HortScience 61(4):711–715. 2026. https://doi.org/10.21273/HORTSCI19164-25

Comparing Apple Orchard Performance, Fruit Quality, and Summer Hedging Between Bi-Axis and Single-Axis Tall Spindle Training Systems in Western New York

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Keywords. biennial bearing, Fuji, Gala, Honeycrisp, RubyMac, TCSA, yield efficiency

Abstract. **Increasing orchard planting density has helped improve grower profits and yields but establishment costs can be high due to a large number of trees. Instead of growing trees with a single leader, two-leader trees could possibly reduce orchard density while maintaining yield and improving fruit quality. To test this hypothesis, an orchard of four cultivars (Gala, Fuji, Honeycrisp, and McIntosh) was established and trained to either Tall Spindle (TS) or Bi-Axis (BA) at 0.9 × 3.6-m spacing. After the third year of growth, all TS trees and half of BA trees were hedged during summer, resulting in three systems to compare from years 4 to 7: 1) TS Hedged (TS Hgd), 2) BA, and 3) BA Hedged (BA Hgd). Measurements of trunk cross-sectional area (TCSA), yield, fruit quality, and biennial bearing index were recorded for 7 years. At the end of the study, total TCSA was larger on BA trees compared with TS Hgd trees across cultivars. The BA and BA Hgd trees had higher cumulative yields compared with TS Hgd trees across cultivars. Fruit size was reduced on BA and BA Hgd trees compared with TS Hgd trees, but all three systems had similar fruit color, firmness, and soluble solids on average. The biennial bearing index was lower with 'Gala' and 'Fuji' compared with 'Honeycrisp' and 'McIntosh' and was lower on BA and BA Hgd trees than TS Hgd trees. After 7 years, there was no obvious benefit of using hedging to improve fruit quality, but higher yield from BA trees over TS trees when planted at the same density for 'Fuji' and 'McIntosh', regardless of hedging during the summer, was achieved. It is possible that some cultivars benefit from the BA system and could be planted at 15% lower planting density than TS trees to achieve the same yield.**

Introduction

Profitability and yield in apple orchards have been greatly improved worldwide due to increased planting density (Robinson 2003, 2008). Optimal planting densities of the TS system is between 1200 and 1300 trees/acre (Robinson et al. 2006, 2011) and this system has been shown to be significantly more profitable over 20 years than lower or higher planting densities (Lordan et al. 2019; Robinson et al. 2007). Apart from planting density, the early economic success of the TS system has been further improved by planting feathered trees from nurseries (Dominguez and Robinson 2025). However, high planting densities cost more for growers during orchard establishment and reducing tree number without sacrificing performance or fruit quality could be potentially helpful. Musacchi (2008) proposed establishing two leaders from each planted tree to reduce orchard establishment costs. A study in Italy provided some support of this theory, as BA trees had higher yield compared with TS in two of the four orchard locations and one location had improved red color on BA compared with TS (Dorigoni et al. 2011). A study in Brazil has also suggested that training 'Fuji' and 'Gala' as BA trees instead of TS may improve red color due to better light distribution (Rufato et al. 2022).

Fruit size and red color are very important qualities that determine the value of harvested apples. Mechanically shortening branches using a mechanical hedger can possibly help expose developing fruit within the canopy to more light and has been historically observed to increase red fruit color (Emerson and Hayden 1984; Schupp 1992). However, more recent studies have shown hedging does not result in higher yields or red fruit color (Campbell et al. 2023; Robinson and Sazo 2013; Robinson et al. 2014).

The aim of this study was to evaluate the first 7 years of BA trees in comparison with TS trees when planted at the same density with four common cultivars and determine whether the two-leader trees would improve productivity and fruit quality. As an additional question, summer hedging was performed after the third year to possibly increase red color. We hypothesized trees with two leaders at the same density would have higher production than single-leader trees due to filling the canopy space more quickly yet have no difference in fruit quality. We also hypothesized that summer hedging would not improve red color in agreement with other recent studies recorded under similar climate conditions.

