

Canopy Development, Yield, and Fruit Quality of 'Empire' and 'Delicious' Apple Trees Grown in Four Orchard Production Systems for Ten Years

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Abstract. A field planting of 'Empire' and 'Redchief Delicious' apple trees (*Malus domestics* Borkh.) was established in 1978 to evaluate four planting systems: 1) slender spindle/M.9, 2) Y-trellis/M.26, 3) central leader/M.9/MM.111, and 4) central leader/M.7a. During the first 5 years, yields per hectare for 'Empire' were positively correlated with tree density. In the second 5 years, the Y-trellis/M.26 trees produced the highest yields while yields of the other systems continued to be related to tree density. Cumulative yields were highest with the Y-trellis/M.26 trees. With 'Delicious', the Y-trellis/M.26 yields were greatest during all 10 years despite lower tree density than the slender spindle/M.9. Yields of 'Delicious' with the other three systems were a function of tree density during the 10 years. At maturity, canopy volume per tree was greatest on the central leader/M.7a trees and smallest on the slender spindle/M.9 trees; however, there were no significant differences in canopy volume per hectare between the systems despite large differences in yield. Trunk cross sectional area (TCA) per hectare was greatest with the Y-trellis/M.26 trees and smallest with the central leader/M.7 trees. Yield was highly correlated to TCA/ha. Yield efficiency with 'Empire' was greatest for the slender spindle/M.9 system, followed by the Y-trellis/M.26, central leader/M.9/MM.111, respectively. With both cultivars, the central leader/M.7a system had the lowest yield efficiency. With 'Delicious', there were no differences in yield efficiency for the other three systems. The greater yield of the Y-trellis/M.26 system was the result of greater TCA/ha and not greater efficiency. 'Empire' fruit size was largest on the central leader/M.7a and the central leader/M.9/MM.111 trees and smallest on the slender spindle/M.9 and the Y-trellis/M.26 trees. With 'Delicious', fruit size was larger with the Y-trellis/M.26 trees than the other systems. When fruit size was adjusted for crop density, there were no significant differences due to system with 'Empire', but with 'Delicious' the Y-trellis/M.26 trees had larger adjusted fruit size than the other systems. Crop density calculated using TCA correlated better to fruit size than did crop density calculated using annual increase in TCA, canopy volume, or land area. Fruit color and quality with 'Redchief Delicious' were not influenced by system. With 'Empire', average fruit color and soluble solids content were lower for the Y-trellis/M.26 and slender spindle/M.9 in some years when canopy density was allowed to become excessive.

The need to improve orchard productivity and profitability has led to a worldwide interest in new orchard planting systems (Jackson, 1978, 1981, 1986; Jackson and Palmer, 1989). Work on this topic has produced several important concepts regarding orchard system productivity and profitability. First, preplant decisions of scion and rootstock cultivars, as well as spacing and arrangement of trees, limit the choice of system and thus are extremely important. Second, preplant decisions of tree number/ha and tree support establish the level of capital investment that must be recovered. Higher capital investments require proportionately higher productivity in the first years of orchard life to achieve similar break-even times.

Once an orchard system is established, its productivity and profitability depend on yield and fruit quality (i.e., fruit value) and costs of management and harvest. The horticultural and economic merits of orchard production systems must be evaluated over at least a significant part of the lifetime of the orchard to give sound recommendations to fruit growers. However, long-term comparative field plantings of orchard systems have been few due to the expense and time commitment required. From the wide range of comparisons made over the last 30 years, it is apparent that no one system is optimum for all scion/rootstock combinations, economic situations, or climates (Barritt, 1987).

Trials therefore must be conducted within each type of cultivar and climate until the underlying principles governing orchard systems behavior are elucidated.

In this paper we present data from a replicated field experiment at Geneva, N.Y., comparing two scion cultivars and four production systems. An orchard production system is defined as the combination of rootstock, tree spacing, and training/pruning regime.

Materials and Methods

In 1978 a 1.8-ha field trial was planted on a Honeoye fine sandy loam soil, (glossoboric, Hapludalf, fine-loam, mixed, mesic) with a 3% east slope. The plot was fumigated in Aug. 1977 with 187 liter of methyl isothiocyanate (Vorlex)/ha. The plot had previously been planted to grapevines for 10 years. No preplant fertilizer or lime was applied.

The trees were planted on 15 May 1978 in four-row plots with a north-south row orientation. Each four-row plot was replicated twice with the two center rows of each plot serving as test rows and the outside rows serving as guard rows. Rows were 43 m long with tree numbers ranging from 28 to 10 trees per row, depending on the planting density of the various systems.

Within each year, all systems of each cultivar received the same rate of N fertilizer per hectare. The trees were fertilized with $\text{Ca}(\text{NO}_3)_2$ in the first growing season, with a 12N-12P-12K fertilizer in years 2-6 and with ammonium nitrate used in years 7-10. Rates of N fertilization (determined from leaf nutrient levels) ranged from 20 to 60 $\text{kg}\cdot\text{ha}^{-1}$ for 'Empire' and

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from 40 to 80 kg·ha⁻¹ for 'Delicious'. In years 7–10 the plots also received (kg·ha⁻¹) 60 K, 37 Mg, and 74 S as potassium-magnesium sulfate (Sulpomag). A band one-third of the row width under the trees was maintained weed free by annual applications of herbicides followed by spot treatments during the summer.

The orchard production systems were: 1) slender spindle/M.9, 2) Y-trellis/M.26, 3) central leader/M.9/MM.111, and 4) central leader/M.7a with 'Empire' and 'Delicious' as test cultivars (Table 1).

Slender spindle/M. 9 (SS/M. 9). This system used the M.9 rootstock "with a wooden post at each tree for support (Table 1). The trees were trained as slender spindles with a central leader and only one permanent tier of four to five scaffold branches (Wertheim, 1968). The leader was headed on both cultivars after planting, but the leader was weakened in years 3–6 by leader replacement on the 'Empire' trees. With the 'Delicious' trees, the leader was stimulated by heading until tree height reached 2 m. Only small, temporary fruiting branches were allowed to develop above the bottom tier of scaffold branches. Limbs were tied down or spread in the second and third seasons after they began to develop. After the 5th year, trees were contained in their space by removing the larger limbs in the top of the tree and by cutting lower scaffold branches back to weak side branches. The larger pruning cuts were made in the dormant season. Summer pruning was begun in the 6th year and consisted of removing unwanted upright shoots and cutting some fruiting branches in the top of the tree back to the first apple. The mature tree height was 2.2 m.

