Varying Density with Constant Rectangularity: II. Effects on Apple Tree Yield, Fruit Size, and Fruit Color Development in Three Training Systems over Ten Years

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Abstract. The effect of increasing planting density at constant rectangularity on the fruit yield, fruit size, and fruit color of apple [*Malus ×sylvestris* (L.) var. *domestica* (Borkh.) Mansf.] in three training systems (slender spindle, tall spindle, and Geneva Y trellis) was assessed for 10 years. Five tree densities (from 1125 to 3226 trees/ha) and two cultivars (Royal Gala and Summerland McIntosh) were tested in a fully guarded split-split plot design. Density was the most influential factor. As tree density increased, per-tree yield decreased, but yield per unit area increased. The relation between cumulative yield per ha and tree density was linear at the outset of the trial, but soon became curvilinear, as incremental yield diminished with increasing tree density. The chief advantage of high density planting was a large increase in early fruit yield. In later years, reductions in cumulative yield efficiency, and in fruit color for ‘Summerland McIntosh’, began to appear at the highest density. Training system had no influence on productivity for the first 5 years. During the second half of the trial, fruit yield per tree was greater for the Y trellis than for either spindle form at lower densities but not at higher densities. The slender and tall spindles were similar in nearly all aspects of performance, including yield. ‘Summerland McIntosh’ yielded almost 40% less than ‘Royal Gala’ and seemed more sensitive to the adverse effects of high tree density on fruit color.

High density plantings have been widely adopted by North American apple growers in the past two decades. High tree density allows greater early productivity, an earlier return on capital investment, and sustained high yields of good-quality fruit (Wertheim et al., 2001). The greater early yield of high density plantings is due in part to their greater leaf area index and therefore greater interception of photosynthetically active radiation (hereafter called “light”), compared to young low density plantings (Jackson, 1989). Relative to large trees, dwarf trees have a greater proportion of well-illuminated canopy and higher labor efficiency. Dwarfing rootstocks such as M.9 also increase the proportion of harvested plant yield (Lakso et al., 1999; Wagenmakers, 1991). For apple [*Malus ×sylvestris* (L.) var. *domestica* (Borkh.) Mansf.], light interception should be optimized rather than maximized, because penetration of light into the canopy interior is important for high fruit quality. Fruit growing in the shade tends

to be poorly colored, small, and low in soluble solids (Barritt et al., 1997).

Tree density is most commonly increased by reducing in-row spacing. When this is done, both density and rectangularity are changed. Rectangularity (the ratio of alley width to in-row spacing) affects both interception and distribution of light, and influences yield, tree size, alternate bearing, flower density, and fruit color in apple (Callesen and Wagenmakers, 1989; Cripps et al., 1975; Wagenmakers and Callesen, 1995; Wertheim, 1985). Rectangularity effects are sometimes large, e.g., 30% to 40% reduction in yield (see Parry, 1978, and references therein). A square layout (1:1) is the most favorable for light interception and distribution (Wagenmakers, 1991; Wagenmakers and Callesen, 1995).

Rectangularity is usually ignored in investigations comparing tree density. Both Cripps et al. (1975) and Vittrup Christensen (1979) held rectangularity constant, but the latter did not prune the trees or thin the fruit, so fruit quality effects could not be assessed, and the former report covered only three cropping years. The adverse effects of high rectangularity increase as the orchard ages and as planting density increases (Wagenmakers and Callesen, 1989, 1995).

In addition to density, the tree training system (especially tree height and canopy shape),

influences total interception and distribution of light. Training systems with angled canopies (e.g., Y or V shapes) have demonstrated better light relations and productivity than slender spindles when rootstock and spacing are held constant (Hampson et al., 2002; Robinson, 1997, 2000). Tall trees can intercept more light and yield more than short trees at the same spacing (Barritt, 2000; Callesen, 1993; Palmer, 1989; Wertheim et al., 2001).

Our objective was to determine the effect of tree density and training system on yield and fruit quality of apple in the absence of confounding factors such as rootstock and rectangularity. A secondary objective was to see whether an angled canopy (Geneva Y trellis) could improve orchard performance relative to the spindle form (pyramid shape) commonly used in this region. Tall spindles were included to see if tree height could be manipulated to advantage at a given rectangularity and density. The present report is the final one for this study. Some of the early results were outlined previously (Hampson et al., 1997, 1998). Final results of the study for tree growth and light interception are covered elsewhere (Hampson et al., 2004).

