical yields would have been substantially higher than predicted in these experiments.

It is clear from practical experience that time to fruit maturity substantially affects the fruit size/crop yield relationship in peaches. This study represents the first attempt to use a computer model to quantify the theoretical limits of these relationships. Our results indicate that the fruit size/crop yield reductions related to shortening the time to maturity are based on physiological/developmental principles. Furthermore, reductions in potential yield as high as 1.8 tons per hectare for each day of earlier fruit maturity are predicted for cultivars with ripening dates prior to those of the existing early cultivars. Currently California processing peach growers are paid a small premium for early maturing fruit (about 10% more) but it is clear that this premium would have to be substantially greater in order to make ultra-early cultivars as profitable as existing mid-season cultivars.

Literature Cited

1. Crisosto, C. H., R. S. Johnson, J. G. Luza and G. M. Crisosto. 1994. Irrigation regimes affect soluble solids concentration and rate of water loss of 'O'Henry' peaches. HortScience 29:1169-1171.
2. DeJong, T. M., J. F. Doyle and K. R. Day. 1987. Seasonal patterns of reproductive and vegetative sink activity in early and late maturing peach *(Prunus persica)* cultivars. Physiol. Plant. 71: 83-88.
3. DeJong, T. M., H. Andris, R. Beede, K. Day, R. S. Johnson, W. Olson, D. Ramos, J. Yeager and F. Yoshikawa. 1993. Feasibility of increasing cling peach yields by early thinning. California Cling Peach Advisory Board Annual Research Reports.
4. DeJong, T. M., K. R. Day, J. F. Doyle and R.S. Johnson. 1995. The Kearney Agricultural Center perpendicular "V" (KAC-V) or-chard system for peaches and nectarines. Hort. Tech. 4:362-367.
5. DeJong, T. M. and Y. L. Grossman. 1995. Quantifying sink and source limitations on dry matter partitioning to fruit growth in peach trees. Physiol. Plant. 95:437-443.
6. DeJong, T. M., W. Tsuji, J. F. Doyle and Y. L. Grossman. 1998. Comparative economic efficiency of four peach production systems in California. HortScience (in press).
7. Grossman, Y. L. and T. M. DeJong. 1994. PEACH: A simulation model of reproductive and vegetative growth in peach trees. Tree Physiol. 14:329-345.
8. Grossman, Y. L. and T. M. DeJong. 1995a. Maximum fruit growth potential and seasonal patterns of resource dynamics during peach growth. Ann. Bot. 75:553-560.
9. Grossman, Y. L. and T. M. DeJong. 1995b. Maximum vegetative growth potential and seasonal patterns of resource dynamics during peach growth. Ann. Bot. 76:473-482.
10. Ho, L. C., R. I. Grange and A. F. Shaw. 1989. Source-sink regulation. In D. A. Baker and J. A. Milbourn (eds.). Transport of Photoassimilates. Longman Sci. and Tech. pp. 312-329.
11. Pavel E. W. and T. M. DeJong. 1993. Source-and sink-limited growth periods of developing peach fruits indicated by relative growth rate analysis. J. Amer. Soc. Hort. Sci. 188:820-824.
12. Wareing, P. F. and J. W. Patrick. 1975. Source-sink relations and the partitioning of assimilates in the plant. In J.P. Cooper (ed.). Photosynthesis and Productivity in Different Environments. Cambridge University Press, Cambridge, U.K. pp. 481-499.