Effects of Tree Lateral Branch Number and Angle on Early Growth and Yield of High-density Apple Trees

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KEYWORDS. crop value, fruit quality, interrow groundcover, *Malus* × *domestica*, shoot growth, trunk growth

ABSTRACT. Initial tree quality from the nursery has an important effect on the early yield and profitability of new high-density apple plantings. Nursery tree quality is often defined as the combination of trunk diameter (caliper) and the number of axillary branches (lateral branches or feathers). In this study, we evaluated the influence of the number of lateral branches (feathers) and the angle of the feathers on growth and yield of five apple cultivars (Mutsu, Gala, Honeycrisp, Jonagold, and Macoun) on M.9 or B.9 rootstocks over the first 5 years after planting in the orchard at Geneva, NY, USA. Yield was positively related to the number of lateral branches. Manual bending the feathers below horizontal increased yield during the early life of the planting, especially for more vigorous cultivars with upright growth. There was a significant economic benefit to a greater number of feathers and to bending feathers below the horizontal.

Early tree growth and cropping of high-density apple trees are influenced by a number of factors, including rootstock genotype (Robinson et al. 2006), initial tree caliper (Lawes et al. 1997; Robinson and Stiles 2004; Sadowski et al. 2007; Van Oosten 1978), initial number of lateral branches (feathers) (Ferree and Rhodus 1987; Sanders 1993; Van Oosten 1978), water supply (Dominguez and Robinson 2024; Pereira and Pires 2011; Robinson and Stiles 1994, 2004), mineral nutrient reserves in the plant (Atay 2023; Cheng and Fuchigami 2002; Stiles and Reid 1991), and crop load (Palmer 1992; Robinson 2008b). With modern high-density plantings, which require high initial investment, it is expected that trees will grow sufficiently to fill the allotted space in the first 2 to 3 years while at the same time beginning fruit production in the second year to recoup the investment costs as quickly as possible (Robinson et al. 2007).

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Planting highly feathered trees in high-density orchards is suggested for the tall spindle system (Robinson et al. 2006, 2011) because it is expected that the number of feathers has a positive effect on early yields. Sanders (1993) defined a feather as a lateral branch or axillary shoot that is the same age as the leader (trunk). Whips are trees consisting of just the leader without any lateral branches. Feathered trees are now being produced in large scale by commercial nurseries. This has been made possible by the use of plant growth regulators that enhance the formation of lateral shoots when the tree is still in the nursery (Cowgill et al. 2014; Elfving and Visser 2005; Forshey 1982; Miranda-Sazo and Robinson 2011; Robinson and Miranda Sazo 2014; Wertheim and Estabrooks 1994).

The main advantage that growers have with the adoption of these highly feathered trees is the potential of high early yields compared with those of whips. Van Oosten (1978) found that the greater the number of feathers the tree has at planting, the higher the early yields. Ferree and Rhodus (1987) tested three cultivars with different growth habits and found an increase in yield attributable to the number of feathers during the third and fourth year, especially for the vigorous cultivar. They stated that adopting feathered trees has an economic benefit for the grower. Robinson et al. (2007) demonstrated that the use of large-caliper feathered trees was more profitable at medium-high densities of 2600 trees/ha.

Bending of lateral branches is a management practice that reduces vegetative growth in cherry and plum (Wareing and Nasr 1961) and increases flowering and fruiting of apple (Luckwill 1969). For apple, Wareing and Nasr (1961) found that when shoots were in a horizontal position, their growth was less than that when shoots were vertical, but the uppermost shoots showed a greater reduction than that of lower ones when trained horizontally. They also found that when the shoots were trained vertically, the upper shoots showed a well-marked apical dominance. Lespinasse (1977) found that branch angles more vertical than 45 degrees resulted in vigorous growth and little flowering. Branches at 45 degrees produced less growth, heavy flowering, good fruit size and quality, while branches bent below horizontal resulted in almost no terminal growth, with small spurs that gave small fruit size. For pears, Lawes et al. (1997) reported that bending the leader increased the development of short shoots (spur) and increased flower number and bloom density of 'Comice' pears. Mahdavi et al. (2020) reported that number of upright shoots in nursery trees can influence mixed bud formation in apples, and induction of these branches can be influenced by scoring, girdling, and application of Promalin.

Bending feathers at planting has become a suggested management practice for some high-density systems and has been integrated into different training systems such as the slender spindle (Robinson 2008a; Wertheim 1970), SolAxe (Lauri and Lespinasse 1998), tall spindle (Robinson et al. 2006, 2011), and Tatura trellis (Fallahi et al. 2024) systems. This technique has been implemented as an alternative to pruning to induce early flowering and maintain the tree within its allowed space.

Some other studies of branch manipulation have been contradictory. Depending on the study, it either increased flower bud formation (Mahdavi et al. 2020; Tromp 1970) or did not have a consistent effect on flower bud formation (Longman et al. 1965). Some of these contradictory results could simply be caused by the growth and fruiting characteristics of the cultivars tested. Lauri and Lespinasse (2001) tested different bending times with two cultivars and concluded that branch bending effects on fruiting are highly affected by the genotype. The time of bending could also influence the type of buds during the year of bending and the following years. This could be the reason for such variability reported by previous work regarding this topic. With more information about differences among cultivars, the recommendation of bending branches with the tall spindle system could be adapted to the specific growth and fruiting habits of each cultivar.

The objective of this project was to evaluate the effect of the number of feathers and the feather angle on growth and yield of five common cultivars in New York when trained to a tall spindle system.

Materials and methods

Plant materials. In 2009, a field study was planted at the New York State Agricultural Experiment Station (NYSAES) in Geneva, NY, USA (lat. 42°N, long. 77°W). The soil was a Honeoye fine sandy loam (He) with good water holding capacity, well-drained, and fertile, with approximately 3% organic matter content and a 6% slope. Five apple scion/rootstock combinations were used in this experiment: 'Mutsu' on M.9T337 rootstock; 'Brookfield Gala' on M.9Pajam2; 'Rubinstar Jonagold' on B.9; 'Honeycrisp' on M.9Nic29; and 'Macoun' on B.9. These main effect treatments are hereafter referred to as cultivar effects using the monikers Mutsu, Gala, Jonagold, Honeycrisp, and Macoun, with the recognition that they represent both scion and rootstock effects with respect to the treatment response.

