

Training and Pruning System Effects on Vegetative Growth Potential, Light Interception, and Cropping Efficiency in Peach Trees

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ABSTRACT. Plant dry matter production is proportional to light interception, but fruit production does not always increase with increased light interception. Vegetative growth potential, the effect of cropping on vegetative growth, light interception and cropping efficiency of a clingstone peach [*Prunus persica* (L.) Batsch 'Ross' on 'Nemaguard' rootstock] were assessed in four production systems differing in tree density and training system. The four systems were a perpendicular V (KAC-V) system, a high-density perpendicular V (HiD KAC-V) system, a cordon system, and an open vase system. Vegetative growth potential, assessed on defruited trees, was higher in the cordon system and lower in the open vase system compared to the V systems. Cropping reduced leaf growth on the V and cordon systems and stem growth on the KAC-V and cordon systems. On a ground area basis, the HiD KAC-V system had the highest crop yields and the open vase system had the lowest. The cordon and HiD KAC-V systems intercepted more light and produced more fruit, stem, and leaf biomass than the open vase system. However, the modified harvest increment, the ratio of fruit dry mass to the sum of fruit, leaf, and stem dry mass, was lower in the cordon system than in the other systems. Thus, on this basis, the cordon system was the least efficient. On a trunk cross-sectional area basis, there were no significant differences in fruit production among any of the four training systems. For current year production, crop production per unit ground area is the best measure of economic efficiency. However, when planning the spacing, training and pruning of orchard trees, the most appropriate goal seems to be a system that increases light interception without increasing vegetative growth potential, such as the HiD KAC-V system.

In general, plant dry matter production is proportional to light interception (Monteith, 1977; Russell et al., 1989). Tree fruit production often increases with increased light interception (Barritt et al., 1991; Jackson, 1978; Lakso, 1994; Palmer, 1989; Robinson and Lakso, 1991; Wünsche et al., 1996), but this is not always the case (Jackson, 1980; Jackson and Palmer, 1972; Verheij and Verwer, 1973). Recently, there has been a trend toward high-density orchard systems to decrease the number of years required for the orchard to reach maximum light interception and full crop production (Jackson, 1985; Wagenmakers, 1991). High-density apple orchards on dwarfing rootstocks have been planted extensively in Europe and North America.

Peach differs from apple in that size-controlling rootstocks are not available for a variety of different orchard situations (Yoshikawa et al., 1989). Thus, under most situations, vegetative growth on peach trees is quite vigorous (DeJong et al., 1994; Miller and Walsh, 1988; Walsh, 1992). DeJong et al. (1998) describe several training and pruning systems that have been used in high-density peach orchard systems to restrain vigorous vegetative growth. One of these systems is a cordon system in which trees are pruned to two major scaffolds that are bent to a horizontal orientation and tied to a rope running down the tree row (Rogers, 1986). The fruit producing branches arise from these cordons. The objectives of this system are high early yields and elimination of ladders in the orchard. This training system results in substantial vegetative growth that requires extensive pruning (DeJong, et al., 1998). The perpendicular "V" (KAC-V) system is another widely used high-density system for peach (DeJong et al., 1994). In this system, each tree has two primary scaffolds oriented perpendicular to the tree

row. Summer pruning and topping are required to control vigorous growth, but the pruning is not as extensive as it is in the cordon system (DeJong et al., 1998). The most widely planted system in California is the low-density open vase system, with three to five primary scaffolds that branch to form a vase with an open center.

No experimental data are available on the effect of peach planting density and training system on vegetative growth potential, the amount of vegetative growth in the absence of competition with other plant organs for carbohydrates (Grossman and DeJong, 1995a, 1995b). Qualitative observations suggest that the vegetative growth potential of trees grown in the high-density systems, particularly the cordon system, is greater than the vegetative growth potential of trees grown in the low-density open vase system (DeJong et al., 1998). The objectives of this study were to compare the vegetative growth potential of peach trees in several different planting densities and training systems and to determine how much cropping reduces vegetative growth.

High-density plantings and some training systems increase light interception (Jackson, 1980, 1985; Palmer, 1988; Robinson et al., 1991; Robinson and Lakso, 1991; Wagenmakers, 1991). An additional objective of this study was to compare the daily and seasonal patterns of light interception in different tree density and training systems. The final objective was to evaluate cropping efficiency on ground area, trunk cross-sectional area, light interception, and harvest increment bases for the different tree density and training systems.

