HortScience 58(6):620–627. 2023. https://doi.org/10.21273/HORTSCI16927-23

Converting Tall Spindle Apple Trees to Narrow Walls with Summer and Dormant Hedging Plus Root Pruning

Thiago Campbell
Department of Plant Science, The Pennsylvania State University, University Park, PA 16802, USA

James R. Schupp
Fruit Research and Extension Center, The Pennsylvania State University, 290 University Drive, Biglerville, PA 17307, USA

Richard P. Marini
Department of Plant Science, The Pennsylvania State University, 203 Tyson Building, University Park, PA 16802, USA

Keywords. fruit quality, *Malus domestica*, summer pruning, vegetative growth

Abstract. **Recently, some commercial apple growers have been adopting hedging as an alternative or supplement to hand-pruning. With increasing labor costs across the United States, alternatives to hand-pruning and current training systems are being considered. One management strategy involves transitioning tall spindle trees to a narrow tree wall and simplifying labor-intensive activities of apple production, such as pruning, harvesting, and fruit thinning. The objective is to form the orchard system into a "fruiting wall" that makes fruit more visible and accessible, thus facilitating harvesting. Four management practices (tall spindle; narrow tree wall with manual pruning; narrow tree wall with dormant and summer hedging; and narrow tree wall with dormant hedging, summer hedging, and root pruning) were used to convert 12-year-old 'Brak Fuji' apple trees from the tall spindle training system to a narrow tree wall. Photosynthetically active radiation (PAR) and ultraviolet light levels within the canopies were improved by summer hedging, but they were still low for all treatments. Light within the canopy was improved most when root pruning was included. Specific leaf weight was not significantly impacted by hedging or root pruning. Detailed spur sampling showed that treatments had no effect on vegetative or reproductive growth on 2- to 3-year-old wood. Although dormant plus summer hedging alone did not affect shoot length, the combination of hedging and root pruning caused a significant reduction in terminal shoot length. Red fruit color was only improved with dormant hedging plus summer hedging plus root pruning. Compared with dormant plus summer hedging, dormant plus summer hedging plus root pruning improved fruit set and yield, but it reduced fruit size. Without root pruning, hedging had little effect on light, specific leaf weight, flower initiation, fruit set, and fruit quality. Conversion to narrow tree walls by manual pruning resulted in more poorly colored fruit and less highly colored fruit compared with maintaining the trees as tall spindles with manual pruning.**

Fruit trees are pruned to maintain a desired tree shape and size to increase light penetration into the canopy, thereby enhancing fruit quality and flower bud development. Most modern apple orchards consist of high-density plantings, and they must be managed to maximize light interception and distribution throughout the canopy. Pruning is essential, especially in modern high-density operations (Sus et al. 2018), and represents approximately 30% of the apple production costs for trees trained as central leaders (Ferree 1976) and vertical axe (Marini and Barden 2004). Manual pruning is one of the most labor-intensive operations in an orchard (Mika et al. 2016; Zahid et al. 2022). To reduce pruning costs, previous studies reported experiments involving central leader trees being hedged during the dormant season (Ferree 1976; Hansen et al. 1968) and semi-dwarf trees being hedged in summer (Ferree 1984). The resulting dense shell of shoots on the tree periphery shaded the tree interior. Ferree (1976) emphasized the need for supplemental manual pruning after dormant slotting-saw hedging of trees to reduce shading of the interior fruiting areas. Dormant slotting-saw hedging involves running a hedging bar equipped with slotting saws alongside a tree row to create a pyramid-shaped row (depending on the angle of the bar), essentially performing nonselective heading cuts and making the entire tree row uniform.

Received for publication 25 Jan 2023. Accepted for publication 21 Mar 2023.
Published online 28 Apr 2023.
T.C. is the corresponding author. E-mail: thiagobell5@gmail.com.

Historically, summer pruning involved heading current season shoots one to three times during the summer (Marini and Barden 1982a; Tukey 1964; Utermark 1977), although some experiments involved thinning cuts during the summer (Autio and Greene 1990). Autio and Greene (1990) found that thinning cuts were more effective for improving red fruit color of cultivars like McIntosh, contrary to previous studies that involved heading cuts in the summer. The thinning cuts were found to increase light distribution within the canopy while preventing excessive regrowth. For intensive plantings, hedging makes nonselective heading cuts as the blades run alongside the tree row, forming what is commonly called a "narrow tree wall." The proposed benefits of summer heading include suppressed tree vigor and increased light penetration into the tree interior, resulting in enhanced fruit quality, flower bud development, and fruit set (Utermark 1977). Although summer heading suppressed late-season root growth, increased light penetration, and sometimes improved fruit red color development, trees responded to summer and dormant heading similarly in most ways (Glenn and Campostrini 2011; Marini and Barden 1987; Saure 1987). Based on research involving vigorous trees, few pomologists recommended summer heading, but trees on dwarfing rootstocks in intensive orchard systems may respond differently to hedging (Robinson et al. 2013).

Some orchardists are interested in transitioning trees to tree walls and using hedging tools as a pruning alternative to maintain narrow tree walls. A transition from tall spindle to narrow tree wall by hedging during the summer would potentially increase light penetration into the canopy and facilitate mechanical harvesting. Even without mechanical harvesting, the resulting "fruiting wall" is easier to harvest by hand. Using tree densities of 370 or 1429 trees/ha, Ferree and Rhodus (1993) concluded that "orchard intensification is accomplished best by choosing appropriate planting distances and not by attempting to control growth mechanically on trees planted too close for optimum performance." Over time, tree spacing recommendations have evolved to higher tree densities. Robinson et al. (2013) suggested that the optimum planting density is approximately 2700 trees/ha, although super spindle orchards can be larger than 5450 trees/ha. Recent studies have examined densities as high as 13,000 trees/ha (Lauzike et al. 2020), although more moderate estimations found peak productivity to be approximately 4762 trees/ha (Leão de Sousa and Gonçalves 2022).

Root pruning is another vegetative growth control method. Root pruning is not a novel concept and has been previously studied, although adoption is limited. Schumacher (1975) found that root pruning was effective only when the correct number of roots were cut; cutting too few roots led to excessive root development and shoot growth, whereas excessive root cutting could lead to tree death, especially in dry years. The correct amount of root pruning ended shoot growth early and encouraged flower bud initiation.

The objectives of this study were to evaluate four management practices (tall spindle; narrow tree wall with manual pruning; narrow tree wall with dormant and summer hedging; and narrow tree wall with dormant hedging, summer hedging, and root pruning) and their effects on light distribution in the canopy, vegetative growth, yield, fruit quality, and flowering when transitioning an intensive orchard from a tall spindle system to a narrow tree wall.

Materials and Methods

Plant material and experimental setup. Twelve-year-old 'Brak Fuji'/M.9 NAKBT337 apple trees growing at the Pennsylvania State University Fruit Research and Extension Center in Biglerville, PA, USA (39.93627, −77.25535) were used for this study. The trees were trained to a tall spindle trellis with three wires at 1.25, 1.88, and 2.5 m aboveground. Tree spacing was 0.9 m × 3.74 m (2971 trees/ha). The tree rows were approximately 100 m long and oriented north–south. Trees were hedged in March and early summer when shoots had 15 to 17 fully expanded leaves with a tractor-mounted FAMA hedger (Provide Agro, Beamsville, ON, Canada). The hedger bar was set at 45.7 to 50.8 cm from the trunk during dormancy and 55.9 to 66 cm from the trunk during the growing season as recommended previously (Courtney and Mullinax 2016). All trees received four applications of prohexadione calcium (Kudos; Fine Americas, Walnut Creek, CA, USA) at 841 $g \cdot ha^{-1}$ starting at petal fall and at 21-d intervals thereafter (Glenn and Miller 2005; Uselis et al. 2020). Fertilization, irrigation, and pest management followed local guidelines (Crassweller et al. 2020).