Y-trellis/M.26 (Y/M.26) This system used the M.26 rootstock and a 2.2-m-tall, Y-shaped trellis to support the trees and to divide them into two single-plane canopies, each at 60° above the horizontal. Trees were headed at planting at 75 cm and were trained in the 3rd year by selecting 8 to 10 branches on the trunk at a height of 60 cm and positioning one-half of the branches on each side of the Y-trellis. The branches were equally spaced along the wires between trees, giving a fan-shaped arrangement of branches. Additional branches that developed were tied to the wires and were maintained until the end of the 7th year, when the canopy was thinned by removing overlapping branches. In the last 3 years, the canopy was kept to a single layer (≈30 cm) by removing overgrowing branches and by renewing branches where a new replacement shoot arose. All pruning in the first 6 years was done in the dormant season but the limb positioning was performed in spring and summer. In the last 4 years, the trees were also summer-pruned by removing upright shoot growth from the center of the Y. Tree height was limited to 2.5 m.

Central leader/M. 9/MM.111 (CL/9/111) This system used an M.9 interstem (20 cm) and an MM.111 understock with no tree support (Table 1). The lower graft union was buried so that only the upper half of the M.9 interstem was exposed. Trees were trained as central leaders with annual heading of the leader and lower tier scaffolds (Heinicke, 1975). Two permanent tiers of

scaffold branches were developed, spaced 1 m apart, with four to five branches per tier. Limb spreading was done in the 3rd and 5th year for both cultivars and again in the 7th year for 'Delicious'. Scaffold branches between the first and second tiers were removed between the 5th and 6th years. All pruning was done in the dormant season until the 7th year, when summer pruning of unwanted watersprouts was begun. The mature tree height was 3 m for both cultivars.

Central leader/M.7a (CL/M.7) This system had the lowest tree densities (Table 1) and used the M.7a rootstock. Trees were trained as freestanding central leaders by heading the leader and the lower scaffold branches annually until they filled their allotted space (Heinicke, 1975). Limbs were spread twice; first with 30-cm spreaders in the 3rd year and then with 1-m spreaders in the 5th year for both cultivars and again in the 7th year for 'Delicious'. Mature trees had three tiers of scaffold branches spaced 1 m apart with four to five branches per tier. Scaffold limbs between the first and second tiers were not removed until the 6th or 7th year. Trees were pruned in the dormant season only in the first 6 years and thereafter were also pruned in the summer. Whole limb removal and heading cuts were made in the dormant season and summer pruning consisted only of removing upright watersprouts. The mature tree height was 4.5 m for the 'Empire' trees and 3.7 m for the 'Delicious' trees.

Data collection and analysis. All trees were de fruited in the first 2 years. All trees received similar applications of chemical thinners in years 5–10. Yields were recorded each year. Fruit number, size, and color were measured in years 7–10 on a 100-apple random sample from each test row. Fruit redness was evaluated visually by estimating the sum of the percentage of the skin surface with "good" red color plus one-half the percentage of the skin surface with "compensating" red color (U.S. Dept. of Agriculture, 1976). Fruit firmness, soluble solids concentration (SSC), and titratable acidity were measured on a 20-apple subsample each year after 2 to 3 months of storage. Firmness was measured with an Effegi penetrometer (11. 1-mm-diameter probe; Effegi, Alfonsine, Italy); SSC was measured with an Atago refractometer (Atago, Japan) using juice from the whole apple; total acidity was measured on a 10-ml sample of juice titrated to pH 7.5.

Canopy height from the lowest scaffold branch, canopy width, and trunk circumference (30 cm above ground) were measured in years 7–10. Canopy volume was calculated by assuming central leader and slender spindle trees to be represented by cylinders capped with cones, with height of the cone equal to the radius of the cylinder. Radius of the cylinder was calculated as the average of one-half the in-row tree width and one-half the between-row tree width. Height of the cylinder was calculated as the canopy height minus the radius of the tree. The volume of the Y/M.26 trees was calculated as the volume of two rectangular-shaped trellis arms that were measured to be 50 cm thick. The length and height of each arm on each tree were measured.

Table 1. Apple orchard management systems studied, 1978–1987.

System	Rootstock/interstock	Empire		Delicious	
		Spacing (m)	Trees/ha	Spacing (m)	Trees/ha
Slender spindle	M.9	1.5 × 3.4	1957	1.8 × 3.7	1495
Y-trellis	M.26	2.1 × 3.7	1283	2.4 × 4.3	961
Interstems	MM.111/M.9	2.4 × 4.3	961	3.0 × 5.5	598
Central leader	M.7a	3.7 × 6.1	450	4.3 × 6.7	348

The experiment was a 2×4 factorial of cultivar and production system in a randomized complete-block design with two replications and two subsamples. Data were collected for each subsample row in each whole plot. The data were analyzed with years as repeated measures. If the variance due to whole plots was not statistically different from the variance due to subsamples, the two variances were combined and used as the error term in the analysis of variance to test significance of treatment effects. The variances due to subsamples and whole plot were combined for all dependent variables except crop density. Regression analysis was performed with fruit size and crop density using data from all 4 years. Analysis of covariance was performed on the residuals to determine the effect of treatment independent of the crop density effect. Fruit firmness was covaried with fruit size, but the effect of size on firmness was not significant; therefore, unadjusted fruit firmness values are presented.

Results

Trunk and canopy development. Trunk cross-sectional area (TCA) per tree of 'Empire' was larger than for 'Delicious' (Table 2). Among management systems, TCA per tree was largest for the CL/M.7 trees of each cultivar followed by the Y/M.26 trees, CL/9/111 and SS/M.9 trees, respectively. There was no interaction of cultivar and systems on TCA. When TCA per hectare was calculated, the Y/M.26 system was the largest, followed by the SS/M.9, CL/9/111, and the CL/M.7, respectively. There was a significant cultivar \times system interaction in TCA per hectare caused by the CL/9/111 trees. With 'Empire', the CL/9/111 had a relatively large TCA per hectare, while with 'Delicious', the CL/9/111 trees had the lowest TCA per hectare. The large TCA per hectare of the Y/M.26 system resulted from the combination of relatively high tree density and the second largest TCA per tree. TCA per hectare of the Y/M.26 system was more than double that of the CL/M.7 system for both cultivars.

-Canopy, volume per tree showed a similar pattern to TCA per tree with the 'Empire' trees having significantly larger canopy

volume than the 'Delicious' trees. Among systems, the CL/M.7 trees had the largest canopy volume and the SS/M.9 trees the smallest (Table 2). However, the Y/M.26 trees had smaller canopy volumes than did the CL/9/111 trees while the reverse was true for TCA. This was likely due to the method of estimating canopy volume and the geometric restriction imposed on the Y/M.26 system that resulted in all the canopy of the tree being confined to the planar arms of the Y.

Canopy volume per hectare was significantly greater for 'Empire' than 'Delicious'; however, within each cultivar, there were no significant differences due to system at the end of 10 years. In early years, CL/M.7 had significantly lower total canopy volume per hectare than the other three systems (data not presented). The SS/M.9 system had filled its allotted space by the end of the 8th year for 'Empire' and by the end of the 9th year for 'Delicious' and was subsequently contained to that space by pruning. In contrast, the CL/M.7 system continued to expand through the 10th year. Canopy volume increased sharply on the CL/M.7 trees between 1984 and 1985 due to a heavy 1985 crop that spread the scaffold limbs in these large trees.