Methods

ORCHARD INFORMATION. Vegetative growth potential, crop yield, and light interception were determined in 1995 for 'Ross' cling peach trees on 'Nemaguard' rootstock planted in four different planting density and training systems. The trees were planted at the Kearney Agricultural Center, Parlier, Calif., in 1990. The research block consisted of 4 replicated plots of 0.80 ha. Each 0.20-ha

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subplot contained one of four training and planting systems. The four systems were a perpendicular V (KAC-V) system (trees spaced 2.0 m in the row, 5.5 m between rows, 6 rows per subplot, 919 trees/ha), a high-density perpendicular V (HiD KAC-V) system (trees spaced 1.8 m in the row, 4.6 m between rows, 7 rows per subplot, 1196 trees/ha), a cordon system (trees spaced 2.4 m in the row, 4.0 m between rows with 4.8 m perpendicular harvest drives spaced every 22 m down the row, 8 rows per subplot, 919 trees/ha), and a standard open vase system (trees spaced 6.1 m in the row and 5.5 m between rows, 6 rows per subplot, 299 trees/ha). Rows were oriented in a north-south direction.

The KAC-V trees were initially trained in early May of the first year by selecting two strong shoots with the proper orientation, eliminating all shoots arising above these shoots and lightly heading the shoots coming off the trunk below the selected shoots (DeJong et al., 1998). In August, the dominance of the previously selected shoots was reinforced by again heading or eliminating competing shoots and redirecting the growth of the selected scaffolds, as necessary, to maintain a proper orientation.

The cordon trees were trained to a horizontal rope at 1.2 m above the ground at the end of July of the first growing season (DeJong et al., 1998). The cordon trees were summer pruned after tying to eliminate vigorous shoots competing with the cordons.

During the first dormant pruning, three to five primary scaffolds were selected in the open vase trees (DeJong et al., 1998). These scaffolds were allowed to branch to produce six major scaffolds at 2 m above the ground.

All systems were dormant pruned and summer pruned. Trees were allowed to bear fruit in the second year (1991). All training systems were irrigated by periodic flooding. Irrigation was scheduled to maintain 100% replacement of evapotranspiration requirements. The row middles were mowed to control the volunteer weed cover. A 1-m-wide weed-free strip was maintained down the tree rows with combinations of contact and preemergence herbicides as deemed appropriate. Insects and diseases were controlled with pheromone confusion techniques and commercially used pesticides as needed.

For the 1995 growing season, the KAC-V and HiD KAC-V trees were pruned and thinned to leave about the same numbers of fruit per tree (≈ 480 fruit/tree), which resulted in $\approx 30\%$ more fruit/ha in the HiD KAC-V system than in the KAC-V system (DeJong et al., 1998). The cordon system was thinned with the objective of leaving the same number of fruit per hectare as the KAC-V. Fruit thinning in the open vase trees consisted of spacing fruit to 10 to 12 cm where possible. All thinning was carried out in late April. Additional details on the management of these trees during the first 5 years of growth may be found in DeJong et al. (1998).

VEGETATIVE GROWTH AND CROPPING. For the vegetative growth portion of this study, 24 dormant trees in each training system of one plot of the research block were selected for structural uniformity in March 1995. All selected trees were centrally located in each subplot. No border trees were used. Sixteen of these trees were defruited early in the growing season (5 Apr. 1995, 6 weeks after bloom). The remaining eight trees and all surrounding trees were cropped as previously described.

Shoot extension growth on defruited trees was destructively sampled at two times to determine if vegetative growth potential differed during the first and second half of the growing season. All current-year extension growth >5 cm was harvested from each of eight defruited trees per training system on 15–16 May (11 weeks after bloom) and the eight remaining defruited trees on 22–23 Aug. 1995 (26 weeks after bloom, 3 weeks after fruit harvest). This represented the majority of current-year growth, but left some

leaves on the trees at nodes where the shoot had extended <5 cm. Fresh mass of the harvested material was obtained for all trees. Leaves and stems from three trees were separated and weighed to estimate the proportion of fresh mass that was due to leaves and stems. In May, all stems and a subsample of leaves were dried at 55°C and used to convert fresh mass to dry mass. In August, subsamples of stems and leaves were dried. At the time of the vegetative growth harvest, trunk circumference was measured at 40 cm above the soil surface.

Vegetative growth potential was calculated on a ground area basis using the area assigned to each tree in the planting system. The vegetative absolute growth rate was calculated on a degree-day basis. Temperature data were obtained from the California Irrigation Management Information System (CIMIS) weather station located at the Kearney Agricultural Center. Degree-days were calculated using the single sine, horizontal cutoff method with critical temperatures of 7 and 35°C (DeJong and Goudriaan, 1989; Zalom et al., 1983). All data were analyzed on the basis of eight single tree replicates per training system per treatment. The effect of cropping on vegetative growth was determined after fruit harvest (22–23 Aug. 1995). Eight trees were destructively harvested as described above.

At commercial fruit maturity (2 Aug. 1995, 23 weeks after bloom), all fruit were harvested from each of the eight cropped trees, counted, and weighed. Subsamples of 20 fruit each were collected from four trees in each training system, dried to a constant mass at 55°C , and used to convert fruit fresh mass to dry mass.