The experimental design was a randomized complete block design with five blocks. Each experimental unit was a plot of 10 to 15 consecutive trees. In Feb 2020, four treatments were established, and they were repeated in 2021. Treatment 1 comprised standard manual dormant renewal pruning to maintain tall spindle form (tall spindle). Treatment 2 comprised manual dormant pruning to transition the training system to a narrow tree wall with five to six renewal cuts (tree wall) and a reduced canopy depth compared with treatment 1. Treatment 3 comprised dormant pruning to transition a narrow tree wall with five to six manual renewal cuts, followed by dormant hedging and hedging in June (summer hedging), when shoots had 12 to 14 leaves (tree wall + dormant hedging + summer hedging). Treatment 4 comprised dormant pruning to transition to a narrow tree wall, followed by dormant and summer hedging coupled with root pruning (tree wall + dormant hedging + summer hedging + root pruning). Treatments are abbreviated throughout this work as follows: tall spindle (TS); narrow tree wall with manual pruning (TW); narrow tree wall with dormant and summer hedging (TW DH+SH); and narrow tree wall with dormant hedging, summer hedging, and root pruning (TW DH+SH+RP). Trees were thinned identically according to standard commercial practices in the Mid-Atlantic region. Trees were root-pruned at the pink bud stage using a tractor-mounted root pruner (Phil Brown Welding Corp., Conklin, MI, USA), with cuts made on both sides of the row at 50 cm from the trunk to a depth of 25 cm. Root pruning was performed at 1.6 to 1.8 $km \cdot h^{-1}$.

Light and ultraviolet measurements. The photosynthetic photon flux (PPF) of PAR was measured with a LI-COR LI-250A light sensor equipped with a LI-COR LI-191R line quantum sensor (LI-COR BioSciences, Lincoln, NE, USA). The line sensor measures integrated PAR over its 1-m length. The PAR was measured at 1, 2, and 3 m aboveground, corresponding to the lower, middle, and upper tree canopy on each of five trees per experimental unit. The average of the measurements was used, resulting in 75 PAR measurements per treatment (N = 75). Middle and upper canopy measurements were obtained using the NBLOSI (self-propelled labor platform). The light sensor was placed halfway through the canopy on the south side of the tree, approximately 15 cm from the trunk, with the operator standing to the north of the sensor. References were obtained before and after each measurement if light conditions were not stable. When there were scattered clouds, references were obtained before and after each tree, and data were expressed as the percentage of ambient PAR. Measurements were performed under mostly sunny skies and obtained within 2 h of solar noon for accuracy and consistency. PAR was measured before summer hedging (14 Jun 2021), after summer hedging (23 Jun 2021), and after shoot growth had ceased (24 Aug 2021). Ultraviolet light was measured at eight canopy locations on five trees per experimental unit with a LightScout ultraviolet meter (Spectrum Technology, www.specmeters.com) on 19 and 20 Jul 2021 (N = 200 per treatment). Ultraviolet light was measured ∼15 cm from the trunk on the north, east, south, and west sides of each tree at approximately 1.0 m and 3.0 m aboveground.

Specific leaf weight. The specific leaf weights (dry weight per unit leaf area) of the shoot and spur leaves were measured to evaluate treatment effects on the previous light environment of leaves. The newest fully expanded leaves on a current season shoot that were expected to be approximately midshoot by the end of the growing season were sampled on 17 Jun 2021. Four leaves were sampled at approximately 1.5 m aboveground on the west and east sides of each of six trees per experimental unit (N = 48 per treatment).

On 17 Jun 2021, spurs with leaves were sampled at approximately 1.5 m aboveground on 2- to 3-year-old wood at approximately 30 cm from the trunk. One nonfruiting spur from the west side and one from the east side were sampled from each of the five middle trees per experimental unit (50 spurs per treatment). All leaves were removed from spurs and counted. The total leaf area per spur was recorded with a LI-COR Model LI-3000 portable leaf area meter (LI-COR Biosciences, Lincoln, NE), and the leaf dry weight was recorded to calculate the specific leaf weight.

Shoot measurements. One terminal shoot on the east side and one on the west side of two trees per experimental unit at five canopy positions were tagged and measured at 110, 180, 250, 320, and 390 cm aboveground. Shoots were measured on 14 and 15 Jun 2021, and again on 24 Sep 2021. While measuring shoots in September, each tagged shoot was designated as 1 if it was headed and as 0 if it was not headed by summer hedging. For the headed shoots, the number of proleptic shoots arising below the heading cut was recorded, as was the length of the most terminal proleptic shoot arising below the cut.

Dormant branch analysis. In Feb 2021, two limbs were removed from their points of origin from the main trunks of two trees per experimental unit. Limbs were oriented east–west in the canopy. One limb was sampled from the upper third of the canopy (approximately 3 m), and one was from the lower third (approximately 1 m). The limbs were renewal limbs that were approximately 4 years old and characteristic of most limbs on the tree; they were oriented slightly above horizontal and expected to be the "workhorse" limbs in 2021 that would carry a crop of fruit on spurs and terminal buds. The length of every shoot arising along the limb was measured starting at the base of the limb, usually 4-year-old wood that originated in 2017. For a 4-year-old limb, growth arising from the 2017, 2018, 2019, and 2020 wood sections were measured. The presence and absence of dormant hedging and summer hedging cuts were recorded for each shoot developing in 2020. The average length of a shoot that grew in 2020 was calculated and used for analysis. All proleptic shoots developing behind summer hedging cuts in 2020 were also measured.

Blossom counts and fruit set. Blossom clusters on four uniform branches per experimental unit (group of 10–15 trees) were recorded on 15 and 16 Apr 2021 (N = 20 per treatment). Two branches were selected from the upper canopy, approximately 3.0 to 3.5 m aboveground on the north and south sides of the row, and two branches were from the lower canopy, approximately 1 to 1.3 m aboveground on the north and south sides of the row (2 heights × 2 sides = 4 branches).

The branch circumference at the point of origin on the trunk was recorded. Starting with 2017 wood and moving along the limb to more recent growth, each short shoot (<4 cm) was measured and marked as flowering or nonflowering (1 or 0). Longer shoots with flowers were also counted. Regarding 2020 growth, the type of flower cluster was recorded as spur flowers (flower clusters on lateral shoots <4 cm long) or terminal flowers (flower clusters arising from the terminal buds of shoots > 4 cm). On 20 Jul 2021, the final fruit set was recorded on the same branches used for blossom counts. Fruit set was expressed as fruit per 100 flower clusters.

Fruit quality. Two trees per experimental unit were harvested in late October for both years. Harvest was determined by commercial harvest time for 'Brak Fuji' in the Mid-Atlantic region. Harvest was approximately 2 weeks later than planned in 2021 because of poor fruit coloring during weeks leading up to harvest. In 2020 and 2021, all fruit were weighed on an electronic single-lane fruit sizer equipped with a digital load-cell (Durand-Wayland, Inc., LaGrange, GA, USA). In 2020 and 2021, 20 fruit per tree (N = 200 per treatment) were used to evaluate fruit quality. The percentage of the fruit surface colored red was recorded by visual estimation. Flesh firmness was measured on two sides of each fruit with a Guss Fruit Texture Analyzer (QA Supplies, Norfolk, VA, USA), and juice was collected to measure the soluble solids concentration with an Atago PR-32 refractometer (Atago USA, Inc., Bellview, WA, USA). Each fruit was cut horizontally, and the cut surface was dipped in iodine solution to evaluate starch hydrolysis using a scale of 1 to 8 (Blanpied and Silsby 1992). Crop density was calculated from the trunk cross-sectional area measurements recorded after harvest in 2020 and 2021.