Materials and Methods

Location, orchard, and treatments. The study occurred in an orchard established at the Cornell University AgriTech Campus in Geneva, NY, USA (42°51′N, 77°01′W). Four apple cultivars (Aztec Fuji, Brookfield Gala, Honeycrisp, and RubyMac McIntosh) were planted in single rows on M.9T337 rootstock. The experiment had two tree types: 1) TS trees (single-leader, 2-year grafted nursery trees with 8–10 feathers) or 2) BA trees (two-leader, 2-year grafted nursery trees with 5–6 short feathers on each leader). The experimental design was a strip split-plot randomized complete block with four blocks (reps). Each cultivar row was planted in a single row to facilitate chemical thinning. Each row was split into four blocks and within each block the TS treatment was composed of a four-tree plot and the BA treatment was composed of an eight-tree plot. All trees were planted at a spacing of 0.9 × 3.6 m (3 × 12 ft) (2990 trees per hectare) and trained to a four-wire, 3-m (10 ft) tall trellis. At planting, no heading cuts occurred on leaders or feathers, but feathers larger than one-half the diameter of the leader were pruned back to the leader leaving a stub. In subsequent years, the leaders were left unpruned until reaching the maximum tree height of 3.5 m. Trees were pruned annually in the winter using standard TS pruning (Robinson et al. 2006) consisting of removing one to two branches larger than 2 cm in diameter (leaving a stub for the development of

Received for publication 21 Nov 2025. Accepted for publication 9 Feb 2026.
Published online 5 Mar 2026.
We would like to thank Leo Dominguez and Spenser Howden who helped to maintain the trees and harvest the trees over the project years.
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renewal branches) and maintaining intact smaller lateral fruiting branches.

For the first 3 years, we compared only the two tree types (TS and BA), with four trees and eight trees per experimental unit in the TS and BA treatments, respectively. However, in summer of the fourth year, all of the TS trees and half of the BA trees were hedged in late July with a side-wall mechanical hedging cutting bar at 18 inches from the trunk. The other half of the BA trees were not hedged during the summer. This resulted in three different treatments each with four trees in each experimental unit for years 4 to 7: 1) TS trees that were hedged (TS Hgd); 2) BA trees that were not hedged (BA), and 3) BA trees that were hedged (BA Hgd).

Horticultural measurements. Trunk cross-sectional area (TCSA) (cm^2) was measured at 30 cm above the graft union on the trunks each year during dormancy and TCSA of BA trees was calculated as the sum of both leaders. Fruit number, yield (kg/tree), fruit size (fruit number/[g yield]), crop load (fruit number/[cm^2 TCSA]), and biennial bearing index (BBI) according to Hoblyn et al. (1936) also were calculated each year. Cumulative fruit number, yield, and yield efficiency (YE) (kg fruit/[cm^2 TCSA]) were also calculated by summing the previous value to the current year. Cumulative comparisons among the three systems included the first 3 years and are expressed as 1) TS trees later managed as TS Hgd trees (TS→TS Hgd), 2) BA trees, and 3) BA trees later managed as BA Hgd trees (BA→BA Hgd).

During the final 2 years of the study, a 50-apple fruit sample from each tree was harvested and assessed for firmness (lb/cm^2) using a pressure texture machine (Fruit Texture Analyzer; QA Supplies LLC, Norfolk, VA, USA), soluble solid content (°brix) with a digital refractometer (Agato PR-101, Tokyo, Japan), and percent (%) green, yellow, and red color with an electronic fruit grader (CombiSort, GREEFA, Grading Machines, Langstraat 12, 4196 JB Tricht, Netherlands).

Statistical design. The study followed a strip split-plot randomized complete block design, with each cultivar planted as a single row of trees (strip) to facilitate orchard management as different cultivars require different spray schedules. Tree type (TS vs. BA) was the sub plot. There were four blocks (reps) for each tree type within each cultivar. Two additional rows were established on either side of the orchard as guard rows and a single guard tree separated each of the blocks within each row. Initial comparisons between year 1 and 3 compared only unhedged TS and BA trees, with four-tree or eight-tree plots per experimental unit, respectively. Individual trees served as subreps. After year 3, three treatments (TS Hgd, BA, and BA Hgd) were compared using a similar tree number per experimental unit either annually or using cumulative values over time (with TS and TS Hgd; BA and BA Hgd sharing the same values the first 3 years). Analysis compared differences between systems by year and cultivar using analysis of variance with the SAS statistical software package (SAS Institute Inc., Cary, NC, USA). Cumulative values were compared using the effect of cultivar, system, and cultivar × system interaction. In both models, replicate was used as a random factor. The data for each experimental unit (average of four or eight trees) was used in the statistical analysis to overcome the differences in sub rep numbers and to have a more conservative analysis when comparing potential differences between main effects. Normality and similar variance were monitored using histograms and Levene's test for the main effect of cultivar and tree type. The error term associated with replicate × cultivar was used to test for differences between cultivars for cumulative value comparisons and differences between tree types was evaluated using the error term associated with replicate × cultivar × tree type. Fruit size differences were explored using a covariate of crop load. When statistical differences were identified, mean separation was performed using Student's least significant difference with a threshold of $\alpha = 0.05$.