PATTERNS OF LIGHT INTERCEPTION. For the light interception portion of the study, measurements were taken in the three plots of the research block that were not manipulated for the vegetative growth portion of the study. Intercepted photosynthetic photon flux density (PPFD) was determined using an Accupar Linear PAR Ceptometer (Decagon Devices, Inc., Pullman, Wash.). Measurements were made ≈ 0.3 m above the soil surface. In each subplot, data were taken on a grid of ≈ 100 points ≈ 0.5 m apart across the tractor row and 1 to 1.5 m apart down the row. Each grid was located in the center portion of the subplot and did not include border trees. Incident PPFD readings were taken in the open away from the trees. Light measurements were made at 2-h intervals every 3 to 4 weeks from April through June and again in August. On some dates, clouds made light measurement in the afternoon impossible. On some occasions, data from two consecutive days were combined. The average light interception for each grid at each time point was used in the analysis.

STATISTICS. SAS software (SAS Institute, Cary, N.C.) was used for all analyses of variance to test for differences among training systems and between defruited and cropping treatments. Multiple means separations were carried out using Tukey's multiple range test.

Results

VEGETATIVE GROWTH POTENTIAL ON DEFRUITED TREES. On defruited trees, leaf and stem dry mass per unit allotted ground area increased significantly from May to August in all training systems ($P < 0.0001$, Fig. 1). Stem mass increased much more (6.6- to 9.4-fold) than did leaf mass (2.5- to 2.8-fold). The cordon system had the highest leaf and stem mass and the open vase system had the lowest ($P < 0.0001$, Fig. 1). In May, leaf mass significantly exceeded stem mass in all training systems ($P < 0.0001$). In August, leaf mass significantly exceeded stem mass in the KAC-V, HiD KAC-V and open vase training systems ($P < 0.01$), however stem mass significantly exceeded leaf mass in the cordon system ($P < 0.05$).

On defruited trees, leaf absolute growth rates were higher from

bloom to May than from May to August ($P < 0.01$, Fig. 2). In contrast, stem absolute growth rates were higher from May to August than from bloom to May ($P < 0.0001$, Fig. 2). In the cordon system, the May to August leaf plus stem absolute growth rate significantly exceeded the bloom to May rate ($P < 0.05$). No differences between growth periods were detected in the KAC-V,

HiD KAC-V and open vase systems. The cordon system had the highest leaf and stem absolute growth rates and the open vase system had the lowest rates ($P < 0.0001$).

VEGETATIVE GROWTH ON CROPPING TREES. Leaf and stem mass per unit allotted ground area on cropping trees in August was highest in the cordon system and lowest in the open vase system (P