Yields per tree. There were significant yield differences between cultivars in all years and between systems in all years but the 5th. There was a significant cultivar \times system interaction in all years except 6, 8, and 9 (Fig. 1 A, B). 'Empire' generally produced 1.5 to 2 times more yield per tree than 'Delicious' under all four systems. In the early years, the ratio of 'Empire' to 'Delicious' yields was $>10:1$. As 'Delicious' began to crop more heavily, the ratio decreased to ≈ 1.5 to 1. In years 4 and 5, a ratio close to 1 was obtained with the Y/M.26 trees, suggesting this system is favorable for early cropping of young 'Delicious' trees. In years 5-10, the ratio within each system remained between 1.5 and 2, which reflects the smaller TCA and tree size of 'Delicious'. Cumulative yield for 'Empire' was 1.8 times that of 'Delicious' (Table 2).

With 'Empire' during the first 5 years, the highest yields were obtained with the SS/M.9 and Y/M.26 systems in years 3 and 4, but in year 5 the CL/M.7 trees had the highest yield per tree. With 'Delicious', yields were highest with the Y/M.26 trees

Table 2. Trunk cross-sectional area (TCA), canopy volume, and yield of 'Empire' and 'Redchief Delicious' apple trees under four management systems for 10 years.

Cultivar	System	Final TCA		Final canopy vol.		Cumulative yield	
		(cm ² /tree)	(m ² ·ha ⁻¹)	(m ³ /tree)	(1000 m ³ ·ha ⁻¹)	(kg/tree)	(t·ha ⁻¹)
Empire		52.4	5.10	7.1	6.12	161	174
Delicious		36.5	2.61	5.0	3.19	87	71
LSD _{0.05} ^z		5.7			0.71	17	
	Slender Sp./M.9	21.6	3.78	2.6	4.53	81	144
	Y-trellis/M.26	50.1	5.79	3.8	4.43	170	198
	C.L./M.9/MM.111	37.3	3.05	6.2	4.94	111	92
	C.L./M.7a	68.7	2.80	11.6	4.73	134	56
	LSD _{0.05} ^z	8.0			1.00	25	
Empire	Slender Sp./M.9	24.0	4.70	2.8	5.47	104	203
	Y-trellis/M.26	60.4	7.75	4.8	6.15	214	275
	C.L./M.9/MM.111	44.5	4.30	6.9	6.67	141	135
	C.L./M.7a	80.7	3.63	13.8	6.20	184	83
Delicious	Slender Sp./M.9	19.1	2.85	2.4	3.59	58	86
	Y-trellis/M.26	39.7	3.82	2.8	2.70	126	122
	C.L./M.9/MM.111	30.0	1.80	5.4	3.21	82	49
	C.L./M.7a	56.7	1.97	9.4	3.25	84	29
LSD _{0.05} ^z			0.97	2.0			33

^zWherever main effect LSD values are not presented, the cultivar \times system interaction was significant at $P = 0.05$. $n = 16$ for cultivar means; $n = 8$ for system means; $n = 4$ for cultivar \times system means.

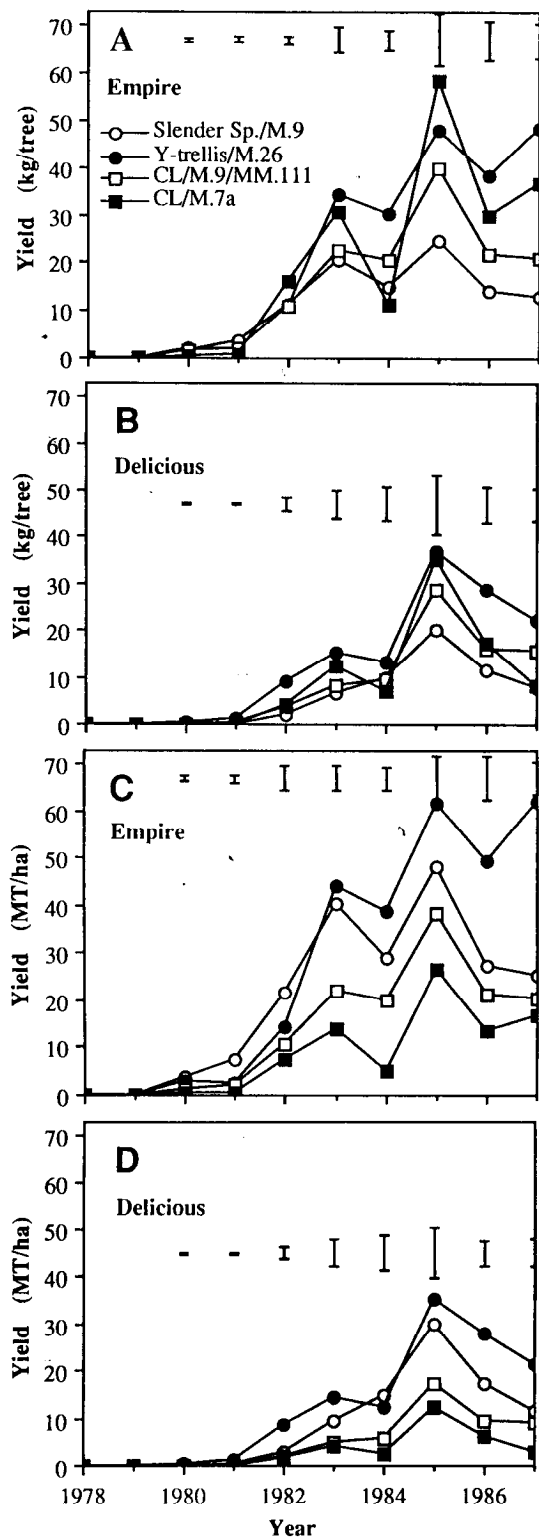


Fig. 1. Yield per tree (A, B) and per hectare (C, D) for 'Empire' and 'Delicious' apple trees grown under four orchard management systems, 1978-1987. Vertical bars represent LSD, $P = 0.05$. $n = 4$.

through year 5. In the second 5 years, the Y/M.26 system generally had the highest yield each year and the SS/M.9 the lowest yield within each cultivar. The 'Empire' CL/M.7 trees had the second highest average yield per tree, but this system had large year-to-year variability in yield per tree during the second 5

years. The CL/9/111 had intermediate yields per tree during the second 5 years. Cumulative yield was highest for the Y/M.26 trees followed by the CL/M.7, CL/9/11 and SS/M.9, respectively (Table 2).