Results

Tree growth and yield. The combined total TCSA of the two leaders of the BA trees was generally larger than the single-leader TS trees from the beginning to the end of the study (Fig. 1). By year 7, both 'Fuji' and 'McIntosh' trees were larger than 'Gala' and 'Honeycrisp' ($F = 8.6$, $P \leq 0.001$) across systems. At the conclusion of the study, the BA trees were consistently larger than TS trees during the study, whereas the BA Hgd trees were statistically similar to TS Hgd trees when analyzed across the four cultivars. Although there was no statistical interaction ($P > 0.05$) of cultivar × system at year 7, trunk size differences between training systems for the cultivars did not appear consistent. For example, the 'McIntosh' BA trees were consistently larger than the TS trees each year throughout the study and hedging (BA Hgd trees) did not significantly reduce TCSA compared with BA unhedged trees. The 'Fuji' and 'Honeycrisp' BA trees were initially larger than the TS trees through year 3, but the hedging treatment reduced the rate of trunk growth rate on BA trees so that all three treatments were statistically similar by year 7. Alternatively, the 'Gala' BA trees were larger than TS trees in years 1 to 2, but all training systems were similar from years 4 to 7.

Across the study years and training systems, the BBI was significantly higher ($F = 24.4$, $P \leq 0.001$) for 'Honeycrisp' and 'McIntosh' (∼0.43) compared with 'Fuji' and 'Gala' trees (∼0.28) (Fig. 2). There were also differences between training systems across cultivars and study years as BBI of the TS Hgd trees (0.39) was significantly higher ($F = 5.9$, $P \leq 0.01$) than the BA Hgd (0.35) and BA trees (0.34). When explored by cultivar and year, the BBI of 'Fuji' TS Hgd trees was significantly higher ($P \leq 0.05$) than the BBI of the BA Hgd or BA trees in year 6. The BBI of TS trees was higher for 'Gala' in year 2 compared with the BA trees. The BBI of TS Hgd trees was higher than that of the BA Hgd or BA trees in year 4. With 'Honeycrisp', the TS trees were higher than BA trees in year 1. The 'McIntosh' BA trees had higher BBI than TS Hgd trees in year 5, whereas the BBI of TS Hgd trees was higher than BA Hgd trees, which were also higher than BA trees in year 6.

Crop load was maintained higher for 'Gala' trees ($F = 26.1$, $P \leq 0.001$) compared with the other three cultivars across the study years. Examined over time there were no crop load differences between training systems across all cultivars ($P > 0.05$) or within individual cultivars ($P > 0.05$). Nonetheless, individual years occasionally showed differences between training systems (Fig. 3).

There were differences in cumulative fruit number, cumulative yield, and cumulative YE between cultivars and/or training systems (Table 1). Comparing cultivars, 'Gala' had the highest number of fruit, followed by 'McIntosh', 'Fuji', and finally 'Honeycrisp' ($F = 71.1$, $P \leq 0.001$). The three training systems also statistically separated by cumulative fruit number, with the BA trees having the highest, followed by BA Hgd, and finally TS Hgd trees across cultivars ($F = 23.8$, $P \leq 0.001$). No significant interaction occurred regarding cumulative fruit number. The cumulative yield per tree or yield calculated as a hectare basis