Data analysis. For most response variables related to shoot growth, flowering, and fruit set, data were analyzed with an analysis of variance using SAS Proc Mixed; trees nesting in a block were a random effect, and pruning treatment, tree side, canopy position, and interactions were fixed effects. Pruning treatments were compared with single degree-of-freedom contrasts. Light was measured at five distances aboveground. Distance was included in the model as a regressor variable and data were analyzed using an analysis of covariance as suggested by Milliken and Johnson (2002). Initially, the model included all possible interactions. The final model was obtained by deleting the highest order interaction with the highest nonsignificant P value, and the model was refit. This manual backward elimination was repeated until only significant ($P = 0.05$) factors remained. Treatments were compared with single degree-of-freedom contrasts.

The presence or absence of a cut tagged shoot was recorded as a binary response (cut, not cut). The predicted probability that a shoot would be headed by the hedger was output to a new data set using the inverse link function in the output statement [predicted(blup ilink) = predprob]. Then, the predicted probabilities were used in Proc Logistic to generate graphs of the receiver-operating characteristic (ROC) curve and the area under the ROC curve (Kiernan 2018). Proc Logistic was also used to compare the ROC curves from competing models (models with different regressor variables) as described by Marini et al. (2022).

Comparing distributions for fruit size and fruit red blush. The empirical distribution function (EDF) is a nonparametric estimate of the cumulative distribution function and is used to describe a sample of observations of a given variable, in this case, fruit weight and percent red blush. The value of the EDF at a given point is equal to the proportion of observations from the sample that are less than or equal to that point. The nonparametric Kolmogorov-Smirnov two-sample test, obtained with SAS PROC NPAR1WAY was used to test the equality of EDFs for three pairs of treatments.

Results and Discussion

Light and ultraviolet measurements. The PPF levels were reported as the average of all trees per treatment across all canopy heights. Prehedging PPF levels were unaffected by treatment during the previous year (Table 1). On 23 Jun, posthedging PPF levels were similar for TS and TW and for TW and TW DH+SH, but PPF was higher for TW DH+SH+RP than for TW DH+SH. The PPF levels in August were higher for TW DH+SH than for TW, but PPF levels were higher for TW DH+SH+RP than for TW DH+SH. Ultraviolet levels were higher for TW than for TS, and ultraviolet levels were higher for TW DH+SH+RP than for TW DH+SH.

Both prehedging and posthedging PPF declined from the top of the canopy to the bottom, but the lowest position was not always different from the middle. The treatment × canopy position interaction was not significant for all response light variables (Table 1). Ultraviolet light was significantly greater in the high position in the canopy when compared with the low position.

TW DH+SH+RP had the highest PPF levels after summer hedging, but the increase was likely inadequate to affect fruit quality. Ferree (1984) stated "It is well known that 30% full sun is needed to saturate photosynthesis of apple leaves and to initiate flower buds." Our results agree with those of Marini and Barden (1982d), who measured light at 50-cm intervals through the canopy at 1.3 m aboveground after summer heading of all shoots on central leader trees. Light declined nonlinearly from the tree periphery to the trunk and was less than 30% full sun when measured at 50 cm from the tree periphery to the trunk. We placed the wand at the same distance from the trunk for all treatments. Because the tall spindle trees had greater canopy spread, the wand was placed further into the canopy than for the tree wall treatments, which may explain why tall spindle trees had slightly lower light levels. For hedged treatments, the light levels were still lower than desired because of shade caused by the shell of foliage resulting from the previous year's hedging. Therefore, summer hedging likely did not improve light penetration enough to influence fruit quality or flower bud initiation. These results were further supported by the specific leaf weight measurements.

Specific leaf weight. Shoot-specific and spur-specific leaf weights were not influenced by treatments (data not shown). Shade leaves typically have lower photosynthetic rates and lower specific leaf weights than sun leaves (Campbell and Marini 1992; Marini and Sowers 1990), and the characteristics of shade leaves can be modified by subsequent exposure to high light levels (Barden 1974). Marini and Barden (1981) suggested that specific leaf weight might be used as a biological integrator of light because net photosynthesis was correlated with specific leaf weight throughout the season, with the poorest relationships early and late in the season. Marini and Barden (1982a) found that heading all current season shoots on a tree in mid-August slightly increased PPF levels throughout the canopy and delayed the late summer decline in net photosynthesis and specific leaf weight. The delayed leaf senescence was likely not

Table 1. The influence of three pruning treatments to transition trees from tall spindle (TS) to tree wall (TW) on photosynthetic photon fluxes (PPF) and ultraviolet light in 'Fuji' apple trees in 2021.

	Prehedging PPF (% ambient PAR)	Posthedging PPF (% ambient PAR or ultraviolet)		
Treatment[i]	14 Jun	23 Jun	8 Aug	Ultraviolet
1: TS	8.5	7.7	8.8	5.2
2: TW	10.9	9.3	11.0	6.9
3: TW+DH+SH	10.5	11.7	13.7	6.8
4: TW+DH+SH+RP	10.8	14.4	17.1	9.7
		Contrast P values		
1 vs. 2	0.1061	0.2068	0.1070	0.0437
2 vs. 3	0.7850	0.0721	0.0428	0.9411
3 vs. 4	0.8280	0.0431	0.0121	0.0005
		Canopy height		
High	21.2 a[ii]	20.3 a	23.2 a	10.25 a
Middle	6.6 b	9.3 b	8.9 b	
Low	2.7 b	2.7 c	6.0 b	4.06 b
		ANOVA P value		
Treatment (T)	0.3215	<0.0001	<0.0001	<0.0001
Position (P)	<0.0001	<0.0001	<0.0001	<0.0001
T × P	0.0548	0.3115	0.2766	0.2026

[i] Trees were summer hedged on 16 Jun. PPF was measured on 14 Jun, 23 Jun, and 8 Aug. Ultraviolet light was measured on 20 Jul. Treatment 1 = tall spindle (TS). Treatment 2 = narrow tree wall with manual pruning (TW). Treatment 3 = narrow tree wall with dormant and summer hedging (TW DH+SH). Treatment 4 = narrow tree wall + dormant and summer hedging plus root pruning (TW DH+SH+RP).

[ii] Means within columns followed by common letters do not differ at the 5% level of significance according to the Tukey-Kramer test.

ANOVA = analysis of variance; PAR = photosynthetically active radiation.

caused by increased light because similar postsummer pruning responses were observed for leaves on container-grown trees that were not shaded (Marini and Barden 1982b). Summer hedging in the current study may not have been severe enough to increase light levels to influence the physiology of leaves at the tree interior.

Shoot measurements. Terminal shoots were measured before and after summer hedging in 2021 (Table 2). Before summer hedging, treatment TW DH+SH had longer shoots than TW DH+SH+RP. After hedging, TW DH+SH had shorter shoots than TW, and TW DH+SH+RP had shorter shoots than TW DH+SH. The average number of shoots developing below the heading cut and average length of regrowth shoots were minimal and similar for TW DH+SH and TW DH+SH+RP. The average shoot length was related to canopy height in a quadratic manner, with the shoot length being greatest at the lower and higher canopy positions (Table 2). The suppression of shoot growth by root pruning in the current study was consistent with previously reported suppression of apple shoot growth (Schupp and Ferree 1987).