The experimental trees were produced in a commercial nursery (Willow Drive Nursery) from 2006 to 2008 in Washington. Rootstock liners were produced in stool beds in 2006. The harvested liners were planted in the nursery in Spring 2007 and chip-budded in Aug 2007, and the scion bud was grown into the finish tree in one year (2008). In 2008, the trees were sprayed with 6-benzyl adenine (Maxcel) three times at 10-d intervals when the scion shoot reached 70 cm in height. The finished tree height was approximately 1.9 m, and the trees all had between 10 and 15 feathers.

The trees were planted in the experimental plot on 18 Apr 2009, at spacing of 1 m within the rows and 3.5 m between rows, resulting in 2857 trees/ha that were trained as tall spindles. The orchard received standard disease, insect, and weed control throughout the five growing seasons. The crop load was managed each year. In the second year, trees were hand-thinned when fruitlets were 10 mm in size to a single fruit per cluster, and then additional thinning was performed to achieve 10-cm spacing between fruitlets. In the third through the fifth seasons, trees were chemically thinned when fruit size was 10 mm and then additional hand-thinned when fruits were 25 mm, leaving a single fruitlet per cluster and 10 cm between fruits.

Experimental design and treatment structure. The experiment was designed as a strip-split-plot, randomized complete block, with the main plot treatment being cultivar (Mutsu, Gala, Honeycrisp, Jonagold, and Macoun) and the subplot treatments being the number of initial feathers and the angle of the feathers. Each subplot was composed of five individual trees, which were assigned randomly to one of the five treatments: zero feathers, five feathers with feathers at the natural angle, five feathers with all feathers tied below horizontal to approximately 135° from vertical, 10 feathers with all feathers at the natural angle, and 10 feathers with all feathers tied below horizontal to 135° from vertical. There were 12 replications of each subplot. A guard tree was planted between each subplot. The experimental orchard was organized in five rows (one row per cultivar), with each row composed of 60 experimental trees and 13 guard trees. Blocking of subplot treatments within each cultivar was based on the initial trunk diameter measured with a digital caliper. Cultivars were laid out as strip treatments to facilitate orchard management, especially chemical thinning. Rows were oriented north–south.

A different number of feathers per tree was achieved by starting with similar-diameter highly branched trees that all had 10 or more feathers and then reducing the number of feathers down to 0, 5, or 10 feathers through pruning at planting. The branches to be eliminated were preferentially the ones that were lower than a height of 60 cm, and any feather with excessive vigor (more than half the diameter of the trunk) or that had a very narrow crotch angle. In the case of trees with 5 or 10 feathers, two branch management techniques were compared. Branches were either left at their natural angle or bent down below the horizontal to approximately 135° from vertical. In the case of the trees with zero feathers, the lateral branches that grew later in the first season were not bent down.

Measurements. Trunk circumference was measured at planting and in November of each year at 30 cm above the graft union and used to calculate the trunk cross-sectional area (TCSA). Shoot growth was recorded in November each year for the first 4 years at the end of the season, but it was not recorded in the final fifth season. The length of every shoot on the tree including the axis was measured. This procedure was performed in 2009, 2010, and 2011. However, in 2012, the methodology was different. The leader and 30 randomly chosen shoots were measured, and the total number of shoots was counted on the whole tree. The number of shoots on the tree was multiplied by the average length of the 30 randomly chosen shoots to estimate total shoot length on the tree. In the spring of each year before budbreak for the first 4 years, the weight of the prunings per tree was recorded. In the second and third seasons, the numbers of floral buds were also counted at bloom, and the numbers of spurs (shoots shorter than 10 cm) at the end of the season were counted.

During the first year, trees were not allowed to crop to allow maximum tree vegetative growth. Beginning in the second growing season, the trees were allowed to crop and production data were collected annually. At each harvest, fruits were counted and weighed. In the third and fourth years, a sample of 10 fruits was collected from each treatment and stored in refrigerated storage for 4 to 5 months with a temperature of 2 °C and relative humidity of 75%. After storage, the fruits of the sample were tested to determine the soluble solids concentration (°Brix) using a portable refractometer

(Atago), and fruit firmness was measured from two peeled sides at the equator of each fruit using a fruit penetrometer (Model EPT-1 pressure tester; Lake City Technical Products Inc., Kelowna, British Columbia, Canada). Storage disorders including bitter pit, soft scald, water core, and senescent breakdown were assessed. In the fourth year, the 10 apple samples were evaluated for fruit size and color using a commercial electronic fruit grader (Pomone fruit grader; MAF RODA, Montauban, France) with a camera system to evaluated red color and load cells to evaluate fruit weight. A simulated packout was calculated with data from the fruit grading machine.

At the end of the 5 years, we calculated the gross cumulative crop value for each treatment by multiplying the cumulative production (t/ha) by the typical fruit price per kilogram for each cultivar ($0.65/kg for Mutsu, Gala, Jonagold, and Macoun, and $1.3/kg for Honeycrisp).

STATISTICAL ANALYSIS. The data were subjected to an analysis of variance (ANOVA) with a strip split plot design where cultivar was the main plot and branch number × branch angle was the subplot factor. When the ANOVA (SAS Proc GLM; SAS Inc., Cary, NC, USA) indicated a significant cultivar or branch treatment effect, mean separation was performed using Duncan's multiple range test with $P \leq 0.05$ using the appropriate error term for cultivar (main plot error) or branch treatment and the interaction of cultivar × branch treatment (subplot error). After the ANOVA, the effect of the number of feathers was evaluated by linear and quadratic regressions, and the effect of branch angle was evaluated using an ANOVA with only the trees with 5 and 10 feathers.

Results

Feather angle

VEGETATIVE GROWTH. During the first year of growth (2009), when feathers were left at their natural angle, total shoot length, average shoot length, and pruning weight per tree were significantly higher than those when feathers were tied below horizontal (Table 1). However, there was a significant interaction between cultivar × feather angle with total shoot length. With 'Mutsu', 'Jonagold', and 'Macoun', when feathers were left at their natural angle, total shoot growth per tree was significantly greater than that when feathers were tied below horizontal. However, with 'Gala' and 'Honeycrisp', there were no differences in shoot length caused by the feather angle.