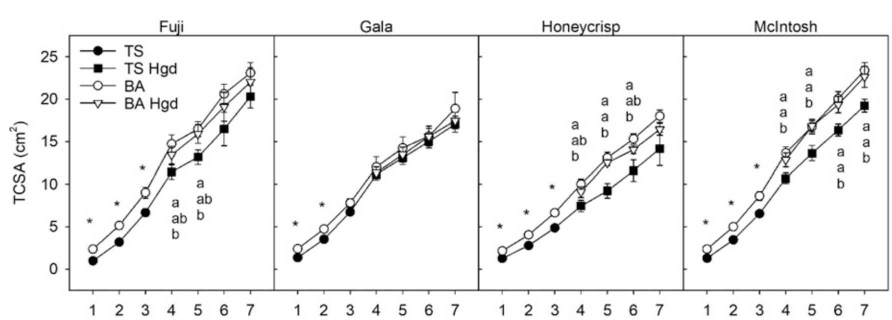

Fig. 1. Trunk cross-sectional area (cm^2) of 'Fuji', 'Gala', 'Honeycrisp', and 'RubyMac' apple cultivars for the first 7 years (1–7) trained as Tall Spindle trees (TS, black circles) hedged after year 3 (TS Hedged, black squares), or Bi-Axis trees that were not hedged (BA, white circles), or Bi-Axis trees that were hedged after year 3 (BA Hedged, white triangles) in Geneva, NY (n = 4). Asterisks denote significant differences between the two training systems before hedging (years 1–3) and letters show differences between treatments after hedging (years 4–7).

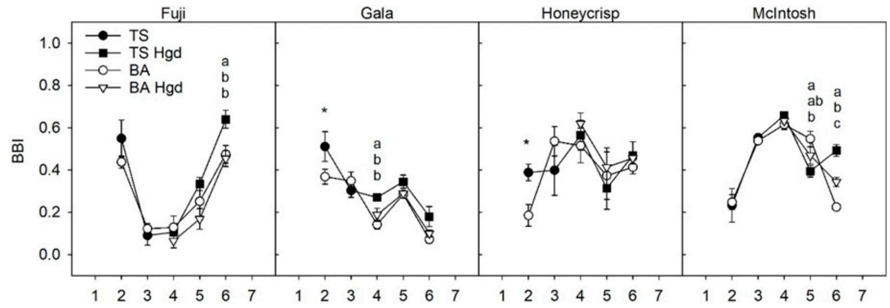

Fig. 2. Biennial bearing index (BBI) of ‘Fuji’, ‘Gala’, ‘Honeycrisp’, and ‘McIntosh’ apple cultivars for the first 7 years (1–7) trained as Tall Spindle trees (TS, black circles) hedged after year 3 (TS Hedged, black squares), or Bi-Axis trees that were not hedged (BA, white circles), or Bi-Axis trees that were hedged after year 3 (BA Hedged, white triangles) in Geneva, NY (n = 4). Asterisks denote significant differences between the two training systems before hedging (years 1–3) and letters show differences between treatments after hedging (years 4–7).

showed the same relationship between cultivars, as ‘Fuji’, ‘Gala’, and ‘McIntosh’ had similar yields, but ‘Fuji’ and Gala’ had higher yields than ‘Honeycrisp’ ($F = 4.1$, $P \leq 0.05$) (Table 1). Among systems, the highest cumulative yields were from BA trees, followed by BA Hgd trees and finally TS Hgd trees ($F = 19.0$, $P \leq 0.001$). There was no significant interaction between cultivar and training systems for cumulative yield per tree or per hectare. The ‘Honeycrisp’ trees had the highest cumulative YE ($F = 8.3$, $P \leq 0.01$) and was higher than ‘Fuji’ and ‘McIntosh’, but similar to ‘Gala’ across training systems (Table 1). There was no difference in cumulative YE between training systems ($P > 0.05$) but a significant interaction ($F = 2.4$, $P \leq 0.05$) occurred between cultivar × system as the ‘Honeycrisp’ TS and later TS Hgd trees were consistently higher than the BA or BA Hgd trees, whereas other cultivars had similar YE among the three systems (Fig. 4).

Comparison of cumulative fruit number over time showed BA trees initially had more fruit ($P \leq 0.05$) than TS trees on ‘Fuji’, ‘Gala’, and ‘McIntosh’ trees, but not ‘Honeycrisp’ (Fig. 4). Hedging also had different effects according to cultivar as the BA Hgd ‘Fuji’ trees had less cumulative fruit compared with BA trees, whereas ‘Gala’ and ‘McIntosh’ trees frequently had similar fruit number on the BA and BA Hgd trees. ‘Honeycrisp’ consistently showed no differences between the systems.