Materials and Methods

Planting description and cultural practices. The experimental materials and methods were described in detail previously (Hampson et al., 2004). Briefly, the plot was designed to keep rectangularity constant while varying density. Rectangularity was 2.5 between-row spacing: 1 in-row spacing throughout, so both alley width and in-row spacing changed with each successive row. The minimum in-row spacing was 1.05 m, excluding guard rows. The experimental design was a split-split plot with four blocks. Cultivars were assigned to main plots, training systems to subplots and densities to sub-subplots. Each sub-subplot consisted of two fully guarded experimental trees. Training system and cultivar were randomized within blocks, but densities were assigned in sequential order to minimize the number of guard trees required and maximize the number of densities that could be tested within the available area. The corresponding tree densities for the experimental rows were 1125, 1587, 2012, 2481, and 3226 trees/ha.

Two cultivars of 1-year-old feathered (i.e., branched) trees were used, ‘Royal Gala’ and ‘Summerland McIntosh’, both on M.9 rootstock. Three training systems were tested: slender spindle (SS), Geneva Y trellis (YT), and a modified vertical axis that we called “tall spindle” (TS). Tree training practices were described earlier (Hampson et al., 2004).

Measurements and statistical analysis. The yield of picked fruit (kg per tree), number of fruit harvested, and number and weight of drops + culls were noted. Culls mainly comprised fruit with gross defects (bird pecks, leafroller damage, limb rub, severe sunburn), and fruit that dropped prior to harvest (mainly ‘McIntosh’). For ‘Gala’, a multiple selective-pick cultivar, separate records were kept for

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CROP PRODUCTION

each pick date and the accumulated totals were analyzed. The proportion (by weight) harvested on the last pick was also calculated. 'McIntosh' trees were harvested in a single pick. All trees were first cropped in the year after planting. Annual yield, cumulative yield, and cumulative yield efficiency [cumulative yield/trunk cross-sectional area (TCA)] were calculated. Calculations for average fruit weight and crop load (number of fruit/TCA) were made using the total number of fruit per tree, not samples. At the end of the experiment, the trees were cut off at the graft union and weighed in the field. C/S ratio (cumulative yield/final scion weight) was calculated as in Barden and Marini (2001).

Color assessments were different for the two cultivars. 'Gala' fruit are usually harvested according to ground color and red color development. The proportion of fruit left for the last pick was used as an estimate of poor and/or delayed color development. For 'McIntosh', random 10-fruit samples were picked from each sub-subplot on the day of harvest. The proportion of surface area occupied by "Red No. 6", a regional commercial standard of red color intensity, was estimated visually to the nearest 5% on each apple.

Statistical analyses were done with the SAS software package (SAS Institute, Cary N.C.). Color assessments for 'McIntosh' were subjected to frequency analysis. All other variables were analyzed with a mixed-model analysis of variance, with block, and interaction terms containing block, as random factors. Cultivar effect was tested against error A (block $\times$ cultivar), system and cultivar $\times$ system were tested against error B (block $\times$ cultivar $\times$ system) and density, and interaction terms for density were tested against error C (block $\times$ cultivar $\times$ system $\times$ density). Main-effect means were separated with the Waller-Duncan K ratio *t* test (K ratio = 100), using error B for system, and error C for density. To determine the appropriate order for equations involving responses to density, orthogonal contrasts were used. Regression equations were obtained with the SAS regression procedure REGR.

Results and Discussion

This experiment spanned 10 years and used a statistical design sensitive to small differences in plant response to different treatments. In some years and for some response variables, two- or three-way factor interactions were statistically significant. In nearly all cases, these interactions were ephemeral (i.e. occurring only once or twice during 10 years) and were due to differences in the degree of the response to a certain combination of factors. In the following discussion, interactions are only mentioned if they occurred at least twice.