In the second year (2010), the trees with feathers at their natural angle had the highest average shoot length, spur number per tree, pruning weight, and number of spurs and limbs pruned compared with those of trees with feathers tied below horizontal (Table 2). There was an interaction between cultivar × feather angle treatment, with a few response variables. The natural angle had the highest pruning weight for almost all the cultivars except 'Honeycrisp', which had no significant difference with the below horizontal treatment. The total numbers of spurs and limbs pruned were the highest with the natural feather angle treatment for all the cultivars compared with the below horizontal treatment, but the difference was much greater for 'Macoun' than that for the other cultivars.

During the third year (2011), the trees with feathers at the natural angle had the highest pruning weight, numbers of spurs and limbs pruned away, and total tree length compared with the trees with feathers below horizontal (Table 3). However, there were significant cultivar × feather angle interactions with pruning weight and numbers of spurs and limbs pruned away. The pruning weight and total numbers of spurs and limbs pruned were consistently higher when feathers were at their natural angle than when feathers were below horizontal, but the difference was much smaller for 'Honeycrisp' than for the other cultivars.

In the fourth year (2012), the trees with feathers at the natural angle had the highest TCSA, average shoot length, pruning weight, number of limbs pruned, and total tree length compared with those of trees with feathers below horizontal (Table 4). There were no significant cultivar × feather angle interactions.

During the last year of the experiment (2013), there were no significant differences in tree growth attributable to feather angle (Table 4). However, feather angle had an effect on cumulative tree growth, with trees with feathers at the natural angle producing more total shoot length and greater average shoot length and pruning weight than those of trees with feathers below horizontal (Table 4). There was a significant cultivar × feather angle interaction with average shoot length. Trees with feathers at the natural angle had the highest average shoot length for 'Mutsu', 'Honeycrisp', 'Jonagold', and 'Macoun'. However, for 'Gala', there was no difference in the average shoot length attributable to feather angle.

FLOWERING AND FRUITING. During the second year (2010) and the third year (2011), feather angle did not influence flowering or fruiting (Tables 5 and 6). In the fourth year (2012), when feathers were tied below horizontal, trees had more blossoms, fruit number, fruit weight, yield, crop load, and yield efficiency than those of the treatment with feathers at their natural angle (Table 7). Fruit size was significantly smaller when feathers were tied below horizontal than when the feathers were at their natural angle. There was a significant cultivar × feather angle interaction with fruit number per tree and crop load. With 'Mutsu', there was no significant difference in fruit number and crop load attributable to feather angle. Nevertheless, with 'Gala', 'Honeycrisp', 'Jonagold', and 'Macoun,' the treatments with feathers below horizontal had higher fruit number and crop load than those of the treatment with the feathers at their natural angle.

In the fifth year of the experiment (2013), fruit number, crop load, and yield efficiency were significantly higher with the feathers below horizontal (Table 8). There was a significant cultivar × feather angle interaction with fruit number. With 'Gala', when feathers were tied below horizontal, fruit number was greater than that when feathers were at their natural angle, but for all other cultivars, feather angle did not influence fruit number.

Over the entire 5 years of the experiment, when feathers were tied below horizontal the yield per tree, yield per hectare, yield efficiency, and crop load were significantly greater than when feathers were grown at their natural angle (Table 9). However, when feathers were at their natural angle, fruit size was greater than that when the feathers were below horizontal.

Table 1. Effect of the number of feathers and feather angle on tree growth of five apple cultivars in the first year (2009) at Geneva, NY, USA.

Cultivar/stock	Feathers (no.)	Feather angle	TCSA (cm^2)	Tree height (cm)	Leader growth (cm)	Total shoot growth (cm)	Avg shoot length (cm)	Spur number per tree	Pruning weight (g)	Total tree length (cm)
Mutsu/M.9T337			4.6 a[i]	192 b	34 b	250 c	21 b	15 c	11.4 b	579 c
Gala/M.9Pajam2			4.3 b	209 a	39 a	471 a	21 b	25 b	17.9 a	939 a
Honeycrisp/ M.9Nic29			3.9 c	196 b	38 ab	256 bc	14 c	43 a	0.8 c	608 bc
Jonagold/B.9			4.1 bc	180 c	40 a	287 b	24 a	18 c	9.1 b	658 b
Macoun/B.9			3.6 d	165 d	42 a	204 d	21 b	18 c	1.7 c	414 d
Cultivar/stock significance			**	**	*	**	**	**	**	**
Mutsu/M.9T337	0	—	194	194	44	333	27	9	3.5	469
Gala/M.9Pajam2	5	Natural	188	188	40	304	22	22	12.2	626
Honeycrisp/ M.9Nic29	5	Pendant	4.1	190	39	275	19	26	7.0	610
Jonagold/B.9	10	Natural	186	186	36	284	17	31	10.5	742
Macoun/B.9	10	Pendant	4.3	185	33	275	16	31	7.6	745
Regression with feather no.			L*	L*	L*	L*	L*	L*	Q*	L*
Angle of feather significance			NS	NS	*	**	**	NS	*	NS
Interaction significance			NS	NS	NS	NS	*	**	NS	**

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \leq 0.05$.

NS, *, ** Nonsignificant or significant at $P \leq 0.05$ or $P \leq 0.01$, respectively.

L, Q, and NS indicate that the number of feathers was related significantly to the response variable linearly, quadratically, and not related, respectively.

TCSA = trunk cross-sectional area.

There was a significant cultivar × feather angle interaction for cumulative yield per tree and per hectare. With 'Mutsu', 'Honeycrisp', 'Jonagold', and 'Macoun', feather angle did not affect yield. However, for 'Gala', yield was higher when feathers were tied below horizontal compared with when the feathers were at their natural angle. Crop load for 'Mutsu, 'Gala', 'Jonagold', and 'Macoun' was higher with feathers below horizontal. However, 'Honeycrisp' did not show any differences in crop load attributable to feather angle. Fruit size with 'Mutsu' was the largest with feathers at the natural angle, while with the rest of the cultivars, there were no significant differences in fruit size.

Number of feathers

VEGETATIVE GROWTH. During the first year (2009), the number of feathers had a positive linear effect on

Table 2. Effect of the number of feathers and feather angle on tree growth of five apple cultivars in the second year (2010) at Geneva, NY, USA.