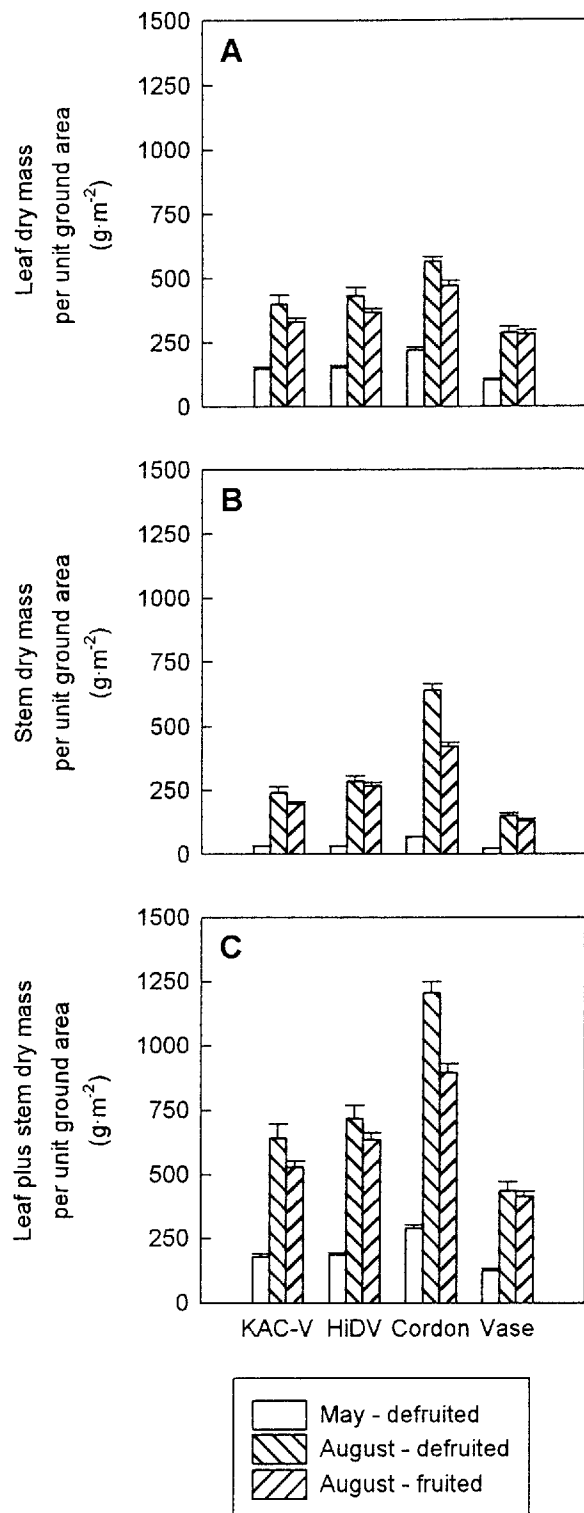


Fig. 1. Leaf (A), stem (B), and leaf plus stem (C) dry mass per unit allotted ground area for defruited trees in May and August and fruited trees in August for the KAC-V, HiD KAC-V, cordon, and open vase systems. Error bars represent one standard error of the mean.

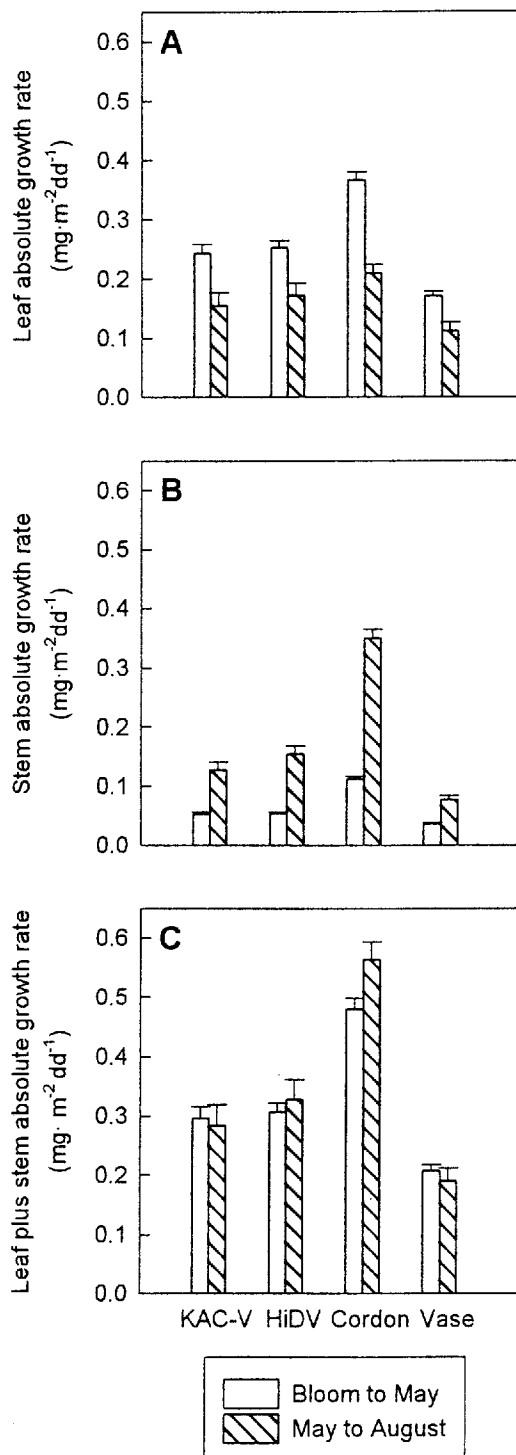


Fig. 2. Leaf (A), stem (B), and leaf plus stem (C) absolute growth rates (mass per unit allotted ground area per degree-day) for defruited trees from bloom to May and May to August for the KAC-V, HiD KAC-V, cordon, and open vase systems. Error bars represent one standard error of the mean.

Table 1. Training system, planting density, tree spacing, and crop yield (mean and standard error) for four planting and training systems in the sixth year after planting.

| Training system | Density (trees/ha) | Spacing (m) | Crop yield ² (t·ha ⁻¹) |
|-----------------|--------------------|-------------|---|
| KAC-V | 919 | 2.0 × 5.5 | 56.5 (3.4) b |
| HiD KAC-V | 1196 | 1.8 × 4.6 | 75.5 (4.0) a |
| Cordon | 919 | 2.4 × 4.0 | 53.7 (3.8) bc |
| Open vase | 299 | 6.1 × 5.5 | 41.2 (1.4) c |

²Mean separation by Tukey's multiple range test, $P < 0.05$.

< 0.0001 , Fig. 1). Leaf mass significantly exceeded stem mass in the KAC-V, HiD KAC-V, and open vase training systems ($P < 0.0001$). There was no significant difference between leaf and stem mass in the cordon system.