Yields per hectare. There were significant per-hectare yield differences between cultivars and between systems in all years. There was a significant three-way interaction of cultivar \times system \times years. With 'Empire', yield per hectare was highest in the first 5 years, with the SS/M.9 system followed by the Y/M.26 system, the CL/9/11 system, and the CL/M.7 system, respectively (Fig. 1C). In the 6th year, yield from the Y/M.26 trees equaled that of SS/M.9 trees and exceeded the yield of SS/M.9 trees during years 7-10 by 30% to 140%. As the trees matured, the difference in yield between the SS/M.9 and CL/9/111 trees narrowed, but the M.9 trees continued to yield more than the medium density CL/9/111 trees. The low density CL/M.7 trees continued to produce the lowest yield in years 6-10.

With 'Delicious', the Y/M.26 system had the highest yields per hectare in all years (Fig. 1D). The SS/M.9 system was second in yield and did not differ from the Y/M.26 system in years 6-8. The CL/9/111 and the CL/M.7 trees had the lowest yield and did not differ significantly except in year 10.

Cumulative yield over 10 years was significantly greater for 'Empire' than for 'Delicious' (Table 2). Within each cultivar, the Y/M.26 system had the highest cumulative yield followed by the SWM.9, CL/9/111, and CL/M.7 systems, respectively. Cumulative yield of each cultivar was positively related to tree density for the central leader and slender spindle systems (Fig. 2). The quadratic component was nonsignificant with both cultivars. Cumulative yield for the Y/M.26 system for each cultivar was an outlier to this relationship with a mean cumulative yield significantly greater than the confidence interval of the regression line ($P < 0.01$). For the first 5 years, the relationship of yield per hectare and tree density for all four systems showed a positive linear relationship. However, in each year from the 6th to the 10th, the Y/M.26 system yielded more than predicted from the linear relationship of yield and tree density. This resulted in 35% greater yield for the Y/M.26 trees than for the higher density SWM.9 trees at the end of 10 years (Fig. 2). For the central leader and slender spindle systems, the relationship

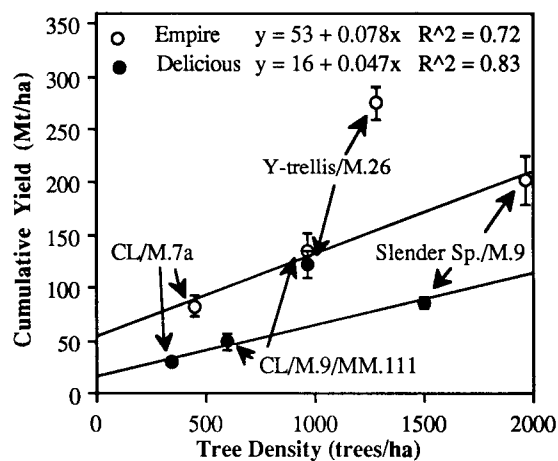


Fig. 2. Regressions of cumulative yield and tree density for 'Empire' and 'Delicious' grown under different management systems (\pm SE). Each point is the mean of four replicates and $n = 12$ for each regression line. Data points for Y/M.26 systems were not included in the regressions of yield and tree density. Refer to Table 1 for tree density of each growing system.

between yield and tree density remained positive and linear in all years except year 2, when there was a significant quadratic component to the relationship. Analysis of covariance to remove the effect of tree density showed that cumulative yield of the Y/M.26 system for both cultivars was significantly greater than the other three systems, which showed no statistical differences after adjustment for tree density.

Cumulative yield per hectare was linearly related to TCA ($r^2 = 0.87$, Cum. yield/ha = $-31 + 0.004$ TCA/ha, $n = 32$) and canopy volume ($r^2 = 0.31$, Cum. yield/ha = $3.1 + 0.026$ Can. Vol./ha, $n = 32$). After adjustment by analysis of covariance for TCA there were no significant differences in yield between cultivars or between systems with 'Delicious'. However, with 'Empire' the SS/M.9 system had significantly larger cumulative yield per hectare than the other three systems after adjustment for TCA. When canopy volume was used as the covariate, the Y/M.26 trees had the largest yields followed by the SS/M.9, the CL/9/111, and the CL/M.7, respectively.

Yield efficiency. Yield efficiency was calculated for each system on the basis of TCA. A second measure of efficiency based on canopy volume was also calculated (Table 3). The cumulative yield efficiency based on TCA or canopy volume was a 10-year cumulative index. When TCA was the denominator for calculating yield efficiency, there was a significant effect due to system in all 4 years it was measured and a significant interaction in 1987. The Y-trellis trees had the highest efficiency in 1986 and 1987 but in the other 2 years the SS/M.9 had the highest efficiency. The CL/M.7 system for both cultivars always had the lowest efficiency. When cumulative efficiency was calculated for the 10 years of the study, the 'Empire' trees were more efficient than 'Delicious', and among systems SS/M.9 had the highest efficiency, followed by the Y/M.26 and CL/9/111 trees, while the CL/M.7 system was significantly lower.

With the canopy volume method of calculating efficiency, the Y/M.26 system had the highest efficiencies each year and

for the cumulative index (Table 3). The only case where it was not significantly higher was in 1984 when the SS/M.9 had a similar efficiency. In all other years, the SS/M.9 was second, the CL/9/111 third, and the CL/M.7 system lowest in yield efficiency.

Crop density. Crop density has been defined as the number of fruit carried on the tree per unit of TCA (Lombard et al., 1988). There were significant differences due to system in each year, but in most years cultivar differences were nonsignificant (Table 4). The SS/M.9 system had the highest crop density in 1984 and 1985 and the Y/M.26 had the highest in 1986 and 1987. The CL/9/111 trees ranked third in crop density but differed significantly from the highest crop density system only in 1984 and 1987. The CL/M.7 trees had the lowest crop density in all years for both cultivars.

Fruit size. 'Delicious' always had larger fruit than 'Empire' (Table 5). There was a significant interaction of cultivar and system in 1986 and 1987 and on the 4-year average fruit size. With 'Empire', the higher yielding systems generally produced smaller fruits. In 1984, fruit from the SWM.9 and the Y/NL26 systems was smaller than that from the lower density systems. In the high crop year of 1985 there was no difference in fruit size with the three higher density systems, and only the CL/M.7 system produced larger fruit size. In 1986 and 1987, the three conic-shaped systems produced larger fruit than the Y/M.26 trees, and in 1987 there were no significant differences in fruit size. Average fruit size over the 4 years of the SS/YM.9 and the Y/M.26 systems was significantly smaller than that of the CL/9/111 and CL/M.7 systems. With 'Delicious', the Y/M.26 system produced the largest fruit in each of the 4 years, even though it also had the highest yield (Table 5). There was no difference in average fruit size among the SS/M.9, CL/9/111, and CL/M.7 systems.

The negative relationship of crop load and fruit size requires that the effect of crop load be covaried with fruit size to deter-

Table 3. Yield efficiency of 'Empire' and 'Redchief Delicious' apple trees under four management systems.

