Quote: *. . . incremental gain in cumulative yield/ha diminishes as density increases . . . .*

Effects of Apple Tree Density and Training System on Productivity

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High density dwarf plantings offer apple growers the opportunity of obtaining greater yield per unit area and high early productivity. Ladder work can be reduced or even eliminated with some of the newer training systems, reducing labor costs for pruning, thinning and picking. The smaller canopies improve pesticide spray penetration. Improved light distribution (and therefore fruit quality) is also possible with high density dwarf trees.

The greater yield of high density plantings relative to conventional low density systems is due to better use of incident light. Models and experimental data on light interception in orchards have demonstrated that dry matter and yield are proportional to total light interception, whereas fruit quality and return bloom depend on light distribution within the canopy (Jackson, 1980; Robinson and Lakso, 1989; Palmer et al., 1992). High density plantings support greater leaf area, so they intercept more light and yield more. The greatest light interception is found in full-field or multiple-row systems, but single rows are usually preferred because they permit better machinery access and higher fruit quality (Wagenmakers, 1991).

In order to achieve high density with single rows and still have alleys wide enough for tractor access, in-row spacing is typically reduced. When this is done, rectangularity (the ratio of alley width to within-row spacing) changes simultaneously. Rectangularity itself affects both interception and distribution of light, and influences yield, tree height, canopy spread, fruit color, flowering and return bloom, and sometimes fruit size (Cripps et al., 1975; Callesen and Wagenmakers, 1989; Wagenmakers and Callesen, 1989). A more square (less rectangular) layout, with between-row and within-row distances fairly similar, is most favorable for light interception and distribution. Problems associated with high rectangularity (less square layouts) become more pronounced as the orchard ages (Wagenmakers and Callesen, 1989). Rectangularity is therefore an important variable on its own, yet studies comparing different densities and training systems rarely hold rectangularity constant. The true effect of density or training system on orchard performance cannot be separated from that of rectangularity in such data.

Here we present early findings on two studies. In one, rectangularity was held constant and density and training system were varied. In the other, different canopy shapes were compared at the same rectangularity and tree spacing, with one canopy shape repeated at a close in-row spacing.

DENSITY TRIAL WITH THREE TRAINING SYSTEMS

The trees were planted in 1992 and were drip-irrigated. Amounts of water and fertilizer were applied on a per tree basis. Cultural practices followed commercial recommendations except that all thinning was done by hand. The cultivars were Royal Gala and Summerland McIntosh on M.9. These cultivars were chosen to represent a range of vigor from high (Gala) to low (McIntosh). Rectangularity was held constant at 2.5 (i.e., the alley width was always 2.5 times the in-row spacing). The five experimental densities corresponded to 1125, 1587, 2012, 2481 and 3226 trees/ha (455, 642, 814, 1004 and 1306 trees/acre).

The training systems were chosen to represent a range of canopy shapes: slender spindle, modified vertical axis and Y-trellis. The modified vertical axis (MVA) was a combination of slender spindle and vertical axis training (Fig. 1). Small heading cuts (1/4 or less of the leader) were made for the first 3 years to improve lateral development at the base of the tree, a weakness of conventional vertical axis training. The lower scaffolds were trained as for the slender spindle. The leader was tied to give it support and maintain dominance, and competing laterals were pinched back or removed. The slender spindle (SS) was expected to be 2.0 m (6.6 ft) high at maturity, and the MVA 3.0 m (9.8 ft). For the Y-trellis (YT), trees were headed at 0.6 m (2 ft) at planting. Two laterals per arm of the Y were tied to the trellis. The arms of the Y were 60˚ apart and the trellis was 2.0 m (6.6 ft) high. Branches that developed between the arms were trained to the trellis. All three training systems were pruned minimally.

Early results of the density trial were published previously (Hampson et al., 1997). For the first 4 years, light interception was directly proportional to tree density and was closely related to leaf area index (leaf area per unit land area). That is, as the number of trees per hectare increased, so did the amount of leaf area and the amount of light that was intercepted. Yield per tree and yield efficiency (kg fruit/cm^2 trunk cross-sectional area) decreased as density increased, but yield/ha increased. Training system had no effect on light interception, yield, yield efficiency, trunk diameter or canopy spread. The YT had greater spur leaf area and was pruned less than the other systems but, despite these advantages, its yield and light interception were no greater in the first

4 years. Light interception and leaf area were not recorded in 1996, but canopy spread, trunk diameter and yield continued to be unaffected by training system.