Productivity. Of the three factors in this study, planting density had the greatest influence on productivity. As has been observed in many density trials, yield per tree declined as density rose. The relationship was linear (except for 'McIntosh' spindles), but the r^2 values were generally low (Fig. 1 and Table 1. Note: the TS and SS did not differ signifi-

cantly in yield, so these data were pooled for Figs. 1 and 2). Averaged over all cultivars and systems, trees at the lowest density produced 50% more per tree than trees at the highest density over the course of the trial (163.7 kg at 1125 trees/ha vs. 108.9 kg at 3226 trees/ha). Reductions in per-tree yield were evident as early as 1994 (second crop) for the highest density (data not shown).

Declining yield per tree was more than compensated by tree number as density rose, so that yield per hectare (yield/ha) increased (Fig. 2). Initially cumulative yield/ha was a linear function of density, and cultivar and system had no significant influence. Later, the relationship became curvilinear as trees at intermediate densities produced more per tree than at high densities (see line for 1997, Fig. 2). Even in the early years, incremental yield gain declined as tree density increased. After the third crop (1995), an increase in tree density

from 1125 to 2012/ha (factor of 1.79) achieved a doubling of yield, but a further increase of 60% in density (to 3226 trees/ha) resulted in $\approx 15\%$ yield gain. By the tenth leaf (ninth crop), a density of 2012 trees/ha yielded 1.67 times that of 1126 trees/ha, while the yield gain of a further increase to 3226 trees/ha remained at $\approx 15\%$. Therefore, the chief advantage of high density was a large increase in early fruit yield per ha. Diminishing incremental yield with increasing density was also reported by Palmer et al. (1989), Sansavini and Corelli Grappadelli (1997) and Weber (2001). Nevertheless, final cumulative yield/ha was greatest at the maximum density (Table 2).

By the eighth year, yield efficiency began to decrease at the highest density. The reduction in yield efficiency was $\approx 17\%$ on a TCA basis, or $\approx 10\%$ as calculated by C/S ratio (Table 2). Reduced yield efficiency at high tree density was also observed by Parry (1978) and Tustin

Fig. 1. Cumulative yield per tree for 'Royal Gala' (black symbols) and 'Summerland McIntosh' (white symbols) trained as (a) Y trellis and (b) spindles at different tree densities in 1998 (seventh leaf, sixth cropping year) and 2001 (tenth leaf, ninth cropping year). Vertical bars show standard errors. Regression equations appear in Table 1.

Table 1. Regression equation coefficients [with standard errors (SE) in parentheses] for Fig. 1, the relation of tree density and cumulative per-tree yields in 1998 (sixth crop, seventh leaf) and 2001 for different combinations of cultivar and training system. In each case Pr > F was <0.01.

Year	Cultivar	System	Intercept (SE)	Linear (SE)	Quadratic (SE)	r ² value	n
1998	McIntosh	YT	110.7 (9.9)	-0.015 (0.005)	NA ^z	0.23	40
1998	McIntosh	Spindle	39.4 (16.1)	0.040 (0.016)	-1.0 × 10 ⁻⁵ (3.6 × 10 ⁻⁶)	0.14	80
1998	Gala	YT	157.9 (15.6)	-0.023 (0.007)	NA	0.22	40
1998	Gala	Spindle	121.0 (7.3)	-0.013 (0.003)	NA	0.16	80
2001	McIntosh	YT	195.4 (14.0)	-0.032 (0.006)	NA	0.40	40
2001	McIntosh	Spindle	77.9 (24.0)	0.050 (0.024)	-1.4 × 10 ⁻⁵ (5.3 × 10 ⁻⁶)	0.21	77 ^y
2001	Gala	YT	278.2 (21.1)	-0.047 (0.010)	NA	0.38	40
2001	Gala	Spindle	210.1 (10.4)	-0.025 (0.005)	NA	0.26	79 ^y

^zNA = not applicable (the quadratic term in the model was nonsignificant at α = 0.05).
^yOne tree of ‘Gala’ and three of ‘McIntosh’ died between 1998 and 2000.