Mean shoot length before summer hedging was similar for TS, TW, and TW DH+SH, indicating that hedging did not influence shoot growth the following year, and this supports previous reports of apple trees on semi-vigorous rootstocks in the field and grown in containers (Marini and Barden 1982c). During those experiments, summer heading reduced whole-tree photosynthesis enough to suppress root growth and late-season trunk growth, but trees were able to compensate for this removal of foliage, and the following season produced shoots that were comparable in length to those of trees that were dormant-headed. The role of tree carbohydrate reserves is not well-understood, nor is what triggers the tree to begin using them. As previously reported by Marini and Barden (1982c), summer hedging did not suppress shoot growth the following year in this study when compared with no summer hedging, indicating a lack of understanding of the role of carbohydrate reserves for early-season tree growth. However, it has been shown that summer pruning reduces leaf carbohydrate levels in tree fruit crops (Glenn and Campostrini 2011; Marini and Barden 1987). A better understanding may lead to modification of orchard practices such as pruning, tree training, and fruit thinning.

The regrowth of shoots after summer hedging was minimal. The average length of regrowth was less than 2 cm (data not shown), and the average number of shoots induced by summer heading was less than 0.5 cm per hedging cut (Table 2). Regrowth data were similar for root-pruned and non-root-pruned trees (Table 2). Recent studies reported that regrowth of proleptic shoots was negligible after summer hedging (Lewis 2018), but no data were reported. In the current study, slight regrowth was induced by summer hedging on 43% and 50% of the heading cuts for TW DH+SH and TW DH+SH+RP, respectively, indicating approximately half of the hedged shoots developed regrowth ranging from short shoots (<3 cm) to some surpassing 10 cm in length. Root pruning is known to restrict shoot growth (Ferree and Rhodus 1993; Schupp et al. 1992). For 'Conference' pear trees, one-sided root pruning twice reduced the growth of the trees in times of drought when trees could not be irrigated, with no significant effect on fruit quality and flower bud development (Vercammen et al. 2005). Although root pruning affected shoot length before summer hedging, there was no significant impact of root pruning on proleptic shoot development after summer hedging.

Probability of shoots being headed by hedger. Because only the hedged trees had shoots that were headed, only the TW DH+SH and TW DH+SH+RP treatments were analyzed with logistic regression. The probability of a shoot being headed was significantly affected by the canopy position ($P = 0.0104$), but not by the treatment, tree side, and all interactions (data

Table 2. Average terminal shoot length recorded at five canopy heights on the east and west sides of 'Fuji' apple trees before and after summer hedging during the 2021 growing season.

Treatment[i]	Length (cm) 14 Jun	Length (cm) 23 Jun	Regrowth (no./shoot)
1: TS	38.36	40.15	0
2: TW	37.63	38.93	0
3: TW+DH+SH	37.79	26.08	0.43
4: TW+DH+SH+RP	28.35	18.08	0.50
Contrast P values to compare treatments			
1 vs. 2	0.7369	0.5189	1.0000
2 vs. 3	0.9431	0.0001	0.4291
3 vs. 4	0.0001	0.0001	0.0650
Height aboveground (cm)			
114	38.66	35.37	0.11
183	35.76	29.34	0.18
251	31.74	27.36	0.24
320	32.02	29.94	0.20
389	39.48	32.03	0.44
Side			
East	35.33	30.16	0.24
West	35.73	31.46	0.23
P values from ANOVA[ii]			
Treatment	0.0001	0.0001	0.3276
Canopy height$_{lin}$	0.7077	0.1947	
Canopy height$_{quad}$	0.0001	0.0004	
Tree side	0.7982	0.3551	0.9289

[i] Treatment 1 = tall spindle (TS). Treatment 2 = narrow tree wall with manual pruning (TW). Treatment 3 = narrow tree wall + dormant and summer hedging (TW DH+SH). Treatment 4 = narrow tree wall + dormant and summer hedging plus root pruning (TW DH+SH+RP).
[ii] The interactions for treatment × side, treatment × height, height side × treatment, and treatment × side × height were not significant at the 5% level and are not shown.
ANOVA = analysis of variance.

Table 3. Terminal and total blossom clusters and fruit set in 2021 on various sections of 'Fuji' limbs following hedging and root pruning treatments in 2020.

Treatment[i]	Terminal clusters	Total clusters	Fruit/100 clusters
	2020		Average
1: TS	2.25	3.80	123.53
2: TW	2.35	4.40	107.29
3: TW+DH+SH	3.45	5.25	57.19
4: TW+DH+SH+RP	2.80	7.55	90.05
Contrast P values			
1 vs. 2	0.8463	0.5279	0.4646
2 vs. 3	0.0363	0.3720	0.0249
3 vs. 4	0.2105	0.0179	0.1420
Canopy position			
Upper	2.43	5.68	94.00
Lower	3.00	4.83	95.02
Canopy side			
North	2.65	5.1	98.07
South	2.78	5.4	90.95
ANOVA P value			
Treatment (T)	0.0898	0.0011	0.0280
Position (P)	0.1186	0.2083	0.9482
Side	0.7319	0.6551	0.6498
T × P	0.1110	0.0284	0.3367

[i] Treatment 1 = tall spindle (TS). Treatment 2 = narrow tree wall with manual pruning (TW). Treatment 3 = narrow tree wall + dormant and summer hedging (TW DH+SH). Treatment 4 = narrow tree wall + dormant and summer hedging plus root pruning (TW DH+SH+RP).
ANOVA = analysis of variance.

Table 4. 'Fuji' fruit quality characteristics in 2021 as influenced by three methods of converting tall spindle trees to tree walls.

Treatment[i]	Starch index	Blush (% red)	Firmness (N)	Soluble solids (%)	Fruit per tree	Yield (kg/tree)	Fruit wt (g)
1: TS	6.9	47.7	7.9	16.1	34.2	8.4	250.99
2: TW	6.8	44.1	8.0	16.6	44.1	10.1	230.85
3: TW+DH+SH	6.8	43.8	7.7	15.2	60.9	12.8	225.17
4: TW+DH+SH+RP	6.5	55.0	7.6	15.1	55.8	11.0	203.55
			Contrast P values				
1 vs. 2	0.2615	0.3010	0.6185	0.1267	0.2016	0.1733	0.1816
2 vs. 3	0.2399	0.9217	0.0489	0.0002	0.0342	0.0252	0.7029
3 vs. 4	0.5183	0.0072	0.3456	0.7339	0.5108	0.1332	0.1527
			ANOVA P value				
Treatment (T)	0.3318	0.0194	0.0187	0.0001	0.0060	0.0066	0.0266

[i] Treatment 1 = tall spindle (TS). Treatment 2 = narrow tree wall with manual pruning (TW). Treatment 3 = narrow tree wall + dormant and summer hedging (TW DH+SH). Treatment 4 = narrow tree wall + dormant and summer hedging plus root pruning (TW DH+SH+RP).

not shown, $P < 0.60$). Although the probability of a shoot being headed was positively related to canopy height, the area under the curve was only 0.6218, indicating that the model with only canopy position had a poor ability to correctly classify which shoots will be headed (Hosmer and Lemeshow 2000).

Dormant branch analysis. The mean length and number of shoots on each section of the 4-year-old branches in Feb 2021 were similar for all treatments applied in Summer 2020 (data not shown). Nonsummer hedged treatments had no regrowth, and the combination of summer hedging plus root pruning induced less regrowth than summer hedging alone on 2020 wood. Branch position (upper vs. lower canopy) did not affect any of the response variables measured, and the treatment × branch position was not significant.