Cumulative yield showed the same relationship whether calculated on a per-tree basis or a hectare basis (Fig. 4), with similar yield the first 2 years when comparing TS and BA trees on all cultivars. There was often lower cumulative yield for TS Hgd trees compared with BA and BA Hgd trees for ‘Fuji’, ‘Gala’, and ‘McIntosh’ but not for ‘Honeycrisp’ throughout the trial ($P \leq 0.05$).

Cumulative YE was very similar over time between treatments in the ‘Gala’ or ‘McIntosh’ trees (Fig. 4). TS trees showed higher cumulative YE than BA trees in year 2 for ‘Fuji’ ($P \leq 0.05$), but all other years YE was similar between ‘Fuji’ treatments. In contrast, the ‘Honeycrisp’ cumulative YE on TS trees was higher than BA trees in years 2 and 3 and consistently higher in years 4 to 7 on TS Hgd trees compared with BA or BA Hgd trees ($P \leq 0.05$).

Fruit characteristics and qualities. Fruit quality measurements of fruit size (years 2–7), as well as firmness, soluble solids, and red blush area taken in years 6 and 7 were significantly different by one or both main effects (Table 2). Across training systems, each cultivar separated into a different average fruit size category by the end of the study ($F = 1203.5$, $P \leq 0.001$) and differences were also found between training systems, as TS Hgd trees had larger fruit size ($F = 26.8$, $P \leq 0.001$) compared with BA or BA Hgd trees across cultivars. For the main effect of cultivar, firmness was lower on ‘McIntosh’ compared with the other three cultivars ($F = 92.6$, $P \leq 0.001$) but similar among the three training systems ($P > 0.05$) across cultivars. Soluble solids were higher in ‘Fuji’ fruit compared with ‘Gala’ and ‘Honeycrisp’, but all three were higher than ‘McIntosh’ ($F = 65.5$, $P \leq 0.001$) across training systems. Across cultivars, TS Hgd trees had higher soluble solids than BA and BA Hgd trees ($F = 15.5$, $P \leq 0.001$). Regarding red blush area, the highest red blush area occurred on ‘McIntosh’ apples, followed by ‘Gala’, ‘Fuji’, and the lowest was ‘Honeycrisp’ ($F = 243.3$, $P \leq 0.001$) across training systems. There were no significant differences in fruit red color among training systems. There was no significant interaction between cultivar × system regarding the fruit qualities measured ($P > 0.05$).

Discussion

When interpreted across all four cultivars, the BA trees produced more total fruit and yield over the study than the TS trees. This

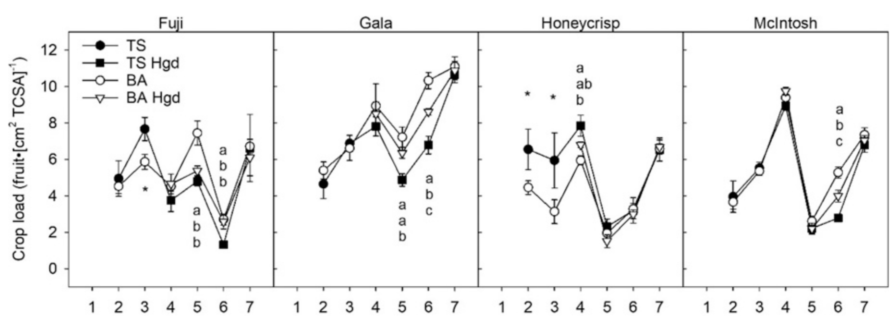

Fig. 3. Annual crop load (fruit/[cm^2 TCSA]) of ‘Fuji’, ‘Gala’, ‘Honeycrisp’, and ‘McIntosh’ apple cultivars for the first 7 years (1–7) trained as Tall Spindle trees (TS, black circles) hedged after year 3 (TS Hedged, black squares), or Bi-Axis trees that were not hedged (BA, white circles), or Bi-Axis trees that were hedged after year 3 (BA Hedged, white triangles) in Geneva, NY (n = 4). Asterisks denote significant differences between the two training systems before hedging (years 1–3) and letters show differences between treatments after hedging (years 4–7).

