HortScience 53(11):1629–1633. 2018. https://doi.org/10.21273/HORTSCI13348-18

Rootstock, Canopy Architecture, Bark Girdling, and Scoring Influence on Growth, Productivity, and Fruit Quality at Harvest in 'Aztec Fuji' Apple

Esmaeil Fallahi[1,4], Michael J. Kiester[2], Bahar Fallahi[2],
and Shahla Mahdavi[3]
Pomology and Viticulture Program, Department of Plant Sciences, Parma Research and Extension Center, University of Idaho, 29603 U of I Lane, Parma, ID 83660

Additional index words. cambium interruption, carbohydrate partitioning, growth control, high density orchards, *Malus* ×*domestica*

***Abstract*. The increasing scarcity of land and water for agriculture mandates an efficient use of these natural resources. Establishment of high-density orchards with the use of a size-controlling rootstock, in combination with a suitable canopy architecture, is an efficient method for fruit production. However, less attention has been paid to the use of size-controlling practices such as trunk girdling in these modern orchard systems. The impacts of two rootstocks, two tree architectures, and three levels of bark cambium cuts (girdling or scoring) on growth, yield, fruit quality attributes at harvest, and leaf nitrogen (N) in 'Aztec Fuji' apple (*Malus domestica* Borkh.) were studied in 2015 and 2016. Trees on Nic 29 had larger canopies, higher yields, and larger fruit, but lower fruit color, sunburn, and firmness than those on Bud 9. Trees with a tall spindle (TS) architecture had higher yield in 2016, higher fruit soluble solids and firmness in 2015, higher fruit russet in 2016, but shorter terminal growth in both 2015 and 2016 and lower leaf N in 2015 than did those with a central leader (CL) training system. Trees receiving a bark girdling in 2015 (BG15) or score girdling in 2015 and 2016 (SG1516) had significantly higher yield than trees on nongirdled trees (NOGD) in 2016. Bark girdling or score girdling in 2015 (BG15 or SG15) increased fruit weight (size), color, and firmness at harvest in the same year, although differences for score girdling were not always significant. However, BG15 or SG15 did not have a "carryover" effect and did not affect fruit size, color, or firmness at harvest in 2016. When bark scoring was repeated in 2016 (SG1516), fruit size was increased in 2016. On the basis of the results of this 2-year study, it appears that bark girdling in one year is sufficient to increase fruit size of the current year and the yield in the following year. If larger fruit size is the critical objective of fruit production, annual score girdling needs to be practiced. However, a further long-term study is needed to monitor the carryover effects of cambium girdling and scoring on tree performance and fruit quality attributes in the subsequent years.**

The increasing trend in the world population and decreasing trend in the available agricultural land and water mandate a more efficient use of orchard land. Using new apple (*Malus domestica* Borkh.) orchard designs with more efficient rootstocks can result in producing higher quality fruit (Autio et al., 1996, 2017a, 2017b; Fallahi et al., 2007a, 2007b; Lordan et al., 2018; Reig et al., 2018). Rootstock can influence ripening, color, and shape of the scion fruit in apples. Autio et al. (1996) reported from the 1984 NC-140 cooperative planting that apple fruit ripening was correlated with tree vigor, and the most dwarfing rootstocks resulted in the earliest ripening. Rootstock can also influence scion leaf and fruit mineral concentrations and thus indirectly affect fruit quality and yield (Chun et al., 2001; Fallahi et al., 2001a, 2001b).

The use of a suitable tree architecture or training in a high-density orchard is determined by the rootstock vigor and soil type. Clements (2011) studied the performance of 'Honeycrisp' and 'McIntosh' apples on Bud 9, M.26, and MM.106 rootstocks with a CL, vertical axis (VA), and TS tree training systems. In both cultivars, trees on Bud 9 had the highest year cumulative yield over 2008–10 (during third through fifth leaf), followed by those on M.26 and MM.106 rootstocks. In that study, trees with TS had the highest production per hectare, followed by those with VA and CL.