A previous report of 'Fuji' trees indicated that the regrowth induced by summer hedging was always less than 20 cm (Lewis 2018). Marini and Barden (1982c) found that regrowth varied with cultivar and year. A few blossoms were observed on regrowth of 'Golden Delicious' during 1 year out of 3 years, but they failed to set fruit (Marini and Barden 1982c). Recent studies reported that regrowth shoots could possess terminal flower buds (Lewis 2018; Robinson et al. 2013), but it seems likely that the terminal ends of the regrowth with flower buds would be removed the following winter with dormant hedging, or the fruit on the terminal ends of regrowth would be removed with subsequent summer hedging. The results of our study showed a stronger regrowth response to summer hedging (TW DH+SH and TW DH+SH+RP) than that reported by Lewis (2018), and they closely resembled that found by Robinson (2013). Root pruning coupled with summer hedging (TW DH+SH+RP) suppressed regrowth compared with summer hedging alone, but the difference was not significant at the 5% level. We followed the hedging guidelines suggested by Robinson et al. (2013) of Cornell University and described by Courtney and Mullinax (2016). Our site had a fertile silty loam soil with good water-holding capacity, and crop density may have been a factor affecting regrowth. There was a light crop in 2020 because of frost, and there was only a moderate crop in 2021; therefore, trees had adequate reserves for normal growth in 2021. The only data we are aware of that show the effect of summer pruning on reserve carbohydrates were reported by Marini and Barden (1987), who found that total nonstructural carbohydrates in the trunk bark was lower for summer-pruned than dormant-pruned trees in November; however, by bloom the following year, carbohydrate levels were similar for both treatments.

Blossom counts and fruit set. The mean number of flowering spurs was not influenced by treatments for 2017 and 2020 branch sections (data not shown). The number of blossom clusters on the 2018 branch section was greatest for TW DH+SH+RP, but contrasts were not significant for all the treatment comparisons of interest (TS vs. TW, TW vs. TW DH+SH, and TW DH+SH vs. TW DH+SH+RP). For the 2019 branch section, TW DH+SH+RP had the most total blossom clusters and significantly more than TW DH+SH, but TW had the highest fruit set (Table 3), indicating that dormant plus summer hedging induced approximately 47% more blossom clusters than no hedging but did not result in more fruit.

One of the proposed benefits of summer heading is increased flowering the following year (Utermark 1977). Most of the blind wood referenced in reports supporting hedging is

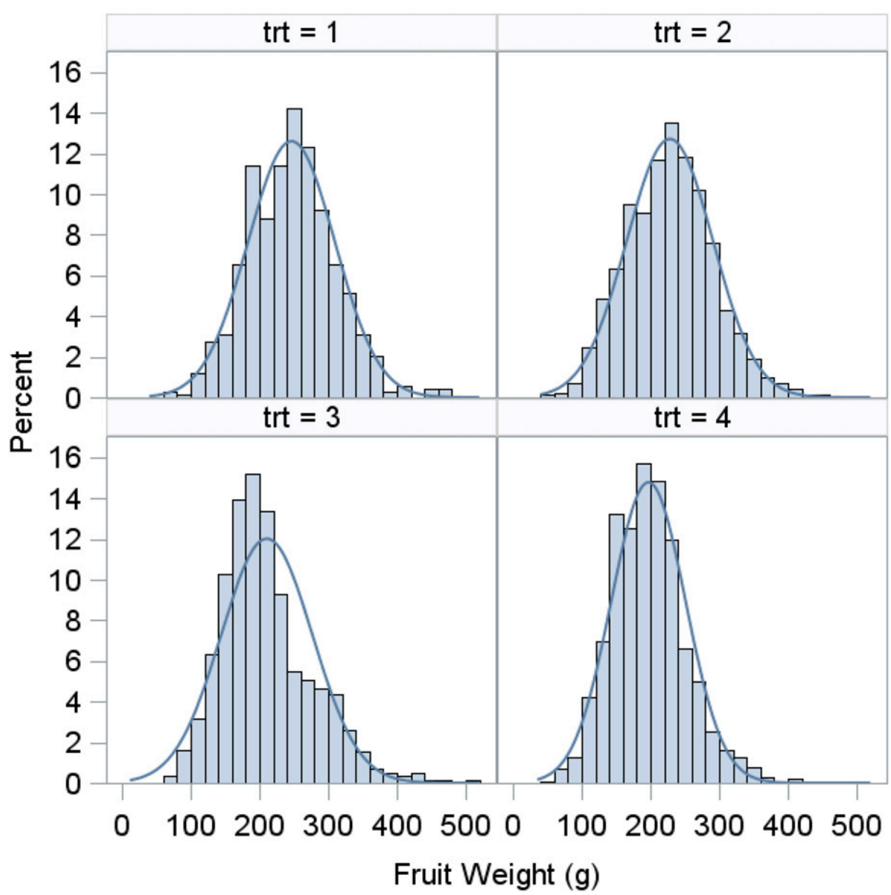

Fig. 1. "Fuji' fruit weight distribution as influenced by four treatments in 2021. Treatment 1 = tall spindle (TS). Treatment 2 = narrow tree wall with manual pruning (TW). Treatment 3 = narrow tree wall + dormant and summer hedging (TW DH+SH). Treatment 4 = narrow tree wall + dormant and summer hedging plus root pruning (TW DH+SH+RP).

concentrated on the 3- and 4-year-old portions of branches, correlating to 2018 and 2017 wood in this study, respectively. The results of the current study contradict the report by Lewis (2018) because there was no significant increase in flowering on 3- and 4-year-old branch sections; however, our results support those of Ferree (1984), Ferree and Rhodus (1993), and Marini and Barden (1982c), who reported that flowering was not enhanced by summer hedging or summer heading. Results of flowering and fruit set of root-pruned trees were inconsistent across studies. Therefore, root pruning needs to be re-evaluated in modern, commercial intensive apple orchards. For citrus, restricted root growth improved flower bud formation (Monselise and Halevy 1964); however, for apples, Schupp et al. (1992) found no impact of root pruning on return bloom. Overall flowering was only improved when summer hedging was combined with root pruning. Therefore, it is unlikely that summer hedging will consistently enhance flower bud initiation, except for a slight increase on terminal shoots.

The current hedging recommendations include setting the hedger closer to the trunk during dormancy and farther out from the trunk when performing summer hedging (Courtney and Mullinax 2016). One purported benefit of summer hedging is the promotion of flower buds on 1-year-old wood, including terminal buds. However, hedging during the following dormant season would remove most of the flower buds that developed. Most of the floral bud differentiation in apple occurs during the summer, beginning in June or July (Kolomiev 1976; Koutinas et al. 2010). These flower buds formed after summer hedging would be cut off by the dormant hedging. If the blade were set closer to the trunk for summer hedging than dormant hedging, then the flower buds formed on the wood would not be removed by the dormant hedging, but the resulting fruit might be removed.

Like blossom clusters, fruit set on older branch sections was not influenced by hedging alone (data not shown). Fruit set was higher for TW DH+SH+RP than for TW DH+SH for only the 2019 branch section. Compared with no hedging (TW), the combination of dormant plus summer hedging (TW DH+SH) did not increase fruit set on any branch section. Total fruit set per branch was approximately 35% lower on hedged trees (TW DH+SH) than on nonhedged trees (TW). The final fruit set in 2021 was unaffected by tree side (east or west), but it was higher for the upper canopy for the 2019 branch section and for the total branch (data not shown).