Cultivar/stock	Feathers (no.)	Feather angle	TCSA (cm^2)	Leader growth (cm)	Total shoot growth (cm)	Avg shoot length (cm)	Spur number per tree	Pruning weight (g)	Spurs pruned per tree	Limbs pruned per tree	Total tree length (cm)
Mutsu/M.9T337			8.6 b[i]	42 b	651 cd	25 b	36 b	93 c	6.3 b	0.57 b	906 cd
Gala/M.9Pajam2			10.1 a	57 a	1363 a	32 a	62 a	255 a	9.4 a	0.50 bc	1834 a
Honeycrisp/ M.9Nic29			7.9 c	29 c	1089 b	21 b	46 b	93 c	8.1 a	0.42 c	1346 b
Jonagold/B.9			7.9 c	46 b	791 c	31 a	37 b	141 b	6.9 ab	0.53 b	1081 c
Macoun/B.9			7.8 c	49 b	554 d	30 a	43 b	97 c	8.5 a	0.75 a	758 d
Cultivar/stock significance			**	**	**	**	**	**	**	**	**
Mutsu/M.9T337	0	—	7.9	45	864	31	39	154	8.4	0.91	1197
Gala/M.9Pajam2	5	Natural	8.8	45	937	28	44	228	13.3	1.08	1244
Honeycrisp/ M.9Nic29	5	Pendant	8.5	46	907	26	40	95	4.6	0.03	1182
Jonagold/B.9	10	Natural	8.9	43	921	26	53	180	11.6	0.87	1205
Macoun/B.9	10	Pendant	8.9	43	903	25	50	83	5.4	0.03	1178
Regression with feather no.			L	NS	NS	Q	Q	L	Q	Q	NS
Angle of feather significance			NS	NS	NS	**	**	**	**	**	*
Interaction significance			NS	NS	*	NS	NS	NS	**	NS	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's at multiple range test at $P \leq 0.05$.

NS, *, ** Nonsignificant or significant at $P \leq 0.05$ or $P \leq 0.01$, respectively.

L, Q, and NS indicate that the number of feathers was related significantly to the response variable linearly, quadratically, and not related, respectively.

TCSA = trunk cross-sectional area.

Table 3. Effect of the number of feathers and feather angle on tree growth of five apple cultivars in the third year (2011) at Geneva, NY, USA.

Cultivar/stock	Feathers (no.)	Feather angle	TCSA (cm^2)	Leader growth (cm)	Total shoot growth (cm)	Avg shoot length (cm)	Pruning weight (g)	Spurs pruned per tree	Limbs pruned per tree	Total tree length (cm)
Mutsu/M.9T337			12.6 b[i]	33 c	1190 c	22 b	330 c	30 c	0.8 b	1849 cd
Gala/M.9Pajam2			13.8 a	48 a	2153 a	27 a	828 a	97 a	1.8 a	3578 a
Honeycrisp/M.9Nic29			10.3 c	29 c	1584 b	23 b	370 bc	54 b	1.0 b	2674 b
Jonagold/B.9			10.9 c	40 b	1281 bc	23 b	469 b	52 b	1.1 ab	2080 c
Macoun/B.9			9.7 c	39 b	855 d	22 b	357 bc	52 b	1.5 a	1409 d
Cultivar/stock significance			**	**	**	**	**	**	*	**
Mutsu/M.9T337	0	—	10.4	39	1354	26	455	53	1.8	2219
Gala/M.9Pajam2	5	Natural	11.8	37	1559	25	655	68	2.0	2507
Honeycrisp/M.9Nic29	5	Pendant	11.4	39	1409	23	297	41	0.2	2316
Jonagold/B.9	10	Natural	11.8	36	1416	23	635	75	1.9	2337
Macoun/B.9	10	Pendant	11.8	37	1339	22	312	48	0.2	2242
Regression with feather no.			L	NS	NS	L	Q	Q	Q	NS
Angle of feather significance			NS	NS	NS	NS	*	**	**	**
Interaction significance			NS	NS	NS	**	NS	**	**	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \leq 0.05$.
NS, *, ** Nonsignificant or significant effect at $P \leq 0.05$ or $P \leq 0.01$, respectively.
L, Q, and NS indicate that the number of feathers was related significantly to the response variable linearly, quadratically, and not related, respectively.
TCSA = trunk cross-sectional area.

TCSA, TCSA increase, spur number, and total tree length (Table 1). However, there was a negative linear effect on tree height, leader length, total shoot length, and average shoot length. Pruning weight showed a quadratic relationship whereby the five-feather treatment had the greatest pruning weight. There was a significant cultivar × number of feathers interaction with TCSA increase, average shoot length, spur number, and total tree length. With 'Gala' and 'Honeycrisp', there was a positive linear relationship between the number of feathers and TCSA increase; however, for the other cultivars, there was no relationship. Average shoot length was negatively related to the number of feathers for all cultivars. With 'Mutsu' and 'Macoun', there was a positive linear relationship between number of feathers and spur number, but a positive quadratic relationship with 'Gala', 'Honeycrisp', and 'Jonagold'. Pruning weight had a positive linear relationship with number of feathers for 'Mutsu', but a quadratic relationship for 'Gala', whereby the 5-feather treatment had the greatest pruning weight. There was a positive linear relationship between the number of feathers and total tree length with 'Mutsu', 'Gala', 'Honeycrisp', and 'Jonagold', but not with 'Macoun'.

In the second year (2010), there was a positive relationship between the number of feathers and TCSA and spur number, and a negative relationship with average shoot length and pruning weight (Table 2). There was a significant cultivar × number of feathers interaction for 'Gala', whereby total shoot length had a positive linear relationship; however, with the other cultivars, there was no effect of the number of feathers. The spur number per tree with 'Gala', 'Honeycrisp', and 'Jonagold' showed a positive linear relationship with the number of feathers, but not with 'Mutsu' or 'Macoun'. Pruning weight with 'Gala' had a quadratic relationship with the number of feathers, whereby the five-feather treatment had the highest pruning weight, but there was no relationship with the other cultivars.

During the third year (2011), there was a positive relationship between number of feathers and TCSA; however, the relationship with average shoot length was negative (Table 3). Pruning weight and the number of spurs pruned showed a quadratic relationship. The interaction of cultivar × number of feathers was significant for average shoot length, whereby 'Mutsu' had a quadratic relationship in which zero feathers had the highest average shoot length and five feathers had the lowest. 'Honeycrisp', 'Jonagold', and 'Macoun' had a negative linear relationship.