Girdling trunks or large branches enhanced fruit set and some quality attributes when performed at specific growth stages on various fruit crops in several studies. Davie et al. (1995) reported that branch girdling, at the stage of rapid fruit growth, on 'Hass' avocado (*Persea americana*) increased the fruit mass by 35%. They recommended that only half the branches of the tree be girdled in any one year to avoid root starvation. Color on stone fruits (*Prunus* spp.) was improved after trunk girdling at the pit-hardening stage (Agusti et al., 1998; Day and DeJong, 1990). In an extensive trial in Río Negro and Neuquén Upper Valley, Argentina, girdling pear (*Pyrus communis*) trees increased yield compared with the ungirdled control in two seasons (Raffo et al., 2011). Vine girdling in table grapes (*Vitis vinifera*) increased berry and cluster weight (Fallahi et al., 2017; Reynolds and de Savigny, 2004) but decreased soluble solids concentration and titratable acidity (Reynolds and de Savigny, 2004). In a study to improve fruit quality, Steyn et al. (2008) observed that scoring and girdling increase yield without decreasing return bloom in 'Triumph' persimmon (*Diospyros virginiana*). Scoring and girdling were equally effective in increasing fruit size in peach and nectarine (*Prunus persica*) (Agusti et al., 1998; Fernandez-Escobar et al., 1987) and loquat (*Eriobotrya japonica)* (Agusti et al., 2005). However, bark girdling may impair trees and vine health if callusing is slow or inadequate (Fallahi et al., 2017; Fernandez-Escobar et al., 1987). In a study with orange (*Citrus reticulate*) trees, vascular connectivity was reestablished much faster after scoring than after girdling (Furr et al., 1945).

The impact of girdling on tree growth and fruit quality attributes, particularly fruit color in apples, has been studied by various researchers, with both consistent and contradictory results. Early spring trunk girdling increased fruit set and flower bud formation and reduced vegetative growth on apple trees (Autio and Greene, 1994; Greene and Lord, 1983; Hennerty and Forshey, 1971; Hoying and Robinson, 1992). Schechter et al. (1994) reported that fruit on girdled limbs had higher fruit dry weight and dry weight concentration than on nongirdled limbs. Leaf area on nongirdled limbs was unaffected by crop load but increased dramatically on girdled limbs with a crop load of less than one fruit per square centimeter limb cross-sectional area. These leaves also had a low photosynthetic rate, high stomatal resistance, and high internal CO_2.

Noel (1970) suggested that girdling in fruit trees can increase carbohydrate supply during fruit maturation, leading to the enhancement of red coloration by increasing anthocyanin synthesis. Girdling apple trees 10 d after petal fall only slightly improved red color in two of three cultivars but increased

---

Received for publication 28 June 2018. Accepted for publication 7 July 2018.

This work is supported in part by U.S. Department of Agriculture National Institute of Food and Agriculture—Specialty Crop Research Initiative project "AppleRoot2Fruit Accelerating the development, evaluation and adoption of new apple rootstocks" (2016-51181-25406). We thank the Idaho Apple Commission and Idaho Experiment Station for their partial financial support of this project. We also thank C & O Nursery and Columbia Nursery in Washington State for providing the experimental trees.

[1] Professor and Director of Pomology and Viticulture Program.

[2] Scientific Aide in Pomology.

[3] Visiting Scientist, Pomologist.

[4] Corresponding author. E-mail: efallahi@uidaho.edu.

background yellow color development of fruit skin (Schumacher et al., 1986). Wargo et al. (2004) reported that midsummer trunk girdling increased red coloration and intensity both years and improved market-grade pack out in 'Jonagold' apple. This effect was not caused by advanced maturity. In that study, girdling reduced fruit size only on trees of low N status.

Despite the use of dwarfing rootstocks and modern training systems in apple orchards, there is no report on the influence of tree girdling and scoring on the performance of trees under these conditions. Therefore, the objective of this experiment was to study the effect of two rootstocks, two tree architectures (trainings), and three levels of girdling on growth, yield, and fruit quality attributes at harvest-time and leaf N status in 'Aztec Fuji' apple trees over the 2015 and 2016 seasons.

Materials and Methods

Orchard establishment and general cultural practices. The experimental orchard was established at the Parma Research and Extension Center, University of Idaho in the spring and early Summer 2010. The experimental site was located at 43.7853° N, 116.9422° W and had a semiarid climate with an annual precipitation of ≈297 mm on a sandy loam soil of pH ≈7.3. In general, cultural practices other than rootstocks, tree trainings, and girdling methods were similar to those recommended for commercial orchards in the Pacific Northwest (Washington State University, 2018).

One 18-mm dripline (Rain Bird Corporation, Azusa, CA) was installed in a 10-cm trench (subsurface), 40.6 cm away from and parallel to the tree row on each of the east and west sides of the tree row. The entire irrigation system was connected to a pressure regulator to keep the water pressure constant at 3.52 $kg\cdot cm^{-2}$. Pressure compensating emitters were spaced at 45 cm on each line, and each emitter delivered 3.48 $L\cdot h^{-1}$ of water. Trees in this system were irrigated twice a week at 100% of daily crop (apple) evapotranspiration (ETc) for mature trees (Proebsting, 1994) but adjusted for the ground shading area (GS), as described by Allen et al. (1998) and Fallahi et al. (2013). Therefore, liters of water applied per tree = (ETc in mm / percent drip efficiency factor) × 0.90 × 3.90 m spacing × %GS.