Table 1. Cumulative fruit (fruit no./tree), cumulative yield per tree (kg/tree), cumulative orchard yield ($t \cdot ha^{-1}$), and cumulative yield efficiency (YE) ($kg \cdot [cm^2]^{-1}$ trunk cross-sectional area [TCSA]) between four cultivars (n = 12, ‘Fuji’, ‘Gala’, ‘Honeycrisp’, and ‘McIntosh’) or training system (n = 16) trained as Tall Spindle trees that were hedged (TS Hedged), Bi-Axis trees that were not hedged (BA), or Bi-Axis trees that were hedged (BA Hedged) in Geneva, NY.

Cultivar	System	Cum. Fruit No.	Cum. Yield (kg/tree)	Cum. Yield ($t \cdot ha^{-1}$)	Cum. YE ($kg \cdot [cm^2]^{-1}$ TCSA)
Fuji		384 ± 23 c	80.3 ± 4.2 a	229.4 ± 12.1 a	6.16 ± 0.31 bc
Gala		575 ± 24 a	84.7 ± 2.9 a	241.9 ± 8.4 a	6.90 ± 0.23 ab
Honeycrisp		271 ± 11 d	70.4 ± 2.8 b	201.2 ± 7.9 b	7.23 ± 0.37 a
McIntosh		443 ± 23 b	76.2 ± 3.6 ab	217.8 ± 10.3 ab	5.58 ± 0.13 c
Significance		***	*	*	**
LSD		48	9.6	27.5	0.82
	TS → TS Hgd	355 ± 26 c	68.5 ± 2.3 c	195.7 ± 6.6 c	6.69 ± 0.37
	BA	474 ± 36 a	86.1 ± 3.1 a	246 ± 8.8 a	6.46 ± 0.26
	BA → BA Hgd	426 ± 31 b	79.1 ± 2.5 b	226.1 ± 7.1 b	6.24 ± 0.19
Significance		***	***	***	NS
LSD		36	5.9	16.9	0.63

NS, *, **, and *** denote nonsignificant or significance of $P \leq 0.05$, 0.01, or 0.001, respectively, and letters show differences for either cultivar or system in each column according to the least significant difference value (LSD) shown.