'Fuji' is a tip-bearer (Ferree and Warrington 2003), and the dormant hedging likely removed many of the terminal flower buds, whereas summer hedging may have removed some of the terminal fruit, thus explaining the lower final fruit set values for 2020 wood. In our study with three treatments for tree walls, TW DH+SH had the lowest total fruit set, whereas TW had the highest fruit set. With the hedging blades removing

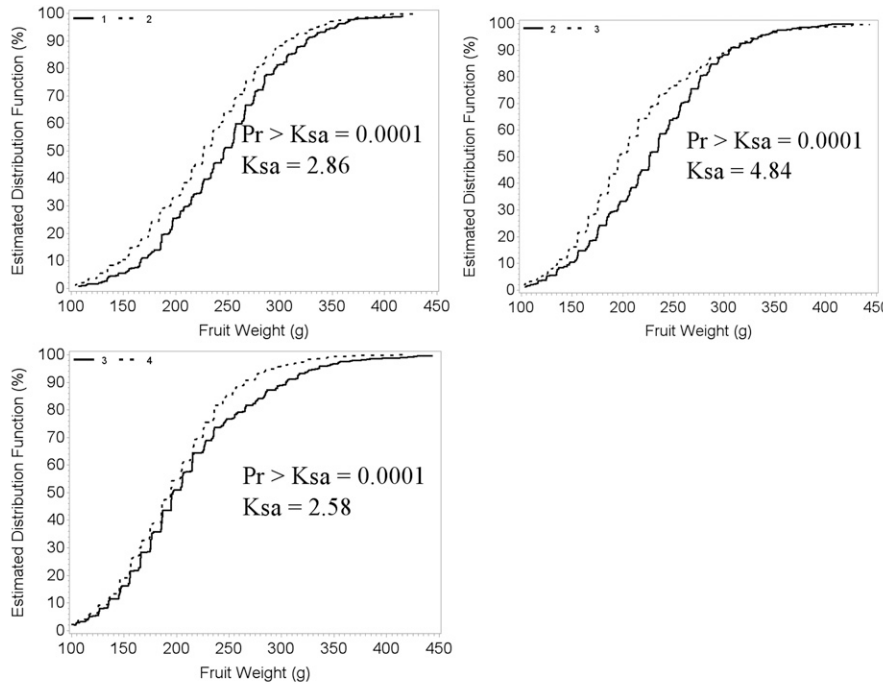

Fig. 2. Estimated cumulative empirical distribution functions (EDF) for 'Fuji' fruit weights of fruit harvested from four treatments in 2021 displayed as three treatment contrasts (treatment 1 vs. treatment 2, treatment 2 vs. treatment 3, and treatment 3 vs. treatment 4). The EDFs for three combinations of treatments were compared with the Kolmogorov-Smirnov two-sample test and the test statistic (Ksa); the *P* values associated with the tests are presented in each figure. Treatment 1 = tall spindle (TS). Treatment 2 = narrow tree wall with manual pruning (TW). Treatment 3 = narrow tree wall with dormant and summer hedging (TW DH+SH). Treatment 4 = narrow tree wall + dormant and summer hedging plus root pruning (TW DH+SH+RP).

potential fruiting wood during summer, this might be expected, although the greatest impact was on 2019 wood, on which the hedger would not have reached. Although no data were reported, Lewis (2018) stated that the promotion of flowering on blind wood near the trunk was one of the main hedging benefits, but our data contradict that statement. Conversely, root pruning improved the fruit set on all branch sections. Detailed data for flowering and fruiting on wood of various branch sections are not available to compare with our results, but there is a clear indication that root pruning, not hedging, positively affected flowering and fruiting on wood near the trunk.

Fruit quality. In 2021, fruit per tree and yield were higher for TW DH+SH than for TW, but the average fruit weight was unaffected by treatment (Table 4). The starch index was unaffected by treatment. Fruit red blush was not enhanced by converting from the tall spindle form to the tree wall with no hedging (TS vs. TW) or by hedging (TW vs. TW DH+SH). Compared with hedged trees (TW DH+SH), trees that were hedged and root-pruned (TW DH+SH+RP) had a greater percentage of fruit surface with red blush. Fruit from nonhedged trees (TW) were slightly firmer and had higher soluble solids than fruit from trees that were hedged (TW DH+SH).

Barden and Marini (1984) found that summer heading all terminal shoots on vigorous trees reduced the fruit weight and soluble solids concentration, but it sometimes increased red fruit surface color, which is consistent with our results. Schupp and Ferree (1987) found that root pruning increased soluble solids during 2 of 3 years. Emerson and Hayden (1984) found that hedging peach trees in winter and summer did not affect yield, but that hedging improved red fruit peel color. Autio and Greene (1990) found that summer pruning with thinning cuts improved red fruit coloring of 'McIntosh' apples and noticed a reduction in preharvest fruit drop. Marini et al. (1993) found that annual dormant heading of the leader and terminal shoots to develop central leader trees reduced the cumulative yield of young trees because of bud removal by pruning and stimulation of growing points to develop into shoots rather than spurs. Variations in the yield response may be cultivar-dependent. Tip-bearing cultivars could benefit from improved shoot numbers when flowers are borne on shoot tips. Dormant and summer hedging could remove the flower buds developed in the growing season, although results have shown that fruit number and yield increased with hedging (Table 4). The numbers of fruits removed by hedging were not counted. The lower soluble solids concentration associated with hedging (treatment 3) and hedging plus root pruning (treatment 4) is contrary to what is expected with light conditions, although higher fruit numbers likely account for the overall reduction in soluble solids.

Ferree and Rhodus (1993) found that hedging and root pruning decreased yield, with root pruning causing the greatest reduction in yield. Unlike our results, Robinson et al. (2013) found that summer hedging caused a nonsignificant reduction in yield and

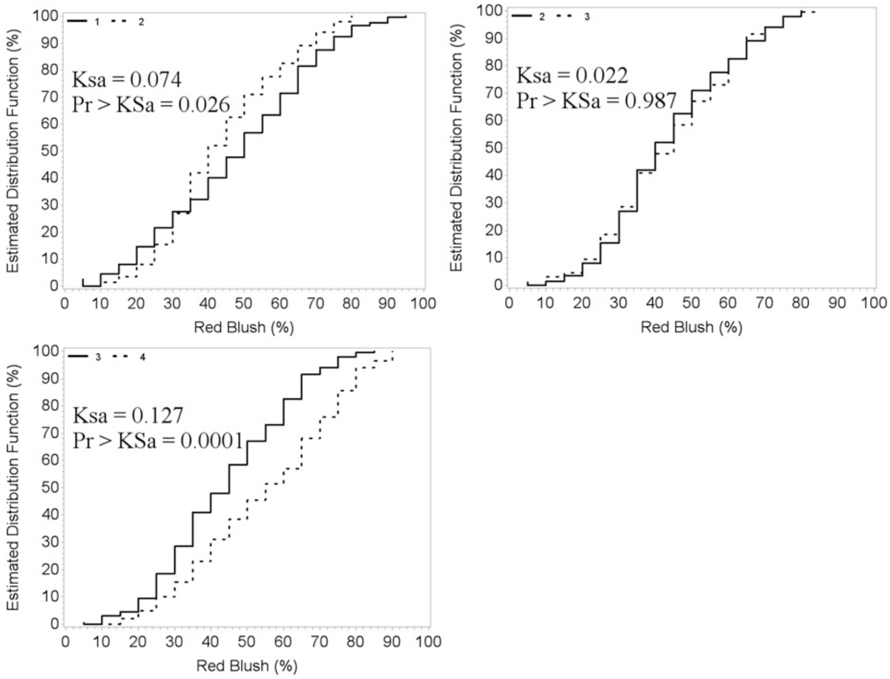

Fig. 3. Estimated cumulative empirical distribution functions (EDF) for 'Fuji' red blush percentage of fruit harvested from different treatments displayed as three treatment contrasts (treatment 1 vs. treatment 2, treatment 2 vs. treatment 3, and treatment 3 vs. treatment 4). The EDFs for three combinations of treatments were compared with the Kolmogorov-Smirnov two-sample test and the test statistic (Ksa); the *P* values associated with the tests are presented in each figure. Treatment 1 = tall spindle (TS). Treatment 2 = narrow tree wall with manual pruning (TW). Treatment 3 = narrow tree wall with dormant and summer hedging (TW DH+SH). Treatment 4 = narrow tree wall + dormant and summer hedging plus root pruning (TW DH+SH+RP).

crop value and a nonsignificant improvement in fruit color. Mika et al. (2016) found results most like those of our study, with hedging increasing yields but decreasing the fruit size and mean fruit weight. Mika et al. (2016) also found a decrease in the area of red blush with hedging, potentially because of tree crowding and poor light penetration into the canopy. In our study, summer hedging improved red blush significantly only when coupled with root pruning, but hedging also reduced soluble solids.