Leaf mass in August was significantly lower on cropping trees than on defruited trees in all training systems except open vase ($P < 0.05$, Fig. 1A). Stem mass in August was significantly lower on cropping trees than on defruited trees in the KAC-V and cordon training systems ($P < 0.05$, Fig. 1B). No significant differences in stem mass on defruited and cropping trees were detected in the HiD KAC-V and open vase systems.

The sum of leaf and stem mass on cropping trees differed among the four training systems ($P < 0.0001$, Fig. 1C). The cordon system produced the largest amount of leaf plus stem biomass, followed by HiD KAC-V, KAC-V and open vase.

CROP PRODUCTIVITY. The HiD KAC-V system produced the highest crop yield ($P < 0.0001$, Table 1). The fruit dry mass per unit allotted ground area was highest in the HiD KAC-V system and lowest in the open vase system ($P < 0.0001$, Fig. 3A). At harvest, individual fruit dry mass in the KAC-V and open vase systems was significantly higher than in the HiD KAC-V and cordon systems ($P < 0.0001$, Fig. 3B). The fruit number per unit allotted ground area was higher in the HiD KAC-V and cordon systems than in the KAC-V and open vase systems ($P < 0.0001$, Fig. 3C). Fruit dry mass did not differ among the training systems when it was estimated on a trunk cross-sectional area basis (Fig. 4).

A modified harvest increment was calculated as the ratio of the crop mass to the sum of fruit, leaf, and stem mass (Fig. 5). The HiD KAC-V, KAC-V, and open vase systems partitioned 57% to 60% of this dry matter to fruit. The cordon system partitioned a significantly lower amount of dry matter to fruit (49%, $P < 0.0001$).

LIGHT INTERCEPTION BY DIFFERENT DENSITY/TRAINING SYSTEMS. The photosynthetic photon flux density (PPFD) was higher at midday than in the morning or evening (Fig. 6). The intercepted PPFD curve was substantially flatter than the incident PPFD curve for all training systems. Values were lower in the early morning and late evening and higher at midday. The amount of intercepted light increased as the season progressed. The percent incident PPFD that was intercepted by the tree canopy was lowest at midday and highest in the morning and evening.

On all dates when measurements were made, the cordon and HiD KAC-V systems intercepted significantly more light than the open vase system ($P < 0.001$). The HiD KAC-V system intercepted more light than KAC-V system in April, May and June ($P < 0.001$), but not in August.

Discussion

COMPARISON OF VEGETATIVE GROWTH POTENTIAL ON DIFFERENT PLANTING DENSITY AND TRAINING SYSTEMS. Vegetative growth on defruited trees can be used to estimate vegetative growth potential

because competition with fruit growth has been eliminated (Grossman and DeJong, 1995b). Crop production reduced leaf growth in all training systems except the open vase system and stem growth in the KAC-V and cordon systems (Fig. 1). This suggests that competition between vegetative and fruit growth resulted in a source limitation on vegetative growth some time between bloom and August. Source limitations on leaf growth were detected on the cordon, HiD KAC-V, and KAC-V trees. Source limitations on stem growth were detected on the cordon and KAC-V trees. Competition between vegetative and reproductive growth has also been detected in other studies on apple (Avery, 1969, 1970; Heim et al., 1979; Maggs, 1963; Quinlan and Preston,