Cultivar	System	Basis of yield efficiency									
		TCA (kg fruit/cm ² TCA)					Canopy vol. (kg fruit/m ³)				
		Tree age (years) and calendar year									
		7	8	9	10	Cum. ^z	7	8	9	10	Cum. ^z
		1984	1985	1986	1987		1984	1985	1986	1987	
Empire		0.65	1.15	0.60	0.57	3.3	5.6	7.8	4.4	5.2	29
Delicious		0.50	1.18	0.62	0.41	2.6	6.6	10.2	5.0	3.8	24
LSD _{0.05} ^y		0.12	0.12	0.11		0.3	1.7	0.8	1.0	0.8	3
	Slender Sp./M.9	0.84	1.34	0.67	0.48	3.7	8.9	10.1	5.0	4.0	31
	Y-trellis/M.26	0.64	1.13	0.79	0.69	3.4	8.9	12.7	8.5	9.1	46
	C.L./M.9/MM.111	0.58	1.19	0.58	0.50	2.9	4.8	7.7	3.3	2.9	18
	C.L./M.7a	0.24	0.99	0.41	0.31	1.9	1.8	5.4	2.0	1.8	11
	LSD _{0.05} ^y	0.18	0.16	0.16		0.4	2.5	1.1	1.4	1.1	4
Empire	Slender Sp./M.9	0.85	1.26	0.63	0.55	4.3	7.3	8.7	5.0	4.8	38
	Y-trellis/M.26	0.81	1.10	0.77	0.80	3.6	9.2	11.3	7.3	10.1	45
	C.L./M.9/MM.111	0.69	1.17	0.56	0.48	3.1	4.2	6.1	3.1	3.0	20
	C.L./M.7a	0.25	1.05	0.45	0.46	2.3	1.5	5.0	2.1	2.7	13
Delicious	Slender Sp./M.9	0.83	1.42	0.70	0.40	3.0	10.4	11.5	5.0	3.2	24
	Y-trellis/M.26	0.47	1.15	0.81	0.57	3.2	8.5	14.0	9.6	8.1	46
	C.L./M.9/MM.111	0.47	1.21	0.59	0.52	2.7	5.3	9.3	3.5	3.0	16
	C.L./M.7a	0.22	0.92	0.36	0.15	1.5	2.1	5.8	1.8	0.9	9
LSD _{0.05} ^y						0.11					

^zCumulative yield efficiency calculated using 10-year cumulative yield and final TCA or canopy volume.

^yWherever main effect LSD values are not presented, the cultivar × system interaction was significant at $P = 0.05$. $n = 16$ for cultivar means; $n = 8$ for system means; $n = 4$ for cultivar × system means.

Table 4. Crop density calculated using trunk cross-sectional area (TCA) of 'Empire' and 'Redchief Delicious' apple trees under four management systems.

Cultivar	System	Crop density (no. fruit/cm ² TCA)			
		Tree age (years) and calendar year			
		7 1984	8 1985	9 1986	10 1987
Empire		5.7	8.6	4.1	3.6
Delicious		3.9	7.6	3.2	2.0
		LSD _{0.05} ^z	2.2	1.2	1.1
	Slender Sp./M.9	7.9	9.7	3.9	2.8
	Y-trellis/M.26	4.8	7.6	4.9	3.8
	C.L./M.9/MM.111	4.7	8.7	3.3	2.7
	C.L./M.7a	1.9	6.3	2.8	1.4
		LSD _{0.05} ^z	3.0	1.7	2.1
Empire	Slender Sp./M.9	8.4	9.6	4.2	3.5
	Y-trellis/M.26	6.9	8.3	5.6	4.9
	C.L./M.9/MM.111	5.2	9.2	3.6	2.9
	C.L./M.7a	2.3	7.2	3.0	2.9
Delicious	Slender Sp./M.9	7.4	9.8	3.6	2.0
	Y-trellis/M.26	2.7	6.9	4.1	2.7
	C.L./M.9/MM.111	4.2	8.1	3.0	2.5
	C.L./M.7a	1.4	5.4	1.9	0.8
		LSD _{0.05} ^z			0.9

^zWherever main effect LSD values are not presented the cultivar × system interaction was significant at $P = 0.05$. $n = 16$ for cultivar means; $n = 8$ for system means; $n = 4$ for cultivar × system means.

mine the true effect of system on fruit size. Fruit size for each cultivar was adjusted separately for crop density based on TCA by analysis of covariance using a linear regression model. After adjustment for the effect of crop density, there were no significant differences due to system or the interaction of cultivar and system in any year except 1986 (Table 5). With 'Delicious' in that year, the Y/M.26 had significantly larger adjusted fruit size than the SS/M.9 or the CL/9/111 trees, and the CL/M.7 had

significantly smaller fruit size than any other system. With 'Empire' in 1986, the Y/M.26 had the smallest adjusted fruit size. The 4-year average adjusted fruit size showed no significant differences among systems for 'Empire', but with 'Delicious', the Y/M.26 system had significantly larger fruit, and the CL/M.7 had significantly smaller fruit than the SS/M.9 CL/9/111 systems.

The relationship between fruit size and crop density was explored for nonlinearity and to determine the best method of calculating crop density. Crop density was calculated based on TCA, annual increase in TCA, canopy volume, or on a land-area basis. The best regression fit between fruit size and crop density for both cultivars was obtained when crop density was determined based on TCA (Table 6). The land-area method gave the poorest fit. The relationship was nonlinear for the TCA method and showed a significant cubic component.

Fruit quality. Percentage of fruit surface with red color was significantly greater for 'Delicious' than for 'Empire' (Table 7). Within 'Delicious', there were no significant differences in fruit color due to system in any year. With 'Empire' there were differences in 1984 and 1987. In 1984, the fruit color from both the SS/M.9 and the Y/M.26 trees was lower than from the CL/9/111 or CL/M.7 trees. In years 8–10, the fruit color from the SS/M.9 system was not different than that of the CL/9/111 system. The Y/M.26 continued to have the lowest fruit red color, although it was not significantly different from the CL/9/111 or the CL/M.7 systems. Average color over the 4 years for 'Empire' was significantly lower for the Y/M.26 than for the other three systems, which did not differ in average color.

Summer pruning was required to maximize fruit color with 'Empire'. The larger trees required more time per hectare to summer prune than the Y/M.26 trees and SS/M.9 trees (data not presented). The CL/M.7 trees required the removal of many water sprouts on the bottom tier of scaffold branches in addition to removal of unwanted shoots in the top of the tree. The SS/M.9 trees had fewer shoots to remove in the summer. The Y/

Table 5. Fruit size of 'Empire' and 'Redchief Delicious' apple trees under four management systems.