Fruit weight was normally distributed for manually pruned treatments (treatments 1 and 2), but not for hedged treatments (treatments 3 and 4) (Fig. 1). Based on kurtosis values less than 3.0 and fruit weight distribution, hedged trees produced more small fruit than manually pruned trees. The estimated cumulative EDFs for all three pairwise comparisons were significantly different ($P = 0.0001$) (Fig. 2). TS had more large fruit than TW, TW had more large fruit than TW DH+SH, and TW DH+SH had more large fruit than TW DH+SH+RP. Based on the EDFs, 50% of the fruit were larger than 246 g, 226 g, 196 g, and 194 g for TS, TW, TW DH+SH, and TW DH+SH+RP, respectively. Previous reports indicated that summer hedging (Mika et al. 2016) and root pruning (Schupp et al. 1992) reduced fruit size. Smaller fruit size caused by hedging and root pruning is important because fruit value often increases with fruit size for both fresh market and processing apples.

The distributions for red blush for TS and TW were different ($P = 0.026$), where TS trees had a higher percentage of highly colored fruit (Fig. 3, Table 5). The distributions for red blush were not influenced by DH+SH because the distributions for TW and TW DH+SH were not different ($P = 0.987$), indicating there was a similar percentage of fruit in each blush category across treatments. However, root pruning did improve the red color because the distributions for red blush for TW DH+SH and TW DH+SH+RP were different ($P = 0.0001$); TW DH+SH+RP had a higher percentage of highly colored fruit than TW DH+SH (Fig. 3, Table 5). Although grade standards are somewhat subjective, some supermarkets require 'Fuji' to have 55% red for fancy fruit and 66% red for extra fancy fruit (M. Boyer, personal communication, 20 Mar 2022). Treatment 4 (TW DH+SH+RP) produced the highest percentage of fruit in the fancy and extra fancy categories.

Table 5. Percentage of 'Fuji' fruit with less than a given red blush as affected by heading and root pruning in 2021. Values were obtained from cumulative empirical distributions (Fig. 3).

	Fruit (%) with less than 40%, 50%, 60%, and 70% of red blush			
Treatment[i]	<40	<50	<60	<70
1: Tall spindle (TS)	40	57	71	87
2: Tree wall (TW)	52	71	82	94
3: Tree wall + dormant hedging + summer hedging (TW DH+SH)	48	67	82	94
4: Tree wall + dormant hedging + summer hedging + root pruning (TW DH+SH+RP)	31	46	57	76

[i] Treatments: 1 = tall spindle (TS). Treatment 2 = narrow tree wall with manual pruning (TW). Treatment 3 = narrow tree wall + dormant and summer hedging (TW DH+SH). Treatment 4 = narrow tree wall + dormant and summer hedging plus root pruning (TW DH+SH+RP).

Summary and Recommendations

Summer and dormant hedging did not confer a clear benefit to the orchard management practices and fruit quality characteristics when not complemented by root pruning. Although hedging and root pruning (treatment 4) reduced shoot growth the year after treatment and increased red fruit color, other fruit quality characteristics suffered, such as firmness, soluble solids concentration, and distribution of fruit size. Additionally, treatment 3 (narrow tree wall with dormant and summer hedging) did not reduce shoot growth the year after treatment or improve red fruit color the current year when compared with treatment 2 (narrow tree wall with manual pruning). Higher light conditions within trees correlated with greater flowering, fruit set, and red fruit color (treatment 4). This is also attributable to decreased vegetative growth associated with the treatment. A proper economic analysis factoring in fruit size distribution and red color percentage is needed to determine the impact of treatments. Hedging without root pruning (treatment 3) produced higher yield compared with manual pruning (treatment 2), although these fruits were smaller in size. The nonsignificant increase in canopy light conditions with hedging failed to explain the yield increase, although a slight improvement in light conditions could have translated into a significantly higher yield.

Ease of harvesting should also be considered. Although narrow canopies facilitate visualization of fruit, current hedging recommendations result in multiple stubs on the tree periphery. These stubs are dangerous for individuals harvesting the fruit and may result in cuts and scrapes on the arms and body, making harvesting conditions less safe and possibly increasing harvest times. This study did not evaluate the amount of time to harvest hedged and nonhedged trees, but this information may be useful to growers interested in implementing hedging in their orchards. Summer hedging, dormant hedging, and root pruning should be studied independently before recommendations can be made about their individual applications. Although a multiyear study will help show treatment effects over time, short-term results indicate that the combination of dormant and summer hedging to convert tall spindle trees into a narrow tree wall is not a beneficial practice for commercial orchards.

References Cited

Autio WR, Greene DW. 1990. Summer pruning affects yield and improves fruit quality of 'McIntosh' apples. J Am Soc Hortic Sci. 115(3): 356–359. https://doi.org/10.21273/jashs.115.3.356.

Barden JA. 1974. Net photosynthesis, dark respiration, specific leaf weight, and growth of young apple trees as influenced by light regime. J Am Soc Hortic Sci. 99:547–551. https://doi.org/10.21273/JASHS.99.6.547.

Barden JA, Marini RP. 1984. Summer and dormant pruning of apple—A four year summary. Acta Hortic. 146:263–268. https://doi.org/10.17660/ActaHortic.1984.146.30.

Blanpied GD, Silsby KJ. 1992. Predicting harvest date windows for apples. I. B. 221. Cornell Coop. Ext. Publ.

Campbell RJ, Marini RP. 1992. Light environment and time of harvest affect 'Delicious' apple fruit quality characteristics. J Am Soc Hortic Sci. 117(4):551–557. https://doi.org/10.21273/jashs.117.4.551.

Courtney R, Mullinax TJ. 2016. Keeping limbs in line with mechanical pruning. Good fruit grower. https://www.goodfruit.com/keeping-limbs-in-line-with-mechanical-pruningvideo/. [accessed 27 Oct 2020].

Crassweller R, Peter K, Krawczyk G, Schupp J, Ford T, Brittingham M, Johnson J, LaBorde L, Harper J, Kephart K, Pifer R, Kelley K, He L, Heinemann P, Biddinger D, Lopez-Uribe M, Marini R, Baugher T, Weber D. 2020. 2020-21 Penn State tree fruit production guide. Penn State Ex. Publ. AGRS-045, p 446. https://extension.psu.edu/tree-fruit-productionguide. [accessed 5 Mar 2021].

Emerson FH, Hayden RA. 1984. Control of tree vigor by mechanical hedging. Acta Hortic. 146: 231–234. https://doi.org/10.17660/ActaHortic.1984.146.26.

Ferree DC. 1976. Influence of slotting saw mechanical pruning and alar on apple fruit size and quality. OSU-OARDC Res. Cir. 220:3–7.

Ferree DC. 1984. Influence of various times of summer hedging on yield and growth of apple trees. OSU-OARDC Res. Cir. 283:3–7.