During the fourth year (2012), the relationship between the number of feathers and TCSA, total shoot length, pruning weight, and total tree length was positive (Table 4). There was a significant cultivar × number of feathers interaction with average shoot length. With 'Mutsu', there was a positive linear relationship, while with 'Macoun', there was a clear negative linear relationship.

In the fifth year (2013), there was a positive relationship between the number of feathers and TCSA (Table 4). The interaction of cultivar × number of feathers was not significant.

Cumulative leader length and cumulative pruning weight showed a negative linear relationship with the number of feathers (Table 4). There was a significant interaction between cultivar × number of feathers for average shoot length in which all the cultivars except 'Jonagold' had a negative linear relationship with the number of feathers. With 'Jonagold', the relationship was quadratic.

Flowering and fruiting. During the second year of growth (2010), the relationship between the number of feathers and blossom number, fruit number, fruit weight, yield, and crop load or yield efficiency was positive and linear (Table 5). There was a significant interaction with cultivar × number of feathers, whereby 'Gala', 'Jonagold', 'Macoun', and 'Honeycrisp' had a positive linear relationship between the number of feathers and

Table 4. Effect of the number of feathers and feather angle on tree growth of five apple cultivars in the fourth year (2012), cumulative growth over the first four years (2009–12), and trunk growth in the fifth year (2013) at Geneva, NY, USA.

Cultivar/stock	Feathers (no.)	Feather angle	TCSA (cm^2)	Leader growth (cm)	Total shoot growth (cm)	Avg shoot length (cm)	Pruning weight (g)	Limbs pruned per tree	Total tree length (cm)	Cum. 2009–12 leader growth (cm)	Cum. 2009–12 total shoot growth (cm)	Cum. 2009–12 pruning weight (g)	Avg shoot length 2009–12 (cm)	TCSA 2013 (cm^2)	TCSA increase 2013 (cm^2)
Mutsu/M.9T337			15.8 a[i]	35 ab	2348 b	24 b	735 b	2.5 b	3538 b	143 c[i]	4447 b	1178 bc	23 b	19.6 a[i]	3.8 a
Gala/M.9Pajam2			15.7 a	37 a	4049 a	26 a	1114 a	3.4 a	6201 a	183 a	7928 a	2082 a	26 a	19.3 a	3.6 a
Honeycrisp/M.9Nic29			11.4 bc	27 cd	1875 cd	21 c	520 c	2.2 b	3460 b	123 d	4805 b	984 bc	20 c	14.5 b	3.0 b
Jonagold/B.9			12.6 b	33 bc	2382 b	24 b	647 b	2.2 b	3662 b	159 b	4727 b	1266 b	25 a	15.0 b	2.4 c
Macoun/B.9			11.0 c	25 d	1412 d	19 d	484 c	1.9 b	2267 c	153 bc	3025 c	940 c	23 b	13.4 b	2.3 c
Cultivar/stock significance			**	**	**	**	**	**	**	**	**	**	**	**	**
Mutsu/M.9T337	0	—	12.1	30	2131	22	637	2.6	3485	158	4682	1250	26.3	15.0	2.9
Gala/M.9Pajam2	5	Natural	14.0	34	2502	24	803	2.8	4062	155	5287	1698	24.7	17.0	3.1
Honeycrisp/M.9Nic29	5	Pendant	13.1	31	2377	22	615	2.0	3786	156	4967	1014	22.5	16.1	3.0
Jonagold/B.9	10	Natural	13.7	32	2619	24	801	2.8	4036	148	5241	1626	22.5	16.9	3.2
Macoun/B.9	10	Pendant	13.7	30	2463	22	645	1.9	3802	142	4980	1047	20.9	16.8	3.0
Regression with feather no.			L	NS	L	NS	NS	L	NS	L	NS	L	Q	L	NS
Angle of feather significance			*	NS	NS	**	**	**	**	NS	**	**	**	NS	NS
Interaction significance			NS	NS	NS	*	NS	NS	NS	NS	NS	NS	**	NS	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \le 0.05$.

NS, *, ** Nonsignificant or significant at $P \le 0.05$ or $P \le 0.01$, respectively.

L, Q, and NS indicate that the number of feathers was related significantly to the response variable linearly, quadratically, and not related, respectively.

TCSA = trunk cross-sectional area.

blossom number, but 'Mutsu' had no relationship.

In the third year (2011), there was no significant relationship between the number of feathers and the flowering and fruiting variables we measured (Table 6).

In the fourth year of growth (2012), there was a positive relationship between the number of feathers and number of blossoms, fruit number, fruit weight, and yield (Table 7). Crop load and yield efficiency were negatively related to the number of feathers. The interactions between the number of feathers with fruit weight and yield were significant. For 'Honeycrisp', the relationship was quadratic, whereby the five-feather treatment had the highest fruit weight, but there was no relationship between yield and the number of feathers for the other cultivars. No significant interaction between cultivar × number of feathers was found this year.

During the fifth year (2013), the number of feathers per tree had a quadratic relationship with fruit number per tree, in which the five-feather treatment had the highest number of fruits and the zero-feather treatment had the least (Table 8).

Cumulative yield per tree and yield per hectare were positively related to the number of feathers (Table 9). There was an interaction of cultivar × number of feathers, whereby average crop load showed a quadratic relationship for 'Mutsu' and the five feathers had the highest crop load. With 'Macoun', there also was a quadratic relationship in which the five-feather treatment had the highest crop load and the zero-feather treatment had the lowest.

Fruit quality, storage disorders, fruit pack-out, and crop value

The number of feathers or the angle of the feathers did not significantly affect fruit quality or storage disorder incidence in 2011 or 2012 (data not presented). There was no effect of the number of feathers or feather angle on fruit pack-out in 2012 (data not presented). Our economic analysis indicated that when averaged over all five cultivars we evaluated, planting trees with 10 feathers resulted in an increase in crop value of \$4290/ha, and that branch bending increased cumulative crop value an additional \$3575, for a combined benefit

Table 5. Effect of the number of feathers and feather angle on flowering and fruiting of five apple cultivars in the second year (2010) at Geneva, NY, USA.