Cultivar	System	Unadjusted fruit size (g)					Fruit size adjusted for crop density (g) ^z				
		Tree age (years) and calendar year					Tree age (years) and calendar year				
		7 1984	8 1985	9 1986	10 1987	4-year mean	7 1984	8 1985	9 1986	10 1987	4-year mean
Empire		143	135	148	161	147	145	148	141	153	147
Delicious		186	157	194	202	185	183	182	185	185	185
		LSD _{0.05} ^y	8	7			6	7		4	
	Slender Sp./M.9	157	138	173	182	162	169	164	164	170	167
	Y-trellis/M.26	164	150	169	186	168	161	170	165	176	168
	C.L./M.9/MM.111	167	138	174	184	166	162	162	164	173	165
	C.L./M.7a	172	158	169	175	168	165	166	158	168	164
		LSD _{0.05} ^y	11	9			8	10		6	
Empire	Slender Sp./M.9	134	131	151	158	143	146	150	143	148	147
	Y-trellis/M.26	135	133	138	162	143	140	147	136	156	145
	C.L./M.9/MM.111	153	128	153	165	150	148	141	144	157	147
	C.L./M.7a	151	146	148	160	151	146	153	139	151	147
Delicious	Slender Sp./M.9	179	145	195	205	181	191	177	186	191	186
	Y-trellis/M.26	192	167	199	209	192	182	192	194	195	191
	C.L./M.9/MM.111	181	148	194	203	181	176	182	183	188	182
	C.L./M.7a	193	169	189	189	185	183	178	176	185	180
		LSD _{0.05} ^y		7	9	6			7		5

^zFruit size adjusted for crop density by analysis of covariance using a linear regression model. Crop density calculated as fruit no./cm² TCA.

^yWherever main effect LSD values are not presented, the cultivar × system interaction was significant at $P = 0.05$. $n = 16$ for cultivar means; $n = 8$ for system means; $n = 4$ for cultivar × system means.

Table 6. Regression between fruit size (y) and crop density (x) based on trunk cross-sectional area (TCA), increase in TCA, canopy volume, and land area for 'Empire' and 'Redchief Delicious' apple trees under four management systems over 4 years (1984–1987).

Method of calculating crop density (x)	Regression equations of fruit size (y) and crop density (x)					
	Type of curve ^z	r ²	Intercept	Slope of x	Slope of x ²	Slope of x ³
<i>Empire</i>						
Fruit no./cm ² TCA	Linear**	0.58	168	-3.9	---	---
	Cubic**	0.65	128	+18.3	-3.5	+0.17
Fruit no./cm ² annual increase in TCA	Linear**	0.41	160	-0.27	---	---
Fruit no./m ³ canopy vol.	Linear**	0.37	160	-0.33	---	---
Fruit no./m ² land area	Linear**	0.32	160	-0.57	---	---
<i>Delicious</i>						
Fruit no./cm ² TCA	Linear**	0.60	208	-5.7	---	---
	Cubic**	0.74	174	+23.8	-6.4	+0.38
Fruit no./cm ² annual increase in TCA	Linear**	0.22	199	-0.40	---	---
Fruit no./m ³ canopy vol.	Linear**	0.33	200	-0.38	---	---
	Cubic*	0.40	191	+0.51	-0.018	±0.0001
Fruit no./m ² land area	Linear**	0.26	199	-1.61	---	---

^zAll linear, quadratic and cubic regressions were examined but only significant regressions are presented.

*,**Significant at $P = 0.05$ or 0.01 , respectively. $n = 64$.

Table 7. Fruit color, soluble solids concentration (SSC), flesh firmness, and titratable acidity of 'Empire' and 'Redchief Delicious' apple trees under four management systems.

Cultivar	System	Fruit red color (%) ^z					SSC (%)					Mean flesh firmness (N)	Mean titratable acidity (meq·liter ⁻¹)
		Tree age (years) and calendar year											
		7 1984	8 1985	9 1986	10 1987	4-year mean	7 1984	8 1985	9 1986	10 1987	4-year mean		
Empire		80	90	85	85	85	12.5	12.6	12.8	13.6	12.9	58.9	0.61
Delicious		93	97	94	93	94	13.4	12.9	13.8	14.6	13.6	61.2	0.27
	LSD _{0.05} ^y	3 ^y	2	4		1		0.2	0.3				0.01
	Slender Sp./M.9	85	94	90	90	90	12.6	12.9	13.5	14.4	13.3	59.7	0.44
	Y-trellis/M.26	84	92	87	88	88	13.0	12.7	13.1	13.7	13.2	60.4	0.44
	C.L./M.9/MM.111	90	93	91	90	91	13.2	12.7	13.5	14.4	13.5	59.6	0.44
	C.L./M.7a	89	93	91	88	90	13.0	12.6	12.9	13.9	13.1	60.6	0.45
	LSD _{0.05} ^y	4	2	5		2		0.3	0.4				0.02
Empire	Slender Sp./M.9	78	92	85	87	86	12.0	12.8	13.1	13.9	13.0	59.1	0.62
	Y-trellis/M.26	76	88	80	83	83	12.2	12.5	12.5	13.0	12.6	59.5	0.59
	C.L./M.9/MM.111	85	89	87	86	87	13.2	12.7	13.0	14.1	13.2	58.8	0.62
	C.L./M.7a	84	89	87	82	86	12.6	12.5	12.6	13.5	12.8	58.2	0.63
Delicious	Slender Sp./M.9	92	96	94	93	94	13.2	13.0	13.9	14.9	13.7	60.2	0.26
	Y-trellis/M.26	92	97	94	93	94	13.8	13.0	13.8	14.4	13.7	61.3	0.28
	C.L./M.9/MM.111	95	97	95	93	95	13.2	12.7	14.1	14.8	13.7	60.4	0.26
	C.L./M.7a	94	97	94	93	94	13.3	12.8	13.3	14.3	13.4	63.0	0.28
	LSD _{0.05} ^y				4		0.7		0.4	0.3	1.0		

^zRed color visually estimated as percentage of area with "good" red color + 1/2 percentage of area with "compensating" red color.

^yWherever main effect LSD values are not presented, the cultivar × system interaction was significant at $P = 0.05$. $n = 16$ for cultivar means;

M.26 trees had relatively few water sprouts in the middle of the Y. These shoots were either removed by summer pruning in August or placed under the first wire and trained as replacement limbs. Through this process, entire scaffold limbs that became too vigorous were replaced. The lack of excessive shoot growth in the center of the Y may have been due to the relatively weak growing cultivars used in this experiment in combination with the heavy yields. More vigorous cultivars might have very different results.