Nitrogen as UAN 32 (urea and ammonium nitrate, 32% N) was applied at the total annual rate of 60 g N/tree via fertigation twice per year. The first N was applied at the rate of 30 g/tree in late May, and the second was applied at the same rate 2 weeks after the first application each year. Potassium was applied as potassium oxide, containing 15% K_2O, via fertigation, once a year in late May. Phosphorous, as monoammonium phosphate (61% P_2O_5), was applied at the rate of 150 g of formulation to each tree-planting hole, only once at the time of planting. Micronutrients, particularly, iron and zinc, were sprayed twice in spring and once in early summer each year. Calcium was sprayed three times with cover sprays during spring every year.

Crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.], a drought-tolerant grass, was planted as the orchard floor cover in all treatments. Trees in all treatments were blossom-thinned at about 80% bloom with 5% lime sulfur, followed by one application of postbloom thinners. The postbloom thinner was a mixture of carbaryl (44.1% by weight a.i.; Sevin XLR; 1-naphthyl N-methylcarbamate; Bayer Crop Science; Research Triangle Park, NC) and Ethephon (21.7% a.i.; Ethrel [(2-chloroethyl) phosphonic acid]; Bayer Crop Science; Research Triangle Park, NC), each compound at a rate of 0.188% of formulation and was applied at petal-fall at a spray delivery rate of 1871 $L\cdot ha^{-1}$, when fruitlet diameter was between 2 to 7 mm. Fruits were subsequently hand-thinned when they were about 18 mm in diameter (approximately mid-June) to maintain a space of at least 12.5 to 15 cm between fruits. Kaolin (95% a.i.; Surround; Englehard; Iselin, NJ) was sprayed for sunburn protection at the rate of 56.8 $kg\cdot ha^{-1}$ in early July, followed by three 1-week interval applications, each at 28.4 $kg\cdot ha^{-1}$ every year.

Rootstock and tree-training treatments. 'Aztec Fuji' trees on M.9 RN 29 (Nic 29) and *Budagovsky* 9 (Bud 9) rootstocks (C & O Nursery, Wenatchee, WA) were planted at 0.9 × 3.90 m spacing with a north-south row orientation. 'Snow Drift' crab apple (*Malus* × 'Snowdrift') on M.26 EMLA rootstock (Columbia Nursery, Quincy, WA) was planted in each row as a pollinizer between every 10 'Aztec Fuji' trees. Trees were trained into either central leader slender spindle with four lower main scaffolds CL or TS during the dormant season in early March each year. Tree leaders were maintained at ≈3.75 m in height.

Girdling treatments. Each rootstock block contained 12 trees, where 6 of the adjacent trees on a row received TS training and 6 trees on the adjacent row received CL training. In 2015, each two adjacent trees of these six-tree plots received one of the three girdling treatments as follows: 1) control or no girdling (NOGD), where no girdling was applied; 2) bark girdling (BG), where a complete 3- to 4-mm ring of the bark from 30 cm above the bud union was cut with a sharp knife until the wood tissue was visible, and removed; 3) score girdling (SG), where the bark of tree trunk was scored in a spiral pattern, going one and a half turns around the tree trunk, from 30 cm above the bud union with a sharp linoleum utility knife. In 2016, the experimental arrangement was like 2015, except for girdling treatments. In 2016, we had five girding treatments, each with one-tree replication in each of the rootstocks blocks (four rootstock blocks) as follows: 1) NOGD in 2015 or 2016; 2) BG in 2015 but not in 2016 (BG15); 3) SG in 2015 but not in 2016 (SG15); 4) repeated bark girdling in 2016, using the same method and on the same tree that was bark girdled in 2015 at about 6 cm above the 2015 bark girdling site (BG1516); 5) repeated score girdling in 2016, using the same method and on the same tree that was score girdled in 2015 at about 6 cm above the 2015 score girdling site (SG1516).

Tree growth. To determine tree growth, four random terminal branches in each experimental tree were tagged, and their final growth was measured in mid-June in 2015 and 2016, using a tape measure. We chose to measure the branch growth in June because this was the most active stage of tree growth. Circumferences of these trees were also measured at 5 cm below and 5 cm above the girdled or scored areas at the end of November in each year and trunk cross-sectional areas (TCSA) were calculated.