Cultivar/stock	Feathers (no.)	Feather angle	Blossom cluster number per tree	Fruit per tree (no.)	Fruit Weight (kg)	Yield ($t\cdot ha^{-1}$)	Crop load (fruit no./cm^2 TCSA)	Yield efficiency ($kg\cdot cm^{-2}$ TCSA)	Fruit size (g)
Mutsu/M.9T337			58 c[i]	21 b	7.1 a	20.2 a	2.4 bc	0.81 a	362 a
Gala/M.9Pajam2			102 a	24 ab	4.6 c	13.2 c	2.3 c	0.44 b	194 d
Honeycrisp/M.9Nic29			101 a	21 b	6.3 b	18.0 b	2.7 ab	0.80 a	301 b
Jonagold/B.9			77 b	25 a	6.4 b	18.2 b	3.2 a	0.81 a	256 c
Macoun/B.9			53 c	17 c	3.0 d	8.7 d	2.2 c	0.40 b	182 d
Cultivar/stock significance		—	**	**	**	**	**	**	**
Mutsu/M.9T337	0	—	59	19	4.8	13.7	2.4	0.63	262
Gala/M.9Pajam2	5	Natural	77	21	5.6	15.9	2.9	0.65	264
Honeycrisp/M.9Nic29	5	Pendant	77	21	5.3	15.2	2.5	0.64	258
Jonagold/B.9	10	Natural	90	23	6.0	17.0	2.7	0.68	258
Macoun/B.9	10	Pendant	90	23	5.8	16.7	2.7	0.68	255
Regression with feather no.			L	L	L	L	L	NS	NS
Angle of feather significance			NS	NS	NS	NS	NS	NS	NS
Interaction significance			**	NS	NS	NS	NS	NS	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \leq 0.05$.
NS, *, ** Nonsignificant or significant at $P \leq 0.05$ or $P \leq 0.01$ levels, respectively.
L, Q, and NS indicate that the number of feathers was related significantly to the response variable linearly, quadratically, and not related, respectively.
TCSA = trunk cross-sectional area.

of planting trees with 10 feathers and bending the feathers below horizontal of $7865/ha (Table 10).

Discussion

VEGETATIVE GROWTH. In our study, the trees in which the feathers grew at a natural angle had more growth than that of trees with the feathers bent down below horizontal. This agrees with the results of Lauri and Lespinasse (2001). The feathers at the natural angle had significantly higher pruning weights than those when feathers were bent below horizontal because the feathers bent down resulted in less total shoot growth (Luckwill 1970). This effect is desirable for high-density systems such as the tall spindle, in which the tree needs to be kept in a very narrow columnar space with short long-term reproductive branches. Therefore, feathers that are not bent down could potentially have more shoot growth, which could represent a problem in managing the trees at very close spacings.

Although the feathers at the natural angle had more growth and higher pruning weights for most cultivars, this was not true for Honeycrisp, which is a weak cultivar (Cline and Gardner 2005). This cultivar tends to

Table 6. Effect of the number of feathers and feather angle on fruiting of five apple cultivars in the third year (2011) at Geneva, NY, USA.

Cultivar/stock	Feathers (no.)	Feather angle	Fruit per tree (no.)	Fruit weight (kg)	Yield ($t\cdot ha^{-1}$)	Crop load (fruit no./ cm^2 TCSA)	Yield efficiency ($kg\cdot cm^{-2}$ TCSA)	Fruit size (g)
Mutsu/M.9T337			34 b[i]	9.5 a	27.1 a	3.0 c	0.82 a	299 a
Gala/M.9Pajam2			64 a	9.6 a	27.4 a	4.8 a	0.71 b	151 c
Honeycrisp/M.9Nic29			23 c	6.1 b	17.4 b	2.4 c	0.64 b	276 a
Jonagold/B.9			40 b	8.4 a	23.9 a	3.9 b	0.80 ab	231 b
Macoun/B.9			37 b	5.9 b	16.8 b	3.9 b	0.62 b	161 c
Cultivar/stock significance			**	**	**	**	NS	**
Mutsu/M.9T337	0	—	40	8.0	22.7	3.9	0.78	221
Gala/M.9Pajam2	5	Natural	39	8.0	22.9	3.5	0.71	225
Honeycrisp/M.9Nic29	5	Pendant	38	7.8	22.2	3.5	0.71	225
Jonagold/B.9	10	Natural	40	8.1	23.2	3.5	0.71	221
Macoun/B.9	10	Pendant	40	7.6	21.8	3.4	0.67	226
Regression with feathers (no.)			NS	NS	NS	NS	NS	NS
Angle of feather significance			NS	NS	NS	NS	NS	NS
Interaction significance			NS	NS	NS	NS	NS	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \leq 0.05$.
NS, *, ** Nonsignificant or significant at $P \leq 0.05$ or $P \leq 0.01$ levels, respectively.
L, Q, and NS indicate the number of feathers was related significantly to the response variable linearly, quadratically, and not related, respectively.
TCSA = trunk cross-sectional area.

Table 7. Effect of the number of feathers and feather angle on flowering and fruiting of five apple cultivars in the fourth year (2012) at Geneva, NY, USA.

Cultivar/stock	Feathers (no.)	Feather angle	Total blossom clusters per tree	Fruit per tree (no.)	Fruit weight (kg)	Yield ($t\cdot ha^{-1}$)	Crop load (fruit no./cm^2 TCSA)	Yield efficiency ($kg\cdot cm^{-2}$ TCSA)	Fruit size (g)
Mutsu/M.9T337			162 d[i]	32 d	8.3 d	24.8 d	2.1 d	0.53 c	261 a
Gala/M.9Pajam2			343 a	127 a	18.1 a	51.6 a	8.2 a	1.17 ab	144 d
Honeycrisp/M.9Nic29			239 b	91 b	17.1 ab	48.8 ab	7.9 ab	1.48 a	191 c
Jonagold/B.9			225 bc	69 c	14.3 bc	40.8 bc	5.7 c	1.16 ab	211 b
Macoun/B.9			184 cd	84 bc	11.0 cd	31.5 cd	7.4 b	1.04 b	141 d
Cultivar/stock significance			**	**	**	**	**	**	**
Mutsu/M.9T337	0	—	208	77	13.0	37.0	6.6	1.11	185
Gala/M.9Pajam2	5	Natural	213	73	13.1	37.3	5.6	0.99	197
Honeycrisp/M.9Nic29	5	Pendant	251	88	14.9	42.5	6.9	1.16	185
Jonagold/B.9	10	Natural	230	73	13.0	37.2	5.7	1.00	194
Macoun/B.9	10	Pendant	253	88	15.0	42.7	6.7	1.13	188
Regression with feather no.			Q	L	L	L	NS	NS	NS
Angle of feather significance			**	**	**	**	**	**	**
Interaction significance			NS	NS	NS	NS	NS	NS	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \le 0.05$.
NS, *, ** Nonsignificant or significant at $P \le 0.05$ or $P \le 0.01$, respectively.
L, Q, and NS indicate that the number of feathers was related significantly to the response ariable linearly, quadratically, and not related, respectiely.
TCSA = trunk cross-sectional area.