Fruit internal quality characteristics were significantly different between cultivars but were not influenced greatly by management system (Table 7). 'Delicious' had a higher SSC, firmer flesh, and lower total acidity than did 'Empire'. Within cultivars, the 'Empire' SS/M.9 and Y/M.26 systems had lower SSC

in 1984 than the other two systems, presumably due to inadequate pruning. After a more aggressive pruning in 1985, there were no significant differences. In 1986 and 1987, the Y/M.26 and the CL/M.7 had lower SSC than the SS/M.9 and CL/9/111 systems. The Y/M.26 system had the lowest average SSC, followed by the CL/M.7, SS/M.9, and the CL/9/111, respectively. With 'Delicious', only the CL/M.7 system had significantly lower SSC than the other three systems. The 4-year average flesh firmness showed an interaction between cultivar and system. With 'Empire' the CL/M.7 had the lowest firmness, while with 'Delicious', the CL/M.7 system had the highest firmness. There were no differences between the other systems in flesh firmness. Flesh firmness was not adjusted for fruit size due to a nonsignificant correlation of size and firmness. Titratable acid-

ity was significantly higher for 'Empire' than for 'Delicious', but there was no significant effect of system on 4-year mean titratable acidity.

Discussion

The smaller canopy volume per tree of 'Delicious' in each system indicates the planting density for this cultivar should have been closer than for 'Empire' for optimum performance. Unfortunately, the planting densities chosen for 'Delicious' were lower than for 'Empire', which resulted in a failure of the 'Delicious' trees to fill their space adequately in any system by the end of the 10th year. Consequently, results presented on a per-hectare basis are not adequate for comparing cultivars since they are biased in favor of 'Empire'. More useful comparisons between cultivars can be made on a per-tree basis. The 'Redchief Campbell' strain of 'Delicious' is a compact-growing strain that produced less shoot growth than desired under all systems. To stimulate more growth, the central leader and scaffold branches of these trees were headed annually on all systems except the Y/M.26 trees. This pruning and the compact stature combined to give smaller TCA values and canopy volumes than 'Empire'. To have obtained similar TCA per hectare would have required that the 'Delicious' SS/M.9 trees be planted at 26% greater tree density than the 'Empire' SS/M.9. For the other three systems, a 52%, 48%, and 42% increase in tree density for 'Delicious' relative to 'Empire' would be required for the Y/M.26, CL/9/111, and CL/M.7 systems, respectively.

Differences in TCA per tree among the systems reflect the size controlling character of the rootstock and the severity of pruning. When these factors were combined with the planting density, there were large differences in TCA per hectare. The 'Empire' Y/M.26 system resulted in 65% greater TCA per hectare than the 'Empire' SS/M.9 system and four times the TCA of the 'Delicious' CL/9/111 system. To obtain similar TCA per hectare would have required much higher tree densities for the other systems.

In spite of twice the TCA per hectare with the Y/M.26 trees compared to the CL/M.7, canopy volumes per hectare were the same at the end of 10 years. This result likely was due to the restriction of the canopy to the planes of the Y arms. The similar canopy volume per hectare of the central leader and slender spindle trees likely resulted from containment pruning of the higher density systems. Ferree (1980) showed the greatest canopy volume per hectare with the highest density systems at age 6 years. In our study, by age eight there were no significant differences in canopy volume between the low and high density systems, yet yields varied by up to 2.5 times (Fig. 1). This result indicates canopy volume is not necessarily well-correlated to performance, especially when restricted canopies are considered.

The positive relationship of yield and tree density reported here is supported by other studies that indicate that, in the first 10 years of an orchard's life, tree number is the prime determinant of yield (Cripps et al., 1975; Ferree, 1980; Palmer, 1988; Parry, 1978; Wertheim et al., 1986; Westwood et al., 1976). This relationship should allow the prediction of the yields at other tree densities when grown under conditions similar to this experiment. However, the Y/M.26 system gave larger yields than predicted from this relationship. In addition, our yield data indicate there are different relationships for each cultivar. Both of these anomalies can be explained by differences in orchard development as seen in TCA per hectare. When yields were covaried with trunk area per hectare, then the differences be-

tween cultivars disappeared, and the Y/M.26 yield fit the relationship. It appears that the Y/M.26 combination resulted in very high TCA per hectare at only moderate tree densities resulting in the high yield reported here. Our study did not answer the question of whether other systems planted at appropriate densities to give the same trunk areas per hectare as the Y/M.26 system would have yields equal to those of the Y/M.26 system. For the 'Empire' CL/M.7 system, this would require a tree density of 960 trees/ha, which would likely be unmanageable due to tree size. It is interesting to note that the 'Delicious' Y/M.26 trees and the 'Empire' CL/9/111 trees had about the same cumulative yield. They also had the same tree density. These data suggest that 'Delicious' grown with the Y/M.26 system might have performance similar to pyramid-shaped trees of 'Empire' if grown at similar densities, although it would still produce less than 'Empire' grown with the Y/M.26 system.

To examine the performance of the cultivars and systems independently of tree spacing, yield efficiencies were calculated. In this paper we used two methods of estimating the efficiency of systems to produce fruit. Yield efficiency calculated with TCA is useful because TCA has been shown to be correlated to above ground weight of the tree (Westwood and Roberts, 1970). Thus, the ratio of yield to TCA is a fruit weight to total tree weight that reflects the efficiency of the entire weight of the tree to produce fruit. This measure of efficiency is useful for comparing across rootstock and systems (Ferree, 1980; Lombard et al., 1988). Yield efficiency based on canopy volume is a weight : volume ratio. This is inherently less sound, since volume is only indirectly related to productive factors in the tree, such as tree weight or leaf area.

In our study, 'Empire' was more efficient than 'Delicious'. The SS/M.9 system had the highest yield efficiency and the CL/M.7 system the lowest. The Y/M.26 and the CL/9/111 were intermediate for 'Empire' and the same as SS/M.9 for 'Delicious'. Since rootstock control the size of the trunk, the use of cumulative TCA as the denominator in calculating annual yield efficiency could bias the results in favor of rootstock with small trunk areas. In addition, the use of annual yield with cumulative TCA becomes more questionable as the trees fill their space since trunk area continues to increase but canopy volume remains static once canopies are maintained by containment pruning. Due to these problems, some have suggested using the annual increase in TCA as the denominator since it would be influenced by pruning and other environmental factors. This index is more properly a partitioning index since the annual increase in TCA is an estimate of the annual vegetative growth of the tree. However, it is not related to the total weight of the tree.

When canopy volume was used as the denominator to calculate yield efficiency, the Y/M.26 system of each cultivar was the most efficient, followed by the SS/M.9, CL/9/111, and CL/M7 systems, respectively. The use of canopy volume measurements to estimate yield efficiency has the problem of determining the proper way to calculate canopy volume. With pyramid-shaped trees, the measurements between systems are probably comparable. However, given the severe geometric restrictions of the Y-trellis, the best way to measure canopy volume is not clear. The method used in our study probably biases in favor of the Y-trellis.

The best method for assessing crop density was found to be fruit number per unit TCA. When fruit size was adjusted for crop density, there were no significant differences between systems with 'Empire', although there were still differences be-

tween systems with 'Delicious'. All systems within each cultivar received the same rate of chemical thinner each year, but there were still large differences in crop density. We did not measure whether the differences in crop density were the result of greater flower density or greater fruit set. With 'Empire', to obtain similar fruit size from the SS/M.9 and Y/M.26 systems compared to the CL/9/111 or CL/M.7 systems would likely require higher rates of crop thinning. With 'Delicious', the Y/M.26 system produced larger fruit than predicted from crop density. The basis for this result is unknown.