In the sixth leaf (1997), density continued to be the dominant factor in the experiment, but effects of cultivar and training system were also observed, as well as interactions among them in some cases. Only the overall means are shown in the data tables, but any significant interactions are described in the following discussion.

In 1997, the light interception of the intermediate tree densities began to catch up to the light interception of the highest density (Fig. 2). Training system had an effect on light interception for the first time in the experiment: the YT trees intercepted more than the others (Table 1). The MVA trees have become taller than the SS trees, but so far have not intercepted more light. Cultivar and density interacted as Gala intercepted more light than McIntosh at the higher densities in the study. Light interception continued to be closely related to leaf area index (Fig. 1).

Shoot leaf area and shoot leaf number per tree were similar for all training systems, densities and cultivars (Table 2). Leaf area index therefore rose as density increased. Trees had fewer spurs as density increased, but leaf area per spur was not affected. The YT trees had more spurs than MVA or SS (Table 1). Possibly bending the branches to the trellis induced more spurs to form. Gala had greater spur leaf area than McIntosh (0.85 m^2 per tree quadrant [quarter] vs. 0.51 m^2), but about the same number of spurs (56 per quadrant vs. 53), suggesting that Gala had either more or larger spur leaves.

An increase in density was associated with smaller TCA and canopy spread (Table 2). As expected, canopy spread and tree height differed among training systems, but TCA did not (Table 1). More containment pruning was required for the SS however. Measures of vegetative growth (TCA, height, pruning weight) confirmed the common observation that Gala is a more vigorous scion than McIntosh (data not shown). Some significant interactions (system x density, cultivar x system x density) were noted among measures of tree size. These appeared to be due to differences in the magnitude of response to various treatment combinations.

In keeping with its greater light interception, greater spurriness and lower pruning weight, the YT had greater yield than the other systems for Gala in 1997 (Table 3). With McIntosh, YT and MVA had higher yield per tree than SS. The McIntosh trees were under-thinned in 1996. Consequently they had smaller fruit in 1996 and were "off" fruiting in 1997. Yield per tree was much less than for Gala. We will attempt to correct this problem in 1998. Average fruit weight was slightly lower on the YT than the other systems, but this appeared to be a function of crop load (Table 3). The YT trees were inadvertently thinned less than the others for the last 2 years, despite a conscious effort to thin uniformly. Perhaps the small fruitlets are more difficult to see in this canopy configuration. Cumulative yield per tree was higher on the YT than SS or MVA for Gala; differences among the systems were small with McIntosh. Data pooled over all spacings and both cultivars appear in Table 3. We plan to continue monitoring the plot to determine whether the greater cumulative yield and lower average fruit weight of the YT are consistent or merely artifacts of slightly overcropping it for the past 2 years.

Density continued to exert an effect, reducing yield per tree but increasing yield/ha (Table 4). Cumulative yield/ha has been much greater at the highest densities. The increase in cumulative yield/ha is approximately proportional to the increase in tree density between 1125 and 2012 trees/ha, but a further 60% increase in tree density (to 3226 trees/ha) has achieved only a 16% increase in cumulative yield/ha. The cumulative yield efficiency, a measure of harvest index, was about the same regardless of density, i.e., the proportion of fruit to wood did not change as density increased (Table 4).

Apple size and color are important measures of fruit quality that affect economic return. To date, the small differences in average fruit weight among systems have been attributable to differences in crop load. Differences in average fruit weight with changing density have not been consistent. The percentage of highly colored fruits decreased with increasing density over the past 3 years (data not shown). The trend has been most noticeable for McIntosh (Table 5) and the last pick of Gala. Because Gala is picked by color, differences in the earlier picks were not expected to be large.

TRAINING SYSTEM TRIAL

The training system trial was planted in 1992. Cultural practices have been the same as for the trial just described. All trees were Royal Gala/M.9. The planting is a fully guarded randomized complete block design with four blocks. Five training systems were chosen to represent a range of canopy configurations: SS and YT (trained as described above), modified Solen, and V-trellis at two densities.