naturally have flat branch angles; therefore, feathers at the natural angle were similar to the feathers below horizontal in terms of growth.

A main hypothesis in our study was that managing the feathers below horizontal would increase the leader growth to attain the desired mature tree height quicker. With the tall spindle system, that goal is to develop a 3.2- to 3.3-m-tall tree based on a between-row spacing of 3.3 to 3.5 m in accordance with the light interception results of Jackson and Palmer (1972). The rationale of bending feathers at planting was that they would use less of the available resources within the tree for growth, leaving more to support leader growth. However, our data did not support that hypothesis because there was no difference in leader length between trees with feathers at a natural angle and those with feathers tied below horizontal.

The number of feathers had an effect on tree growth. The 5- and 10-feather treatments at either the natural angle or below horizontal had a positive effect on TCSA over the 5-year duration of this experiment. Similar results were found by Atay (2023). We assume that the reason for this increase in TCSA was because there were more shoots with significantly more leaves that were intercepting more of the available light, which

Table 8. Effect of the number of feathers and feather angle on fruiting of five apple cultivars in the fifth year (2013) at Geneva, NY, USA.

Cultivar/stock	Feathers (no.)	Feather angle	Fruit per tree (no.)	Fruit weight (kg)	Yield ($t\cdot ha^{-1}$)	Crop load (fruit no./cm^2 TCSA)	Yield efficiency ($kg\cdot cm^{-2}$ TCSA)	Fruit size (g)
Mutsu/M.9T337			130 b[i]	32.9 a	94 a	6.9 ab	1.7 a	253 a
Gala/M.9Pajam2			140 a	23.0 b	66 b	7.5 a	1.2 c	165 d
Honeycrisp/M.9Nic29			43 d	8.8 e	25 e	3.4 c	0.7 e	224 c
Jonagold/B.9			88 c	21.4 c	61 c	5.9 b	1.4 b	247 b
Macoun/B.9			80 c	12.3 d	35 d	6.2 b	0.9 d	155 e
Cultivar/stock significance			**	**	**	*	**	**
Mutsu/M.9T337	0	—	93.2	18.68	53.4	6.22	1.23	206.6
Gala/M.9Pajam2	5	Natural	91.0	19.1	54.7	5.45	1.11	211
Honeycrisp/M.9Nic29	5	Pendant	105.6	20.82	59.5	6.71	1.31	202.1
Jonagold/B.9	10	Natural	93.1	19.6	56.1	5.67	1.17	214
Macoun/B.9	10	Pendant	97.7	20.25	57.9	5.86	1.2	212.3
Regression with feather no.			Q	NS	NS	NS	NS	NS
Angle of feather significance			**	NS	NS	**	**	NS
Interaction significance			NS	NS	NS	NS	NS	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \le 0.05$.
NS, *, ** Nonsignificant or significant at $P \le 0.05$ or $P \le 0.01$, respectively.
L, Q, and NS indicate that the number of feathers was related significantly to the response variable linearly, quadratically, and not related, respectively.
TCSA = trunk cross-sectional area.

Table 9. Effect of the number of feathers and feather angle on cumulative fruiting of five apple cultivars during 5 years at Geneva, NY, USA.

Cultivar/sock	Feathers (no.)	Angle of feather	Cumulative Yield (kg/tree)	Cumulative Yield ($t\cdot ha^{-1}$)	Cumulative Yield efficiency ($kg\cdot cm^{-2}$ TCSA)	Avg Crop load (fruit no./cm^2 TCSA)	Avg Fruit size (g)
Mutsu/M.9T337			58 a[i]	165 a	3.1 b	3.6 c	294 a
Gala/M.9Pajam2			55 a	158 a	3.0 b	5.9 ta	163 d
Honeycrisp/M.9Nic29			38 c	109 c	2.8 c	4.1 c	247 b
Jonagold/B.9			50 b	143 b	3.4 a	4.7 b	236 c
Macoun/B.9			32 c	92 c	2.5 c	4.9 b	160 d
Cultivar/stock significance			**	**	**	**	**
Mutsu/M.9T337	0	—	44	127	3.0	4.8	219
Gala/M.9Pajam2	5	Natural	46	131	2.8	4.2	225
Honeycrisp/M.9Nic29	5	Pendant	49	139	3.1	4.9	218
Jonagold/B.9	10	Natural	47	134	2.8	4.4	222
Macoun/B.9	10	Pendant	49	139	3.0	4.7	220
Regression with feathers no.			L	L	NS	NS	NS
Angle of feather significance			*	*	**	**	**
Interaction significance			NS	NS	NS	*	NS

[i] Means within columns and sections with the same letter are not significantly different using Duncan's multiple range test at $P \leq 0.05$.
NS, *, ** Nonsignificant or significant at $P \leq 0.05$ or $P \leq 0.01$, respectively.
L, Q, and NS indicate the number of feathers was related significantly to the response variable linearly, quadratically, and not related, respectively.
TCSA = trunk cross-sectional area.

would increase dry matter accumulation per tree. Jackson (1980) showed that an increase in leaf area can increase trunk circumference linearly. Those results support our findings that tree TCSA was consistently greater with 10 feathers than that of the whips.