The lack of differences in fruit red color among systems of 'Delicious' was not unexpected, since a high-coloring strain was used. Red pigment development in 'Empire' requires relatively high light levels within the canopy, and any shaded part of the apple remains green. In 1984, both the SS/M.9 and the Y/M.26 trees had fruit that was less red than the CL/9/111 and CL/M.7 trees, which was likely a result of retaining too many limbs in the canopy of these two systems. The SS/M.9 trees had five to six limbs in the bottom tier of branches with many overlapping each other. The Y/M.26 trees in many cases had two layers of limbs on each arm of the Y. In the dormant season before the 1985 season, several large pruning cuts were made in the bottom of the SS/M.9 trees, and the limbs in the Y/M.26 trees were thinned to a single layer on each arm. With the more-open canopies, fruit color of both systems was improved but the Y/M.26 system continued to have the least-red fruit, resulting in significantly lower average color values over the 4 years (Table 7). The color difference was likely the result of shading on the underside of the trellis due to either too flat of a trellis angle or too narrow of a gap between rows at the tips of the trellis arms. Although the original trellis angle was 60° above the horizontal, after the heavy crops of 1985-87 the trellis angle was closer to 50°. This lower angle allowed too small an opening between rows for sufficient direct light penetration to the underside of the trellis.

Fruit SSC is strongly influenced by light exposure of leaves in the immediate area around the fruit (Jackson et al., 1977; Robinson et al., 1983). The data for SSC show a similar pattern as those for fruit color and likely reflect poorer light distribution in those systems with low SSC. The pruning used to open the canopy resulted in no significant differences in SSC in 1985. In 1987, SSC of the 'Empire' Y/M.26 trees was significantly lower than with any other system. This result could reflect a worsening light climate on the underside of the trellis or it could be related to the significantly higher crop load of the Y/M.26 system in 1987 than of other systems.

In this experiment, cumulative yield in the first 10 years was related to tree density. This result confirms previous work that increasing tree density is one approach to increasing cumulative yield for apples (Ferree, 1980; Jackson et al., 1987; Palmer and Jackson, 1974; Wertheim et al., 1986; Westwood et al., 1976). Given the range of dwarfing rootstock that exists for apple, there is great latitude of manageable densities. An additional approach to increasing cumulative yield might be the Y-trellis. In this study the Y/M.26 system produced substantially higher yields than were predicted for its tree density; however, fruit color was slightly poorer. The physiological basis for the higher yield could be related to the angle of the trellis arm. It is well-known that as the limb angle of apple becomes more horizontal, flowering increases and apical dominance and extension growth

decrease. It is possible that the angle chosen for this study optimizes the balance between cropping and vegetative growth. However, to fully access this system, additional studies of the optimum trellis angle, as well as spacing, rootstock, and pruning studies to optimize the balance between yield and quality are needed.

Literature Cited

- Barritt, B.H. 1987. Orchard systems research in deciduous trees: A brief introduction. *HortScience* 22:548-549.
- Cripps, J. E. L., F. Melville, and H.I. Nicol. 1975. The relationship of 'Granny Smith' apple tree growth and early cropping to planting density and rectangularity. *J. Hort. Sci.* 50:291-299.
- Ferree, D.C. 1980. Canopy development and yield efficiency of 'Golden Delicious' apple trees in four orchard management systems. *J. Amer. Soc. Hort. Sci.* 105:376-380.
- Heinicke, D.R. 1975. High density apple orchards—planning, training, and pruning. U.S. Dept. Agr. Hdbk. 458.
- Jackson, J.E. (ed.) 1978. Symposium on high density planting. *Acts Hort.* 65.
- Jackson, J.E. (ed.) 1981. Symposium on research and development of orchard and plantation systems. *Acts Hort.* 114.
- Jackson, J.E. (ed.) 1986. Third international symposium on research and development on orchard and plantation systems. *Acts Hort.* 160.
- Jackson, J.E. and J.W. Palmer. (eds.) 1989. Fourth international symposium on research and development on orchard and plantation systems. *Acts Hort.* 243.
- Jackson, J. E., J.W. Palmer, M.A. Perring, and R.O. Sharples. 1977. Effects of shade on the growth and cropping of apple trees. III Effects on fruit growth, chemical composition and quality at harvest and after storage. *J. Hort. Sci.* 52:267-282.
- Jackson, J. E., S.J. Wertheim, B. Buenemann, F. Winter, J.V. Christensen, S. Sansavini, and A. Mika. 1987. The international planting systems trial. *HortScience* 22:550-551.
- Lombard, P. B., N.W. Callan, F.G. Dennis, Jr., N.E. Looney, G.C. Martin, A.R. Renquist, and E.A. Mielke. 1988. Towards a standardized nomenclature, procedures, values, and units in determining fruit and nut tree yield performance. *HortScience* 23:813-817.
- Palmer, J.W. 1988. Annual dry matter production and partitioning over the first 5 years of a bed system of Crispin/M.27 apple trees at four spacings. *J. Applied Ecol.* 25:569-578.
- Palmer, J.W. and J.E. Jackson. 1974. Effects of tree population and variations in spacing within and between rows of Golden Delicious on M.9. Rpt. E. Mailing Res. Sta. for 1973:66-68.
- Parry, M.S. 1978. Integrated effects of planting density on growth and cropping. *Acts Hort.* 65:91-100.
- Robinson, T. L., E.J. Seeley, and B.H. Barritt. 1983. Effect of light environment and spur age on 'Delicious' apple fruit size and quality. *J. Amer. Soc. Hort. Sci.* 108:855-861.
- U.S. Department of Agriculture. 1976. United States standards for grades of apples. U.S. Dept. Agr., Food Safety and Quality Serv., Washington, D.C.
- Wertheim, S.J. 1968. The training of the slender spindle. Pub. Proefstation Fruiteelt, Wilhelmdorpp, Netherlands. no. 7.
- Wertheim, S. J., A. de Jager, and M.J.J.P. Duyzens. 1986. Comparison of single-row and multi-row planting systems with apple, with regard to productivity, fruit size and colour, and light conditions. *Acts Hort.* 160:243-258.
- Westwood, M.N. and A.N. Roberts. 1970. The relationship between trunk cross-sectional area and weight of apple trees. *J. Amer. Soc. Hort. Sci.* 95:28-30.
- Westwood, M. N., A.N. Roberts, and H.O. Bjornstad. 1976. Influence of inrow spacing on yield of 'Golden Delicious' and 'Starking Delicious' apple on M9 rootstock in hedgerows. *J. Amer. Soc. Hort. Sci.* 101:309-311.