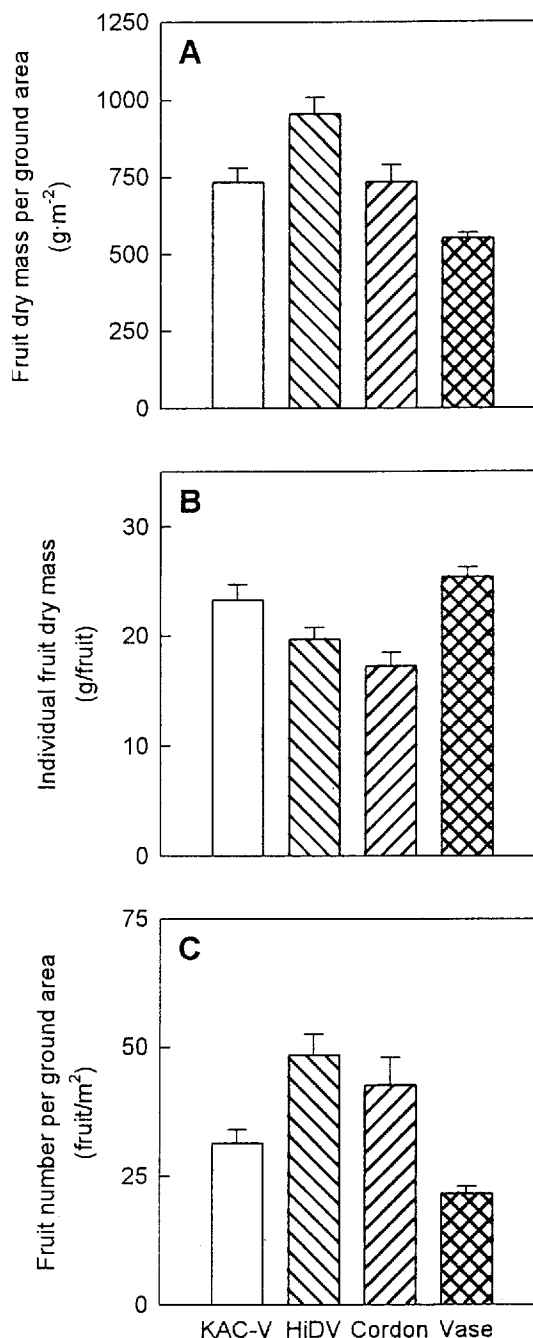


Fig. 3. Fruit dry mass per unit ground area (A), individual fruit dry mass (B), and fruit number per unit ground area (C) at harvest for fruited trees in the KAC-V, HiD KAC-V, cordon, and open vase systems. Error bars represent one standard error of the mean.

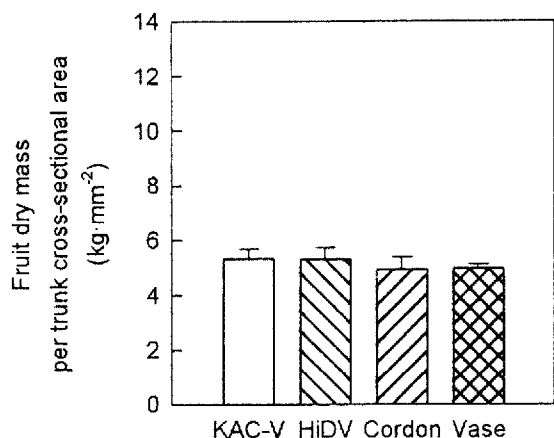


Fig. 4. Fruit dry mass per unit trunk cross-sectional area at harvest for fruited trees in the KAC-V, HiD KAC-V, cordon, and open vase systems. Error bars represent one standard error of the mean.

1971), cherry (Kappel, 1991), peach (Grossman and DeJong, 1995b; Miller and Walsh 1988, Proebsting, 1958), birch (Tuomi et al., 1982), and red raspberry (Waister and Wright, 1989).

The cordon system had the highest vegetative growth potential, followed by the two KAC-V systems, and the open vase system, respectively (Fig. 1). Leaf and stem mass in the cordon system were greater than the V systems, although stem mass was proportionally greater than leaf mass. The higher vegetative potential of the cordon system trees resulted from high leaf and stem absolute growth rates, which exceeded V system growth rates in the spring and summer growth periods (Fig. 2). In the cordon system, partitioning to leaves and stems together occurred at a higher rate from May to August than from bloom to May (Fig. 2C). In contrast, in the other systems, partitioning to leaves plus stems occurred at the same rate during both periods. Partitioning to trunk growth on defruited central leader trees of early and late maturing peach cultivars was also reported to be constant through the growing season (Grossman and DeJong, 1995b). Marcelis (1992) reported a different temporal pattern for cucumber in which dry matter partitioning alternated between fruit and vegetative growth.

The higher vegetative growth of the cordon system trees was characterized by vigorous upright shoots on the upper side of the horizontal cordons (DeJong et al., 1998). This is consistent with data reported for the peach cultivar 'Golden Queen' indicating that shoots arising from the basal portion of near-horizontal branches were significantly longer than similar shoots on more vertical branches (Dann et al., 1990).

Trees in the KAC-V and HiD KAC-V systems had similar vegetative growth potentials that were lower than the vegetative growth potential of the cordon system trees. Chalmers et al. (1981) reported reduced vegetative growth on cropping 'Golden Queen' peach trees when they were grown at more than twice the density of the HiD KAC-V trees.

The lower vegetative growth potential on a ground area basis of the open vase system probably resulted from the fact that the dripline circumference was substantially smaller than the ground area "assigned" to each tree at this density. That is, the ground area used in the calculation of vegetative growth potential was larger than the ground area being "used" by each tree. On a trunk cross-sectional area basis, open vase vegetative growth potential did not differ from the KAC-V systems, but it was significantly less than cordon vegetative growth potential ($P < 0.0001$, data not shown).