For the Solen, two branches were selected in the second leaf, pulled across over the trunk and tied to the wire (Fig. 3). Laterals from these two cordons were trained upward on wires. A modification was made in training the Solen, called the Solen Y or "Miketech" after Mike Sanders. Instead of training the upright branches horizontally, they were trained into a Y. An important advantage of the Solen Y was that the junction of the arms and trunk was higher above the ground than on the YT, thus making training and picking easier. For the V-trellis, the trees were leaned alternately to one side or the other (Fig. 3). The YT and V-trellises were 2.0 m (6.6 ft) tall. Tree spacing was 1.2 m x 2.8 m (3.9 ft x 9.2 ft) for all training systems but the high density V, which was 0.5 m x 2.8 m (1.6 ft x 9.2 ft). The corresponding densities were 2976 and 7143 trees/ha (1204 and 2891 trees/acre).

Training system affected tree height, TCA and canopy spread, but not yield per tree or cumulative yield per tree, among the four systems at 2976 trees/ha (Table 6). The Solen Y system has had greater cumulative yield efficiency to date than the V-trellis or SS, in spite of the setback resulting from the pruning and training of the cordons in year 2.

Compared to the low density V, the high density V trees were taller and narrower in spread and trunk girth (Table 6). They had lower cumulative yield/tree but were not different in yield efficiency compared to trees in the low density V. The advantage of high tree density to yield in the early years is again clear from the figures on cumulative yield/ha.

The high density V has consistently ranked lowest in average fruit weight among the five training systems for the past 3 years. Average fruit weight was lower at the high density, although crop load (no. of fruit/cm^2 TCA) was similar to other training systems. For example, compare the fruit size for low density and high density V in 1997 (Table 6). The effect could be one of rectangularity or density or both, as the two were not separated in the training system trial.

The only consistent training system effect on fruit color observed so far is that the low density V has tended to have among the highest proportion of highly colored fruit (Fig. 4). The high density V and SS have been similar for fruit color. Other training systems have varied from year to year in fruit color without a consistent pattern.

CONCLUDING REMARKS

1. Density was the predominant factor affecting tree growth, leaf area, light interception and fruit yield/ha in the early life of the orchards. Greater density resulted in greater light interception and fruit yield in early years regardless of training system. The increment in yield was not strictly proportional to density, but rather decreased incrementally with increasing density.

2. Rapid establishment of high leaf area is the key to achieving large early yields with high density plantings. Minimal pruning is clearly indicated, in order to facilitate canopy development

without discouraging cropping. Placing trees very close within the row may not be the best way to achieve the goal of rapid attainment of leaf area. Highly rectangular layouts have been associated with reduced fruit quality (Callesen and Wagenmakers, 1989).

3. Because the incremental gain in cumulative yield/ha diminishes as density increases, at some point the gain in yield is not sufficient to cover the extra costs incurred in planting at extremely high density. By the sixth leaf, intermediate densities were beginning to catch up to the highest density in light interception and cumulative yield/ha. A crop loss in the early years of the orchard could have a dramatic effect on the early economic advantage of extremely dense plantings. At high density and/or rectangularity, heavy pruning or tree removal may become necessary later in the life of the planting if tree vigor is high, raising costs.

4. Up to the sixth year, very few differences in yield, light interception or fruit quality emerged among training systems with quite different canopy shapes, if density and rectangularity were held constant and pruning was minimal. Any training system advantages appear to take considerable time to develop. One should be cautious about accepting training system recommendations based on a few years' data, or if the training systems have not been compared on an equal footing (e.g., different rootstock, spacing).

5. Although not always consistent, fruit color and size tended to be poorer at very high densities. Inconsistencies may be caused by year-to-year effects of pruning, training and branch spreading. More time will be required to determine the persistence of these trends in fruit quality. We plan to continue monitoring the planting to determine whether the system differences seen in 1997 will be consistent, change or disappear in coming years, especially the effects on yield, light interception and fruit quality. Training system, rectangularity and density effects may become more important over time. The findings reported here echo the principles that Robinson et al. (1996) presented at a recent IDFTA conference. The similarity between results in such different geographic and climatic situations re-affirms the soundness and general applicability of those principles.