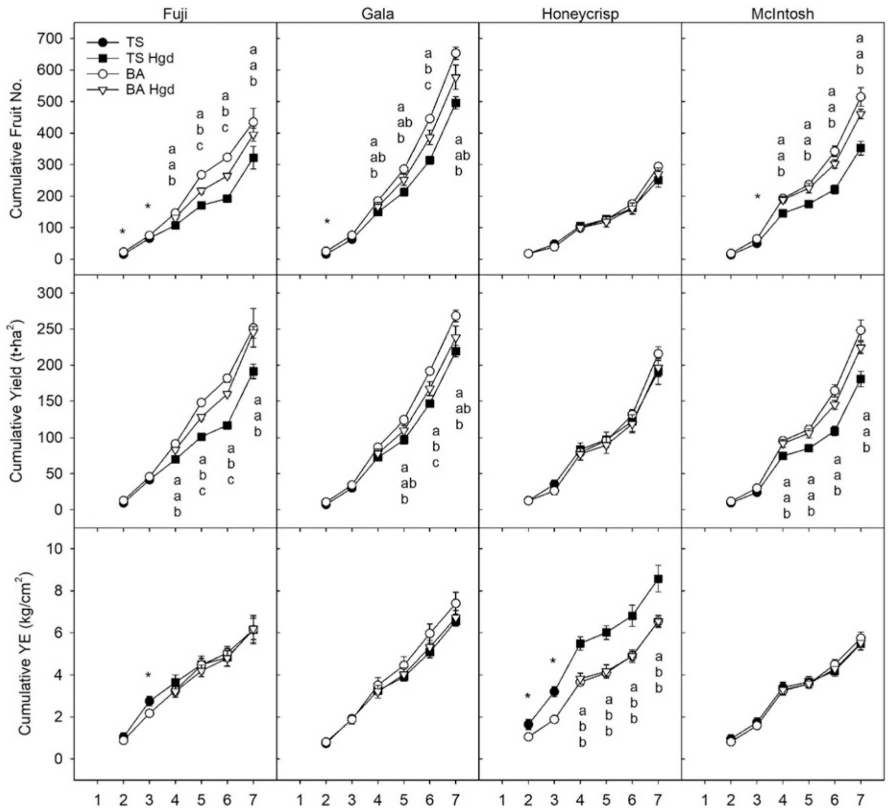

Fig. 4. Cumulative fruit number, cumulative yield (t·ha^{-1}), and cumulative yield efficiency (YE) (kg·[cm^2]$^{-1}$) over the first 7 years of production of 'Fuji', 'Gala', 'Honeycrisp' or 'McIntosh' apples trained as Tall Spindle trees (TS, black circles) hedged after year 3 (TS Hedged, black squares), or Bi-Axis trees that were not hedged (BA, white circles), or Bi-Axis trees that were hedged after year 3 (BA Hedged, white triangles) in Geneva, NY (n = 4). Asterisks denote significant differences ($P \leq 0.05$) between the two training systems before hedging (years 2–3) and letters show differences between treatments after hedging (years 4–7) according to Student's least significant difference test.

was largely due to larger TCSA (combined for the two leaders) compared with the single-leader TS trees and not greater crop load, agreeing with work done in Italy by Dorigoni et al. (2011). Although not consistent among cultivars, the higher yield observed on 'Fuji', 'Gala', and 'McIntosh' may justify establishing an orchard at a slightly lower initial planting density to achieve the same yield as the optimal planting density of TS orchards at ~3000 trees/ha (Ho et al. 2024; Lordan et al. 2019; Robinson et al. 2014). Across all cultivars, there was a 16% yield increase between the average of BA and BA Hgd systems compared with the TS → TS Hgd systems. This suggests a 16% reduction in planting density (2520 vs. 3000 trees/ha) would produce similar yields. However, other factors including the length of time to fill the canopy space and water availability due to larger soil volume per tree would need to be considered when adjusting plant spacing. In addition, growers would need to consider the higher purchasing cost of two-leader trees compared with single-leader trees from nurseries. Most importantly, the yield responses between the systems were not similar between cultivars. Both 'Fuji' and 'McIntosh' trees benefited in terms of yield being trained as BA system, regardless of hedging. Although no cumulative yield comparison can be made between BA and TS trees that were not hedged, there was a 22% and 19% increase for BA Hgd compared with TS Hgd trees for 'Fuji' and 'McIntosh', respectively. In contrast, only an 8% or 2% increase of yield was observed for the same BA Hgd vs. TS Hgd comparison for 'Gala' and 'Honeycrisp', respectively. Therefore, although growers may save initial costs by planting at wider spacing, cumulative yield results were cultivar dependent, and little improvement to yield was observed planting 'Gala' or 'Honeycrisp' using the BA system compared with TS.

Table 2. Average fruit size (g, years 2–7) and average fruit firmness (lb), soluble solids (SS, °brix), and red blush area (%) (years 6–7) between four cultivars (n = 12, 'Fuji', 'Gala', 'Honeycrisp', and 'McIntosh') or training system (n = 16) trained as Tall Spindle trees that were hedged (TS Hgd), Bi-Axis trees that were not hedged (BA), or Bi-Axis trees that were hedged (BA Hgd) in Geneva, NY.

Cultivar	System	Fruit size (g)	Firm (lb)	SS (°brix)	Red (%)
Fuji		217.0 ± 2.5 b	16.2 ± 0.7 a	15.9 ± 0.1 a	49.8 ± 1.8 c
Gala		153.1 ± 1.6 d	16.5 ± 0.1 a	14.3 ± 0.3 b	65.6 ± 2.8 b
Honeycrisp		258.6 ± 1.5 a	16.1 ± 0.1 a	14.4 ± 0.1 b	26.3 ± 1.4 d
McIntosh		159.3 ± 1.7 c	9.7 ± 0.2 b	13.9 ± 0.2 c	86.9 ± 0.7 a
Significance		***	***	***	***
LSD		4.6	1.1	0.34	5.2
	TS Hgd	202.9 ± 11.1 a	14.8 ± 0.5	14.9 ± 0.2 a	58.2 ± 4.0
	BA	192.6 ± 11.3 b	14.3 ± 0.7	14.6 ± 0.2 b	55.8 ± 4.4
	BA Hgd	195.5 ± 11.4 b	14.8 ± 0.6	14.5 ± 0.2 b	57.4 ± 4.3
Significance		***	NS	***	NS
LSD		3.0	0.84	0.16	2.9

NS and *** denote nonsignificant or significance of $P \leq 0.001$, respectively, and letters show differences for either cultivar or system in each column according to the least significant difference value (LSD) shown.