CROP PRODUCTION. Crop fresh and dry mass on a ground area basis was highest on the HiD KAC-V system and lowest on the

open vase system (Table 1, Fig. 3A). Similar results were obtained in 1992-1994 when the crop was harvested in two or three picks (DeJong et al., 1998). The high fruit number per ground area in the HiD KAC-V system resulted from the pruning and thinning goals (Fig. 3C). The inverse relationship between fruit number and individual fruit mass that is generally observed for fruit trees was apparent for all systems (Fig. 3 B and C; Cain and Mehlenbacher, 1956; DeJong and Grossman, 1995). The low fruit number and fruit dry mass per ground area on the open vase system again resulted from the fact that the dripline circumference of each tree was smaller than the area assigned to the each tree within the planting system.

COMPARISON OF DAILY AND SEASONAL PATTERNS OF LIGHT INTERCEPTION ON THE DIFFERENT DENSITY AND TRAINING SYSTEMS. The intercepted photosynthetic photon flux density (PPFD) was relatively constant from ≈ 0900 to 1500 for all training systems (Fig. 6). The HiD KAC-V and cordon systems, the highest density and most horizontal-canopied systems, respectively, intercepted more light than the KAC-V and open vase systems. Apple trees trained to the Y-trellis system, a system that has arms that grow over the tractor row, intercepted more PPFD than apple trees trained in pyramidal shapes (Robinson and Lakso, 1991). Even in the systems that intercepted the most light, nearly 50% of available PPFD reached the orchard floor at midday. This contrasts greatly with herbaceous crop systems in which nearly all light is intercepted after canopy closure (Acock, 1991; Loomis and Connor, 1992).

The cordon and HiD KAC-V systems intercepted more light and produced more fruit, stem, and leaf biomass than the open vase system (Figs. 1, 3, and 6). This result is consistent with the general observation that biomass production is proportional to light interception (Monteith, 1977; Russell et al., 1989).

CROPPING EFFICIENCY. Cropping efficiency may be assessed on the basis of crop yield per unit ground area, crop yield per unit trunk cross-sectional area, light interception, or harvest index. For current year production, crop production per unit ground area is the best measure of economic efficiency. On this basis, the HiD KAC-V system would be judged the most efficient (Fig. 3A). Alternatively, yield comparisons are often made on the basis of trunk cross-sectional area. For example, Chalmers and van den Ende (1975) used this parameter to examine the effects of tree size and age on peach production, finding that fruit production increased with trunk circumference. On this basis, there were no significant differences in fruit production among any of the four training systems (Fig. 4).

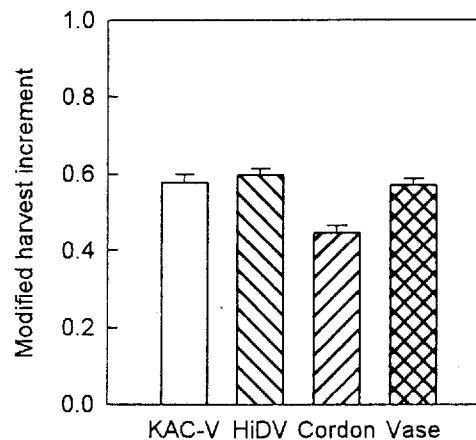


Fig. 5. Modified harvest increment (ratio of the crop mass to the sum of crop, leaf, and current year stem mass) for fruited trees in the KAC-V, HiD KAC-V, cordon, and open vase systems. Error bars represent one standard error of the mean.