Fig. 2. Cumulative yield per hectare in 1994 (third leaf, second crop year), 1997 and 2001 for trees at different planting densities. Vertical bars show standard errors. Cultivar and training system had no significant effect in early years, so data were pooled for 1994 and 1997. Regression equations (where x = density in trees/ha): 1994, yield = 6.17 + 0.012x, r² = 0.36, n = 240; 1997, yield = -51.87 + 0.135x - 2.12 × 10⁻⁵x², r² = 0.37, n = 240; 2001, ‘McIntosh’ YT, yield = 136.0 + 0.056x, r² = 0.31, n = 40; 2001, Gala YT, yield = -100.4 + 0.39x - 7.3 × 10⁻⁵x², r² = 0.34, n = 40; 2001, ‘McIntosh’ spindles, yield = -122.3 + 0.27x - 4.4 × 10⁻⁵x², r² = 0.66, n = 77; 2001, ‘Gala’ spindles, yield = 107.8 + 0.10x, r² = 0.58, n = 79. All relationships were statistically significant (α = 0.05).

Table 2. Mean cumulative yield per hectare, cumulative yield efficiency (kg of fruit/cm² of trunk cross-sectional area), and the ratio of cumulative yield to final scion weight (C/S ratio) for ‘Royal Gala’ and ‘Summerland McIntosh’ apple trees in three training systems at five tree densities after 10 years.

	Cumulative yield (t·ha ⁻¹)	Cumulative yield efficiency (kg·cm ⁻² TCA)	C/S ratio (kg·kg ⁻¹)
Training system (n = 80)			
Slender spindle	273.3	4.82	19.59
Tall spindle	275.7	5.25	20.32
Y trellis	302.8	5.70	19.74
MSD ^z	25.0	0.59	2.57
Density (trees/ha) (n = 48)			
1125	184.1	5.63	20.90
1587	244.5	5.58	22.26
2012	307.2	5.19	18.40
2481	330.7	5.11	19.14
3226	351.3	4.81	18.82
MSD ^z	20.0	0.42	1.62
Cultivar (n = 120)			
Royal Gala	328.9 a ^y	4.95 b	18.95
Summerland McIntosh	238.5 b	5.58 a	20.83

^zMinimum significant difference determined by Waller-Duncan K ratio t test (K ratio = 100).
^yMeans followed by different letters are significantly different at the 5% level.

(1993), but not Robinson (1997). Barden and Marini (2001) obtained C/S ratios of ≈15 for ‘Gala’ on M.9 after 14 cropping years, slightly lower than the C/S ratios we found after only nine cropping years (Table 2).

Training system did not exert any significant effects on productivity until the sixth leaf. Beginning in 1997, the YT began to yield slightly more than spindle trees, culminating in ≈14% greater per-tree yield averaged over all densities (155.1 kg/tree for YT, 134.3 kg/tree for SS, 137.4 kg/tree for TS). The effects of training system and density interacted significantly beginning in the seventh leaf. The YT out-yielded the spindle forms at lower densities but not at high density, and the difference became larger over time (Fig. 1). This was the only consistent interaction observed in the study, and it supports the findings of Robinson and Lakso (1989) that the YT can yield more than SS even when the latter are at a higher tree density. System and density also influenced cumulative yield per ha, but they did not interact significantly for that variable (Table 2). Although tall trees have yielded more than short ones in some studies (Barritt, 2000; Callesen, 1993), in this study the two systems probably did not differ sufficiently for height to exert any influence on productivity (Hampson et al., 2004).

Greater cumulative yield on the YT may have been due in part to crop load differences. Despite a concerted effort to thin all systems equally, the crop load was slightly higher on the YT than spindles in three of the last five cropping years (Table 3). Hand-thinning difficulties with the YT may have contributed to its higher crop load. Fruitlets were harder to see and reach inside the arms of the Y after the trellis was filled. Alternatively, the better yield of the YT could be related to its greater light interception than the TS or SS (Hampson et al., 2004). The YT has out-yielded spindles in previous studies by a similar percentage (Hampson et al., 2002; Robinson et al., 1991; Robinson, 1997).

Training system effects were small relative to density effects on productivity per unit area. Large training system effects are most often reported when confounding factors such as rootstock, rectangularity and tree density are not taken into account. If these factors are held constant and pruning is not severe, training system effects on productivity tend to be relatively small, at least within the time frame of most experiments (10 years or less).