Results found by Mika et al. (2003) showed that trees that were heavily pruned resulted in less trunk growth than that of those that were lightly pruned. Our data showed a similar trend whereby the 5- and 10-feather trees with feathers at the natural angle required more pruning every year than the whips. However, when the feathers were positioned below horizontal, then the pruning weights were reduced. Mika et al. (2003) suggested that less growth in TCSA was probably because stored reserves were used to produce more shoots every season, which were then pruned away, supporting trunk growth. When the feathers were managed below horizontal, TCSA was larger because very little pruning was performed, allowing resources to be allocated to storage organs including the trunk. Trees with zero feathers (whips) always required more pruning than the trees with feathers that were trained below horizontal. It should be noted that part of the reason for this is that the new shoots growing from the trunk of the zero-feather treatment were never tied down. In this treatment, some of the new shoots grew strong and upright, with very narrow crotch angles, and were competing with the leader. This required them to be pruned away in the dormant season, resulting in more pruning with the whips. When feathers were not trained below horizontal, many shoots also had narrow crotch angles, were vigorous, competed with the leader, and needed to be pruned away.

Flowering and fruiting. In our trial, the effects of the feather management angle were inconsistent in the second and third growing season. No clear effect of feather angle treatment was found on the number of blossoms, fruit number, yield, fruit quality, or fruit pack-out. This agrees with the results of Longman et al. (1965), who found no consistent effect

Table 10. Effect of the feather angle and feather number on cumulative crop value during the first 5 years of a tall spindle planting averaged over five apple cultivars at Geneva, NY, USA.

Feather angle treatment	Feathers (no.)	Cumulative yield ($t\cdot ha^{-1}$)	Cumulative crop value ($/ha)	Difference between 10 feathers and 0 feathers ($/ha)
Natural angle	0	126.9	$82,485[i]	
	5	130.8	$85,020	$4,290
	10	133.5	$86,775	
Below horizontal	0	126.9	$82,485	
	5	138.5	$90,025	$7,865
	10	139.0	$90,350	

[i] The economic analysis used fruit prices of $0.65/kg for 'Mutsu', 'Gala', 'Jonagold', and 'Macoun', while the fruit price for 'Honeycrisp' was $1.3/kg.

of bending feathers on fruiting and flowering. However, our data show that bending of the feathers resulted in an increase in cumulative yield by the end of the fifth year. It seems that the effect of bending feathers at planting on yield is more pronounced in the fourth and fifth year of the life of the planting. Other studies have also reported inconsistent results regarding fruiting, with some studies reporting an improvement in fruiting and yield (Preston 1978) but Mullins (1965) showing no increase in bloom or yield.

For some of the cultivars we tested, bending of the feathers was more beneficial than for others in terms of blossom number and fruiting. Lauri and Lespinasse (2001) found that the effect of bending on the mean number of fruits was dependent on the fruiting type of the genotype, but they also found that the time of bending greatly influenced the number and type of buds that later developed, affecting fruiting in the following years.

In our trial, bending feathers below horizontal resulted in increased cumulative yield for ‘Crispin’, ‘Gala’, and ‘Macoun’; however, for ‘Honeycrisp’ and ‘Jonagold’, bending the feathers below horizontal did not improve yield compared with leaving the feathers at their natural angle. This can be explained by studies by Lauri et al. (1995), who found that growth and fruiting are defined by morphological traits. They tested type IV, type III, and type II cultivars classified according to Lespinasse et al. (1977) and recorded the type of growth of these cultivars for five successive years in a solen training system. Based on their work, the growth and fruiting habit of ‘Honeycrisp’ and ‘Jonagold’ in our study suggested that these two cultivars tend to have very flat horizontal branches in the first year of growth, even with no feather management. In the second growing season, the weight of the crop helped maintain those branches flat and even below horizontal. Therefore, bending of the feathers at planting did not have a significant effect for these two cultivars.

Although the 10-feather treatment with feathers bent below horizontal had the highest yield of any treatment, the number of feathers on trees with the feathers trained at a natural angle did not have a significant effect on yield; in this case, the number of fruits and yield were very similar for 0, 5, and 10 feathers. The results of feathered trees and pruning severity reported by Mika et al. (2003) indicated similar results as ours for the feathers at a natural angle. They found that trees planted with side shoots produced approximately the same yield as those without shoots; however, there was no branch manipulation in their trial.

Van Oosten (1978) tested feathered trees of two cultivars, Cox’s Orange Pippin and Golden Delicious, and found that trees with more feathers had higher yields in the early life of the plantings. It is noteworthy that the feathered trees from this experiment had feathers that grew almost horizontal, whereas the whips often grew more vertical branches. These results were similar to those of our study, in which whips with new shoots that were never tied down developed upright-growing branches that required more pruning. Consequently, more shoot growth occurred and fewer flower buds were formed (Forshey 1976). In a more recent study, Atay (2023) also found that cumulative yield was related to the number of feathers on the tree at planting.

Neither feather angle treatment nor the numbers of feathers affected fruit quality, pack-out or storage disorders. ‘Honeycrisp’ had high bitter pit incidence in 2011, but this was independent of the feather treatment or the number of feathers. However, the number of feathers and the angle of the feathers when averaged over all five cultivars showed a large economic benefit to planting feathered trees and positioning the feathers below horizontal, in agreement with the findings of Ferree and Rhodus (1987).

Conclusions

The success of a high-density apple orchard depends on growing the trees as quickly as possible to fill the allotted space while at the same time stimulating the trees into full production as fast as possible so that the high investment of planting a new orchard can be recovered as soon as possible. However, many orchards experience inadequate tree growth in the early life of the planting, thus affecting both early and mature cropping. Early growth and cropping can be improved by planting taller trees with more feathers and greater caliper and greater levels of stored nitrogen, boron, iron, and calcium. Irrigation or fertigation can also improve performance. In addition, our study has shown that branch bending can improve tree performance.

Bending the feathers below horizontal is one of the management practices that growers often do not use because the cost of this practice is approximately 70 to 80 human hours/ha or $1200/ha. However, our study shows that bending the feathers below horizontal had a positive effect on yield in the first 5 years, especially with vigorous cultivars with more upright growth, such as Mutsu, Gala, and Macoun. Our economic estimates indicate that this increase in yield could potentially result in an economic benefit of $4000 to $7000/ha. Therefore, the cost of bending the feathers could be easily repaid by the increase in yield. However, this is not true for weak cultivars with naturally flat angle feathers such as Honeycrisp and Jonagold, for which bending of the original feathers did not result in yield improvement.

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