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Table 1. Light interception and vegetative growth measurements of apple trees in three orchard systems in t

Training system	Light interception (%)	Tree height (cm)	Canopy spread (cm)	TCA[y] (cm^2)	Spur no./tree quadrant	Lea ind
Slender spindle	33.6 b	232 b	189 a	17.11 a	44.8 b	1.6
Modified vertical axis	34.2 b	262 a	178 b	15.78 a	48.5 b	1.5
Y-trellis	43.7 a	206 c	177 b	15.97 a	70.3 a	1.6

[z]Means with a column followed by the same letter are not significantly different at the 5% level. Means are f cultivars and all densities.

[y]TCA, trunk cross-sectional area, is a measure of tree size.

Table 2. Vegetative growth measurements in the sixth leaf of apple trees at five different densities.[z]

Density (trees/ha)[w]	Shoot leaf area[y] (m^2)	Shoot leaf number[y]	Spur number[y]	Leaf area index	Tree height (cm)	Canopy spread (cm)	TCA[x] (
1125 (455)	1.44 a	226 a	57.0 abc	0.92 c	221 b	189 a	16.9 ab
1587 (642)	1.46 a	236 a	58.9 ab	1.40 b	231 ab	188 a	17.2 a
2012 (814)	1.42 a	229 a	65.7 a	1.90 a	242 a	191 a	17.7 a
2481 (1004)	1.21 a	216 a	48.6 bc	1.78 ab	243 a	176 b	15.4 bc
3226 (1306)	1.09 a	191 a	42.4 c	2.08 a	230 b	163 c	14.2 c

[z]Means within a column followed by the same letter are not significantly different at the 5% level. Means ar
both cultivars and all training systems.

[y]Figures are per tree quadrant.

[x]TCA, trunk cross-sectional area.

[w]Trees/acre in brackets.

Table 3. Yield data for apple trees in their sixth leaf with three training systems.[z]

Training system	Yield/tree (kg)[y]	Cumulative yield (kg/tree)[x]	Cumulative yield (t/ha)[x]	Cumulative yield efficiency (kg/cm^2 TCA)[x]	Average fruit weight (g)[y]
Slender spindle	13.1 b	59.9 b	122.3 a	3.60 b	199 a
Modified vertical axis	12.9 b	59.4 b	121.0 a	3.81 ab	196 ab
Y-trellis	17.5 a	67.2 a	134.2 a	4.17 a	183 b

[z]Means within a column followed by the same letter are not significantly different at the 5% level. Means ar
both cultivars and all densities.

[y]1997 crop.

[x]1993 to 1997.

Table 4. Yield data for apple trees in their sixth leaf grown at five densities.[z]

Density (trees/ha)[w]	Yield/tree (kg)[y]	Cumulative yield (kg/tree)[x]	Cumulative yield (t/ha)[x]	Cumulative yield efficiency (kg/cm^2 TCA)[x]	Average fruit weight (g)[y]
1125 (455)	13.2 ab	64.5 ab	72.5 d	3.87 a	202 a
1587 (642)	16.4 a	66.2 ab	105.0 c	3.95 a	186 b
2012 (814)	15.6 a	69.2 a	139.2 b	3.94 a	194 ab
2481 (1004)	15.8 a	60.8 b	150.9 a	3.94 a	188 b
3226 (1306)	11.6 b	50.1 c	161.6 a	3.60 a	194 ab

[z]Means within a column followed by the same letter are not significantly different at the 5% level. Means ar both cultivars and all training systems.

[y]1997 crop.

[x]1993 to 1997.

[w]Trees/acre in brackets.

Table 5. Frequency of McIntosh apples showing the stated amount of "Red No. 6" blush in 1997 for different planting densities.

Density (trees/ha)[z]	More than 30% of fruit surface
1125 (455)	68.3
1587 (642)	60.8
2012 (814)	59.6
2481 (1004)	60.8
3226 (1306)	52.5

[z]Trees/acre in brackets.

Table 6. Vegetative growth and yield of Royal Gala apple trees in their sixth leaf with five orchard systems.