CROP PRODUCTION

Table 3. Mean average fruit weight (AFW) in grams and crop load (CL, number of fruit/cm² of trunk cross-sectional area) for ‘Royal Gala’ and ‘Summerland McIntosh’ apple trees in three training systems at five tree densities.

	1995		1996		1997		1998		1999		2000		2001	
	AFW	CL	AFW	CL	AFW	CL	AFW	CL	AFW	CL	AFW	CL	AFW	CL
Training system (n = 80)														
Slender spindle	169	6.4	156	7.5	199	4.2	201	5.7	185	3.6	172	4.6	183	3.5
Tall spindle	169	6.6	149	8.7	196	4.3	191	6.8	182	3.6	161	5.6	173	4.0
Y trellis	157	7.0	139	9.9	183	6.0	190	8.0	176	3.9	159	6.4	174	4.3
MSD ^a	6	1.3	7	1.7	15	1.0	15	1.2	15	1.1	7	1.0	5	0.7
Density (trees/ha) (n = 48)														
1125	174	7.1	146	10.4	202	4.1	199	7.6	187	4.3	170	6.4	179	4.4
1587	164	6.9	151	8.3	186	5.4	200	6.7	180	4.0	159	5.5	168	4.7
2012	162	7.1	146	9.1	194	4.6	197	6.7	182	4.0	168	5.3	180	3.7
2481	158	6.5	147	8.1	188	5.5	187	6.8	178	3.3	161	5.5	180	3.8
3226	167	5.7	148	7.7	194	4.5	187	6.3	176	2.9	163	4.8	177	3.3
MSD ^a	7	0.9	8	0.9	11	1.2	15	0.8	15	1.4	8	0.8	6	0.7
Cultivar (n = 120)														
Royal Gala	159 b ^a	7.5	163 a	7.6 b	202 a	5.9 a	205 a	5.4 b	180	3.8	166	5.5	183 a	3.7
Summerland McIntosh	171 a	5.8	132 b	9.8 a	183 b	3.8 b	183 b	8.3 a	182	3.6	162	5.5	170 b	4.2

^aMinimum significant difference determined by Waller-Duncan K ratio *t* test (K ratio = 100)

^bMeans followed by different letters are significantly different at the 5% level

Clayton-Greene (1993) and Robinson (1997) also commented on the “remarkable similarity” in performance of systems quite different in tree training and final canopy shape.

The major effect of cultivar in this experiment was on yield. Starting in 1997 (sixth leaf), ‘Gala’ was significantly more productive than ‘McIntosh’, with ≈40% greater yield by the end of the trial (‘Gala’, 166.1 kg per tree, ‘McIntosh’, 118.3 kg per tree). Graphs of annual yields showed that ‘McIntosh’ was more susceptible to alternate bearing, but yielded less than ‘Gala’ even in “on” years (data not shown). However, ‘McIntosh’ was more yield-efficient than ‘Gala’ (Table 2).

Fruit size and color. Training system and density had little effect on average fruit weight once crop load was taken into account (Table 3). Fruit size of ‘Golden Delicious’ on M.9 began to decrease above 1800 trees/ha in Italy (Corelli and Sansavini, 1989), and of ‘Gala’ on MM.106 at 1250 trees/ha in New Zealand (Tustin, 1993). In contrast, Weber (2001) reported reduction in fruit size only >6400 trees/ha on superspindle trees in Germany. None of these studies held rectangularity constant. Shade is known to reduce fruit size (Barritt et al., 1997), so factors affecting light relations in the canopy, such as rootstock vigor, training system, and rectangularity, can also affect fruit size.

Color development on ‘Gala,’ as measured by the proportion of fruit not ready until the last pick, was not affected consistently by either

density or training system (data not shown). In the early years of the trial, we collected ‘Gala’ fruit samples at each pick date for a color assessment similar to that done with ‘McIntosh,’ but no consistent differences were found among treatments with that method either. A greater proportion of fruit was left for the last pick at higher tree densities in some years, but not in any of the last 3 years of the trial. Similarly, Meland and Hovland (1997) remarked that fruit size and color of ‘Summerred’ were not influenced by training system so much as crop load.