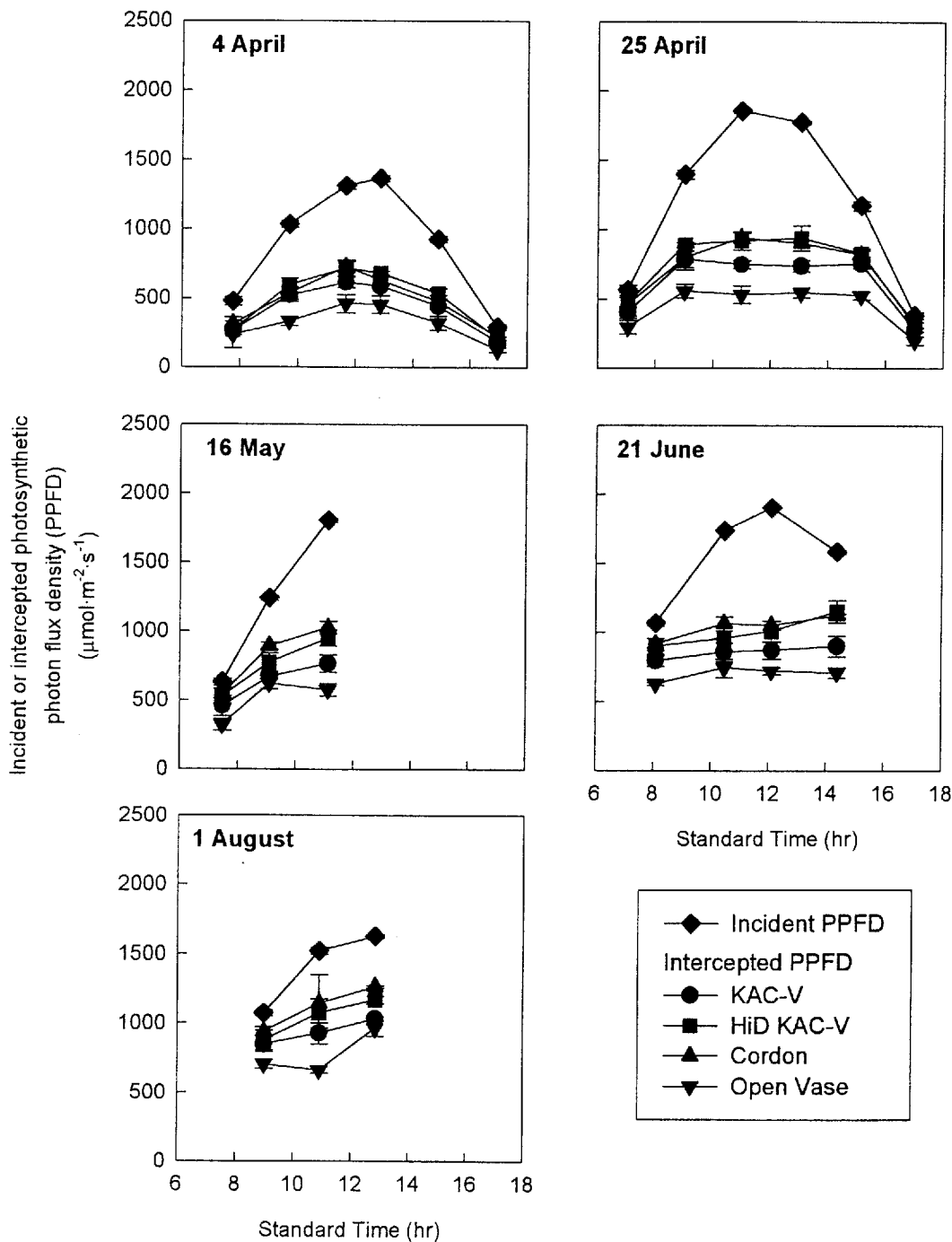


Fig. 6. Daily patterns of incident and intercepted photosynthetic photon flux density (PPFD) on 4 Apr., 25 Apr., 16 May, 21 June, and 1 Aug. 1995 for fruited trees in the KAC-V, HiD KAC-V, cordon, and open vase systems. Error bars represent one standard error of the mean.

When planning the spacing, training and pruning of orchard trees, the relationship between light interception and biomass production suggests that increasing light interception should be a major goal (Monteith, 1977; Russell et al., 1989). The cordon and HiD KAC-V systems intercepted the highest amounts of light through the growing season (Fig. 6). Thus, on light interception grounds, these two systems would be preferred. However, the modified harvest increment, the ratio of fruit dry mass to the sum of fruit, leaf, and stem dry mass, was lower for the cordon than for the other systems (Fig. 5). This indicates that the cordon system partitioned a lower proportion of biomass to the crop than the other

systems. The extensive pruning and scaffold orientation of these trees appear to have increased vegetative growth. The resulting competition appears to have reduced the resources available for fruit growth, and therefore crop production. Thus, high light interception and biomass production did not necessarily result in high crop production. The high leaf and stem growth potentials on cordon trees (Fig. 1) appear to have been responsible for the low harvest increment.

The four systems analyzed in this study were planted at different densities. The highest density system, HiD KAC-V, had high light interception (Fig. 6) and an average harvest increment (Fig. 5), resulting in the highest crop yield per ground area (Table 1, Fig. 3A). The high tree density did not reduce the vegetative vigor on the HiD KAC-V trees (Fig. 1). Both intermediate density systems, cordon and KAC-V, had moderate crop yields per unit ground area. The cordon yield resulted from high light interception and a low harvest increment, whereas the KAC-V yield resulted from moderate light interception and an average harvest increment.

The best goal for a high-production orchard system seems to be a system that increases light interception while decreasing or at least not increasing vegetative growth potential.

Development of a vegetative growth controlling rootstock might be one way to accomplish this goal. The HiD KAC-V system appears to best satisfy this goal on currently available rootstocks. This conclusion is supported by an analysis of the economic efficiency of the four density and training systems analyzed in this study (DeJong et al., 1998). The economic analysis indicated that the cumulative gross profits (returns before land, chemical, and equipment costs were considered) over the first 5 years from planting in the HiD KAC-V and KAC-V systems were similar. Although the HiD KAC-V system produced higher yields than the KAC-V system, the cost to establish the higher density orchard offset this difference. The cordon and open vase systems were the least economically efficient. The low economic efficiency of the cordon system was due to moderate yields and high pruning costs. The low efficiency of the open vase system was due to low yields.

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