System[w]	Tree height (cm)[y]	Canopy spread (cm)[y]	TCA (cm^2)[y]	Yield (kg/tree)[y]	Cumulative yield (kg/tree)[x]	Cumulative Yield (t/ha)[x]	Cumulative yield efficiency (kg/cm^2 TCA)[x]
Slender spindle	2.41 c	1.75 b	14.9 a	14.1 a	36.9 a	110 b	2.59 c
V—low density	2.67 b	2.17 b	12.7 b	15.3 a	33.8 a	101 b	2.85 bc
V—high density	2.89 a	1.67 a	9.2 c	11.6 a	30.0 b	185 a	2.99 bc
Y-trellis	2.29 c	1.60 b	12.2 b	16.9 a	38.5 a	115 b	3.23 ab
Solen Y	2.49 bc	1.60 b	10.1 c	15.6 a	35.2 a	105 b	3.69 a

[z]Means within a column followed by the same letter are not significantly different at the 5% level.

[y]1997 crop.

[x]1993 to 1997.

[w]Tree density 2976 trees/ha (1204 trees/acre) for all systems but V-high density which was 7143 trees/ha (28

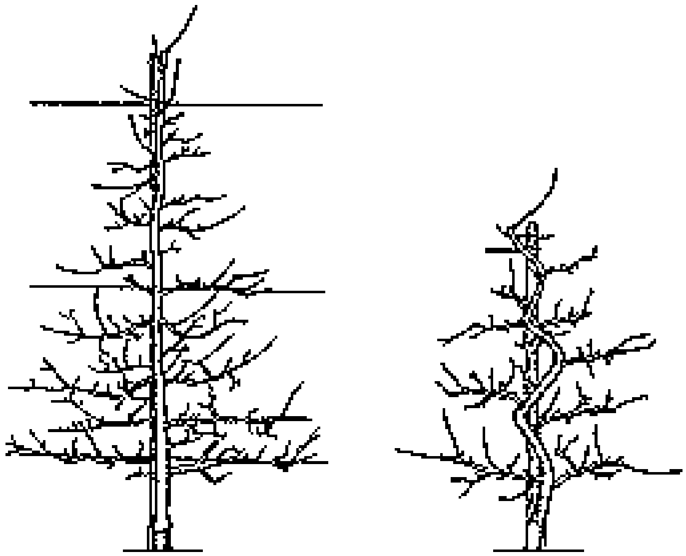

Figure 1. Tree training for slender spindle and vertical axis systems.

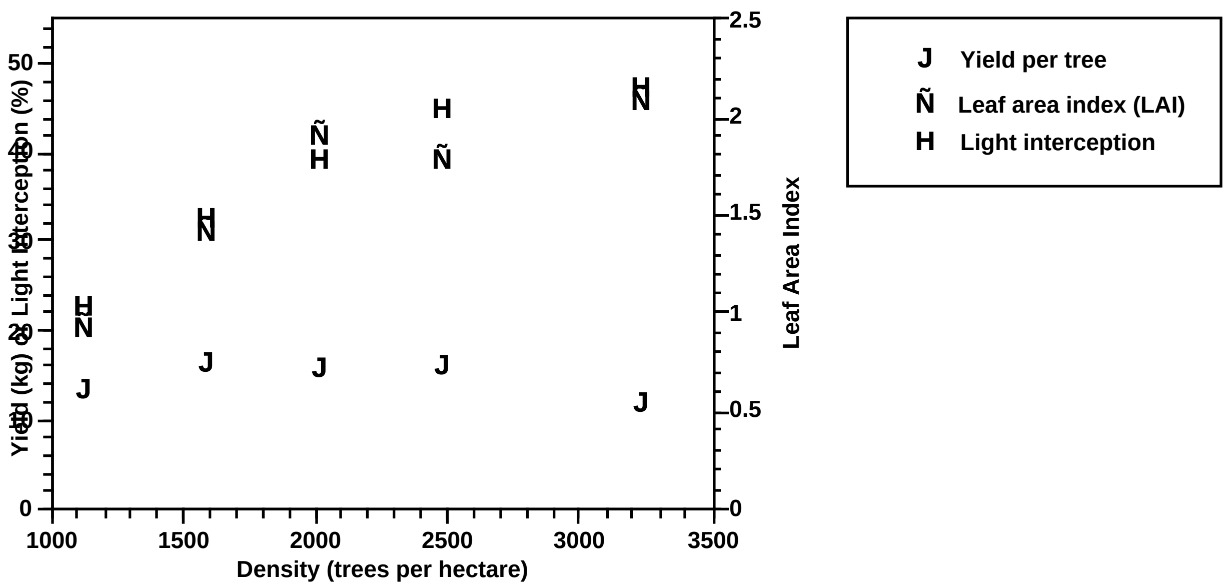

Figure 2. Relation between planting density and light interception, leaf area index and yield per tree in the sixth leaf.