Ferree DC, Rhodus WT. 1993. Apple tree performance with mechanical hedging or root pruning in intensive orchards. J Am Soc Hortic Sci. 118(6):707–713. https://doi.org/10.21273/jashs.118.6.707.

Ferree DC, Warrington IJ (eds). 2003. Apples: Botany, production and uses. CABI Publishing, Cambridge, MA, USA.

Glenn DM, Miller SS. 2005. Effects of apogee on growth and whole-canopy photosynthesis in spur 'Delicious' apple trees. HortScience. 40(2): 397–400. https://doi.org/10.21273/hortsci.40.2.397.

Glenn DM, Campostrini E. 2011. Girdling and summer pruning in apple increases soil respiration. Scientia Hortic. 129:889–893. https://doi.org/10.1016/j.scienta.2011.04.023.

Hansen CM, Larsen RP, Monroe G. 1968. Hedge pruning fruit trees. Mich. Agri. Expt. Sta. Quart. Bul. 50:331–341.

Hosmer DW, Lemeshow SL. 2000. Applied logistic regression (2nd ed). John Wiley and Sons, Inc. New York, NY, USA.

Kiernan K. 2018. Insights into using the GLIMMIX procedure to model categorical outcomes with random effects. SAS Global forum proc. Paper SAS2179-2018. https://www.sas.com/content/dam/SAS/support/en/sas-global-forumproceedings/2018/2179-2018.pdf. [accessed 19 July 2021].

Kolomiev IA. 1976. Surmounting of periodicity of bearing in the apple, p 17–50. Urozaj, Kiev, Ukraine.

Koutinas N, Pepelyankov G, Lichev V. 2010. Flower induction and flower bud development in apple and sweet cherry. Biotech. & Biotech. Devel. 24(1):1549–1558. https://doi.org/10.2478/V10133-010-0003-9.

Lauzike K, Uselis N, Kviklys D, Samouliene G. 2020. Orchard planting density and tree developmental stage affects physiological processes of apple (*Malus domestica* Borkh.) tree. Agronomy (Basel). 10:1912. https://doi.org/10.3390/agronomy10121912.

Leão de Sousa ML, Gonçalves M. 2022. Effects of planting density on light interception and distribution, physiological and agronomic performance of 'Gala' apple orchards. Acta Hortic. 1346: 337–345. https://doi.org/10.17660/ActaHortic.2022.1346.42.

Lewis K. 2018. Mechanical hedging in apples. WSU Ext. http://treefruit.wsu.edu/article/mechanical-hedging-in-apples/. [accessed 15 Aug 2021].

Marini RP, Barden JA. 1981. Seasonal correlations of specific leaf weight to net photosynthesis and dark respiration of apple leaves. Photosynth Res. 2:251–258. https://doi.org/10.1007/BF00056262.

Marini RP, Barden JA. 1982a. Effects of summer vs. dormant pruning and NAA treatment on growth of one- and two-year-old apple trees. J Am Soc Hortic Sci. 107(4):604–607. https://doi.org/10.21273/JASHS.107.4.604.

Marini RP, Barden JA. 1982b. Net photosynthesis, dark respiration, transpiration, and stomatal resistance of young and mature apple trees as influenced by summer or dormant pruning. J Am Soc Hortic Sci. 107:170–174. https://doi.org/10.21273/JASHS.107.1.170.

Marini RP, Barden JA. 1982c. Growth and flowering of vigorous apple trees as affected by summer or dormant pruning. J Am Soc Hortic Sci. 107:34–39. https://doi.org/10.21273/JASHS.107.1.34.

Marini RP, Barden JA. 1982d. Light penetration on overcast and clear days, and specific leaf weight in apple trees as affected by summer or dormant pruning. J Am Soc Hortic Sci. 107: 39–43. https://doi.org/10.21273/JASHS.107.1.39.

Marini RP, Barden JA. 1987. Summer pruning of apple and peach trees. Hortic Rev. 9:351–375. https://doi.org/10.1002/9781118060827.ch9.

Marini RP, Barden JA, Sowers D. 1993. Growth and fruiting responses of 'Redchief Delicious' apple trees to heading cuts and scaffold limb removal. J Am Soc Hortic Sci. 118(4): 446–449. https://doi.org/10.21273/jashs.118.4.446.

Marini RP, Barden JA. 2004. Yield, fruit size, red color, and a partial economic analysis for 'Delicious' and 'Empire' in the NC-140 1994 systems trial in Virginia. J Am Pomol Soc. 58:4–11.

Marini RP, Lavely EK, Baugher TA, Crassweller R, Schupp JR. 2022. Using logistic regression to predict the probability that individual 'Honeycrisp' apples will develop bitter pit. Hort Science. 57:391–399. https://doi.org/10.21273/HORTSCI16081-21.

Marini RP, Sowers DL. 1990. Net photosynthesis, specific leaf weight, and flowering of peach as influenced by shade. HortScience. 25(3):331–334. https://doi.org/10.21273/HORTSCI.25.3.331.

Mika A, Buler Z, Treder W. 2016. Mechanical pruning of apple trees as an alternative to manual pruning. Acta Sci Pol Hortorum Cultus. 15(1):113–121.

Milliken GA, Johnson DE. 2002. Analysis of messy data (vol. III): Analysis of covariance. Chapman and Hall/CRC, New York, NY, USA.

Monselise SP, Halevy AH. 1964. Chemical inhibition and promotion of citrus flower bud induction. Proc Am Soc Hortic Sci. 84:141–146.

Robinson TL, Hoying S, Sazo M, DeMarree A, Dominguez L. 2013. Advances in mechanization of the tall spindle apple orchard system: Part 2—Harvest mechanization prospects. NY Fruit Quart. 21(3).

Saure MC. 1987. Summer pruning effects in apple—A review. Scientia Hortic. 30(4):253–282.

Schumacher R. 1975. Einfluss des Wurzelschnittes auf die Fruchbarkeit von Apfelbaumen. Schweiz. Zeitschr. Obst. Weinbau. 111(5):115–116.

Schupp JR, Ferree DC. 1987. Effect of root pruning at different growth stages on growth and fruiting of apple trees. HortScience. 22:387–390. https://doi.org/10.21273/HORTSCI.22.3.387.

Schupp JR, Ferree DC, Warrington IJ. 1992. Interactions of root pruning and deblossoming on growth, development and yield of 'Golden Delicious' apple. J Hortic Sci. 67:465–480. https://doi.org/10.1080/00221589.1992.11516272.

Sus J, Zeinerova R, Zika L. 2018. Influence of the pruning system on the growth and productivity of slender spindle apple trees. Hortic Sci (Prague). 45(2):55–63. https://doi.org/10.17221/63/2017-HORTSCI.

Tukey HB. 1964. Dwarfed fruit trees: For orchard, garden and home with special reference to the control of tree size and fruiting in commercial fruit production. Macmillan, New York, NY, USA.

Uselis N, Viškelis J, Lanauskas J, Liaudanskas M, Janulis V, Kviklys D. 2020. Effects of growth control on yield and fruit quality of the apple cultivar 'Rubin'. Agric Food Sci. 29(3):245–252. https://doi.org/10.23986/afsci.90757.

Utermark H. 1977. Summer pruning to control growth and maintain fruiting in mature apple 550 trees. Comp. Fruit Tree. 10:86–90.

Vercammen J, van Daele G, Gomand A. 2005. Root pruning: A valuable alternative to reduce the growth of 'Conference'. Acta Hortic. 671:74. https://doi.org/10.17660/ActaHortic.2005.671.74.

Zahid A, Sultan Mahmud Md, He L, Schupp J, Choi D, Heinemann P. 2022. An apple tree branch pruning analysis. HortTechnology. 32(2):90–98. https://doi.org/10.21273/HORTTECH04924-21.