In addition to yield, any improvement to fruit quality may encourage growers to use the BA system over TS. BA trees have been suggested to have a better light distribution (Rufato et al. 2022) or narrower and less vigorous canopy, both possibly resulting in superior fruit color and fruit quality than single-axis trees (Dorigoni et al. 2011). In a study with spur-type 'Delicious' apple trees on 10 rootstocks and four systems, the strategy of planting lower densities with a three-leader tree resulted in lower long-term profitability, thus refuting the claim that multileader trees allow lower planting densities than single-stem trees (Gonzalez Nieto et al. 2026). The BA trees of our study planted at the same 0.9 m in-row spacing as TS were manageable and did not outgrow their space, and the authors did not observe the BA trees had less vigor or were narrower than the TS trees. The few differences in fruit quality observed in the present study were most likely due to higher crop load on the BA and BA Hgd trees for three of the four cultivars during year 6, whereas no benefit to red color was observed. Hedging is an effective strategy to narrow the canopy; however, additional years of data may be needed to understand potential fruit quality benefits in our study as only 2 years were measured. Regardless, no improvement to red blush area that could increase the crop value was observed, agreeing with previous work in the growing region (Robinson and Sazo 2013; Robinson et al. 2014).

Although no statistically significant interactions were found on the variables measured throughout the study, cumulative fruit number, yield, and YE variables were not the same for all four cultivars, and growers should be cautioned against assuming the comparative results between systems can be applied to all cultivars. Different cultivar scions convey different levels of vigor despite being on the same rootstock (Tworkoski and Fazio 2015) and the few cumulative performance differences observed among the three training systems for 'Honeycrisp' is perhaps indicative of lower vigor of this cultivar (Lordan et al. 2018). Flower and fruiting location of the cultivars also played a role in cumulative fruit number and cumulative yield, as the BA→BA Hgd treatment showed reduced cumulative yield on the tip-bearing cultivar Fuji compared with BA in years 5 and 6. This result agrees with Campbell et al. (2023), who identified that summer hedging removes fruit from terminal shoots. Despite slightly reducing yield, the hedging treatment may benefit growers economically if it reduces pruning labor costs, but additional economic study is required for this conclusion.

The cumulative YE was similar among the three systems for ‘Fuji’, ‘Gala’, and ‘McIntosh’, whereas the cumulative YE of ‘Honeycrisp’ was consistently higher on TS trees. The difference regarding YE agrees with previous work that suggested the YE between different training systems is dependent on the cultivar (Crassweller and Smith 2011). Under similar growing conditions, TS trees with less vigorous scions, such as ‘Honeycrisp’, appear to be a superior training system compared with two-leader systems, especially if the purchase cost of two-leader trees is higher than the single-leader trees for similar cultivars. Regardless, additional work could explore system differences when planting at wider spacings, perhaps improving the YE of BA trees on low vigor scions.

Conclusions

Planted at the same density, BA trees or BA Hgd trees had higher production after 7 years compared with the TS trees across cultivars. However, the benefit was strongly cultivar dependent, as ‘Honeycrisp’ trees showed no benefit in cumulative fruit or yield among the three systems, resulting in much higher cumulative YE on the TS system from smaller TCSA. Although additional years of production may have produced a different story, the critical timing of increasing production by filling the canopy was satisfied within the timeline presented. Reducing canopy volume by hedging only appeared to reduce fruit production of ‘Fuji’, ‘Gala’, and ‘McIntosh’ and did not significantly improve fruit quality, or red color percentage. Growers in similar growing conditions could potentially save money by reducing tree density but only if the additional cost of a two-leader tree is less expensive than the estimated yield increase. The results of this study suggest that a significant yield increase could be possibly observed for higher vigor scions, whereas there appears to be no benefit in using the BA system (with or without hedging) for less vigorous scions, such as ‘Honeycrisp’.

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