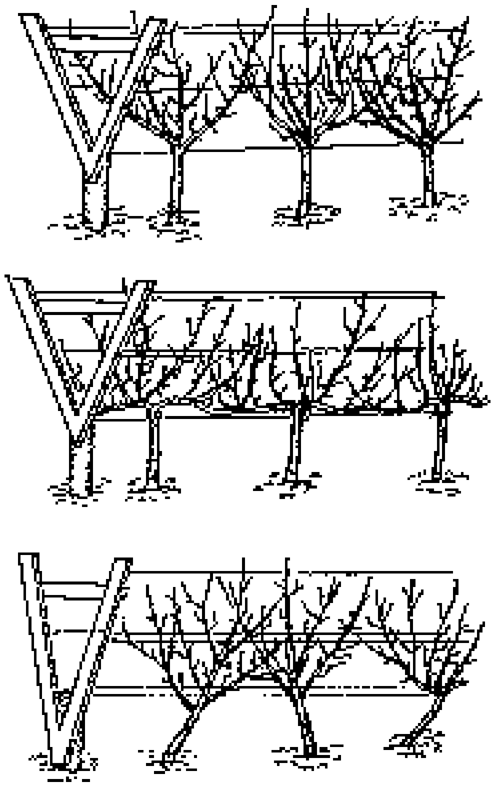

Figure 3. Tree training for a) Y-trellis, b) Solen Y and c) V-trellis training systems.

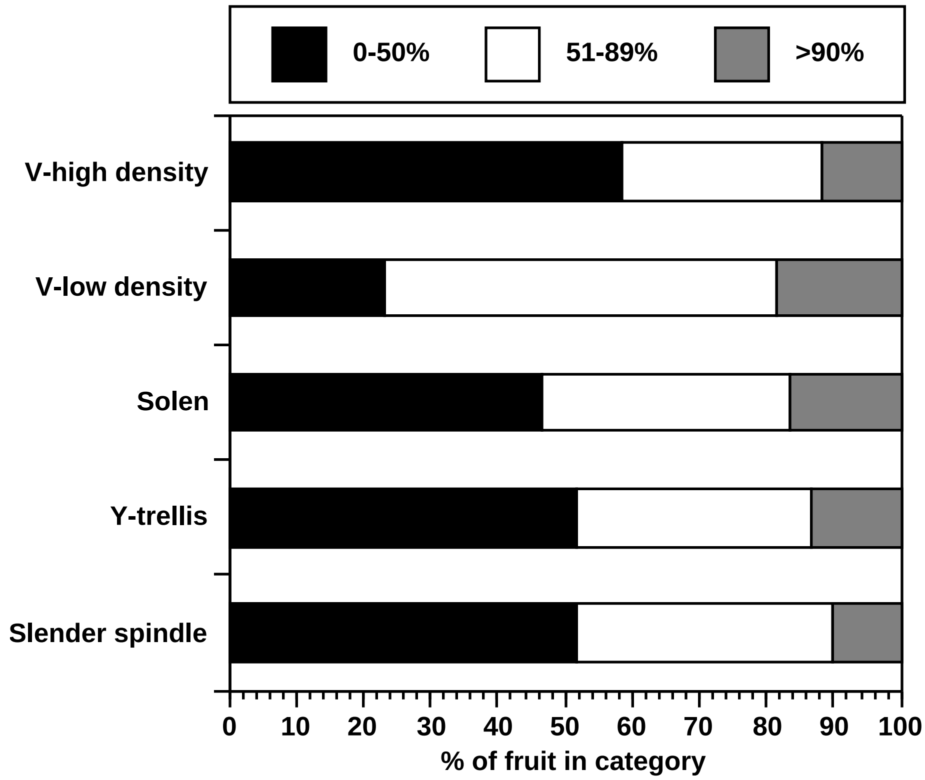

Figure 4. Frequency of Royal Gala apples showing the stated amount of solid red fruit surface in three orchard systems (sixth leaf).

Figure 4. Frequency of Royal Gala apples showing the stated amount of solid red fruit surface in three orchard systems (sixth leaf).