Despite some variability, the percentage of highly colored fruit in ‘McIntosh’ tended to decline at the highest tree densities (Table 4). The color reduction was not a crop load effect, because crop loads were the same or lower at the higher tree densities in these years (Table 3). Robinson (1997) noted reduced color of ‘Jonagold’ and ‘Empire’ at high tree density. Color is believed to be more sensitive than fruit size to light environment (Mika et al., 1981; Mika and Piskor, 1997; Palmer et al., 1989).

Projected yields. Economically, biological yield is less important than the yield of top quality fruit. At the moment, most growers are paid according to fruit size and color. In our region, yields of ≈28.5 t·ha⁻¹ of apples box size 100 or larger, with 80% or more having color grades of Extra Fancy or higher are needed

for economic viability, with the proviso that numerous other variables are also at play (Rob Dawson, Cawston, B.C., Canada, personal communication).

We do not have the breakdown for fruit size and color for each particular combination of cultivar, system and density in our trial, nor do we have labor records. Profitability is a crucial question that cannot be answered from our data. We can only comment on the gross shipped yield (total yield minus orchard culls). Orchard culls were ≈5% for ‘Gala’ and 5% to 10% for ‘McIntosh’ each year. Totals for the average shipped yield over the last 4 years of the trial appear in Table 5. Not all of this fruit would be in the desired size and color categories. As an example, the percentage of ‘Gala’ fruit in the desired categories in mixed shipments from this and two other trials at the research station was ≈75% in 1998 and 1999, according to packing house records. Theoretically then, if shipped yields were ≈40 t·ha⁻¹, then 30 t·ha⁻¹ would be in the desired category. Such yields were obtained at 2012 trees/ha for spindles and 1587 trees/ha for YT on average with ‘Gala’ (light interception 40% to 47%, data not shown).

The highest average shipped yield for ‘McIntosh’ was 38 t·ha⁻¹, and 56 t·ha⁻¹ for ‘Gala’ (Table 5). Not only was ‘McIntosh’ less productive, it seemed more sensitive to the adverse effects of high density on fruit color. In “off” years, the gross shipped yields were below the equivalent of 30 t·ha⁻¹ in many instances, regardless of density or training system. In “on” years, desired fruit size and color were more difficult to achieve.

Summary

Of the three factors in this study, planting density influenced yield the most. As density increased, yield per tree decreased, but yield/ha increased. The chief advantage of high density was a large increase in early fruit yield/ha. Training system did not begin to exert any significant effects on productivity until the sixth leaf. The yield per tree for YT was higher than for spindle forms at the lower

Table 4. The percentage [standard error (SE) n = 4] of ‘Summerland McIntosh’ apples with ≈50% Red No. 6 blush in fruit samples from five tree densities in 4 years.

Year ^a	Density (trees/ha)				
	1125	1587	2012	2481	3226
1997	35 (3)	26 (10)	32 (5)	26 (3)	28 (3)
1999	74 (6)	67 (9)	53 (10)	49 (9)	56 (4)
2000	69 (4)	50 (5)	45 (4)	43 (9)	47 (4)
2001	72 (6)	59 (12)	57 (6)	53 (4)	52 (8)
Mean ^b	62 (5)	50 (6)	47 (4)	43 (4)	46 (4)

^aIn 1998, the autumn weather was very hot (≥25 °C) during fruit maturation. Less than 10% of the fruit had ≥50% Red No. 6 regardless of density.

^bn = 16.

Table 5. Average shipped yield in t·ha⁻¹ (total yield – orchard culls) over the last 4 years of the trial of ‘Royal Gala’ and ‘Summerland McIntosh’ for different tree densities and training systems.

	Slender spindle	Tall spindle	Y trellis
Gala			
1125	24.7	30.9	35.2
1587	36.1	34.3	43.6
2012	42.1	42.0	52.8
2481	45.6	51.8	50.7
3226	50.1	55.9	47.4
McIntosh			
1125	18.4	17.8	28.0
1587	24.4	23.9	29.4
2012	30.3	31.9	38.4
2481	31.7	37.7	36.9
3226	36.9	36.1	36.1

tree densities but not at higher densities. The major effect of cultivar in this experiment was on yield, with ‘Gala’ being more productive than ‘McIntosh.’

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