Yield and quality attributes. Yield per tree was recorded at harvest time. Twenty fruits were randomly sampled from each tree on Oct. 17–20 during 2015–16. For quality attribute evaluation at harvest, fruits were weighed and fruit color was visually ranked on a scale of 1 to 5, with 1 = 20% red, progressively to 5 = 100% red. Soluble solids concentration (SSC) was measured by a temperature-compensated refractometer (Atago N1, Tokyo, Japan). Fruit firmness was measured on three peeled sides of each fruit with a Fruit Texture Analyzer (Guss, Strand, Western Cape, South Africa). This texture tester measured the force needed to puncture a 7.9-mm-deep hole on each of the three peeled sides of the fruit, using an 11-mm tip. Starch degradation pattern (SDP) of equatorial slices of each fruit was recorded by comparison with the SDP standard chart developed for 'Fuji' apples (Bartram et al., 1993). In that chart, SDP is scaled from 1 (least fruit SDP, progressively to 6 = most SDP or starch hydrolysis).

Percentages of fruit russet, water core, and sunburn at harvest were calculated by counting the total number of fruit with each of these incidences, divided by the total number of fruit in the subsample and multiplied by 100.

Leaf nitrogen measurements. Thirty leaves were sampled at random per tree from the middle of the current-season shoots in mid-August each year. These leaves were put in a cooler and taken to the University of Idaho Pomology and Viticulture laboratories where their leaf N concentrations were measured each year. Leaves were washed in a mild solution, containing 1% Liqui-Nox anionic detergent (AlcoNox Inc., White Plains, NY), rinsed in four 25-L containers of distilled water, and dried in a forced-air oven at 65 °C. The dried leaves were ground to pass a 40-mesh screen using a Cyclotec Sample Mill (Model 1093; Tecator, Hoganas, Sweden). Leaf N concentration was determined by combusting the dry leaf tissues using a LECO Protein/Nitrogen Analyser (Model FP-528; LECO Corp., St. Joseph, MI).

Experimental designs and statistics. The experimental design in each year was a randomized complete block split-split plot with two rootstocks as the main effects, two tree architectures (trainings) as subplot, girdling treatments as sub-subplots, and four blocks (replicates).

Data were collected during 2015 through 2016 for measuring fruit quality attributes at harvest time, leaf N concentration, and yield. The assumption of normal data distribution was checked by computing univariate analyses for all tree responses in this study. Analyses of variance were conducted using SAS (SAS Institute, Cary, NC), with generalized linear model and means were compared by least significant difference at $P \leq 0.05$.

Results and Discussion

Interaction. Other than a case between rootstock and tree architecture for yield per tree in 2016, no significant interaction was observed between rootstock-training or rootstock-training-girdling treatments for any measurements in this study. Thus, only direct effects of rootstock, tree architecture, and type of girdling are reported in Tables 1–3.

Rootstock effect. Trees on Bud 9 had significantly shorter terminal shoots and smaller TCSA and formed smaller but more open canopies with better light penetration than those on Nic 29 in both 2015 and 2016 (Table 1).

Trees on Nic 29 had significantly higher yield than those on Bud 9 in 2015 (Table 2) and 2017 (data not shown). There was a significant interaction between rootstock and tree architecture for yield per tree in 2016. In this interaction, trees on Nic 29 with CL training had significantly lower yield (39.9 kg/tree) than those on Nic 29 with TS tree training that had 53.9 kg/tree in 2016 (data not shown). Trees on Nic 29 with CL training had denser and darker canopies (personal observation), resulting in excessive shading and lower fruit bud formation, and thus lower yield than those on Nic 29 with TS training.

Trees on Nic 29 also had larger average fruit size (heavier in weight) than those on Bud 9 in both 2015 and 2016, despite their higher yield (Table 2). Usually heavier yield is associated with smaller fruit size. However, trees in all treatments were thinned at about 15-cm spacing at the time of hand thinning. Therefore, higher yield and larger fruit size in trees on Nic 29 compared with those on Bud 9 is due to their larger canopy, leading to a higher leaf-to-fruit ratio in trees on Nic 29. It is extremely difficult to determine true effects of rootstock on the scion cultivar fruit quality and other characteristics. This is mainly because confounding effects such as rate of light penetration, crop load, and tendency of biennial bearing can confuse the results. Similar to our assessment, Autio (1991) experienced the same challenge in evaluating the impact of six rootstocks on fruit quality attributes of 'Delicious' apple. However, he concluded that fruit size consistently was largest from trees on M.9 EMLA and smallest from trees on OAR 1 rootstocks.

Despite their high yields and large fruit size, trees on Nic 29, either with a CL or TS training, needed more time for training and pruning, and this issue should be considered when choosing this rootstock. 'Fuji' trees on Nic 29 rootstock can be suitable for planting at farther than 0.9 m spacing between trees in a row and in the lighter soil in the region. Bud 9 is also a suitable rootstock for 'Fuji' apple if extra-large fruit size is not the main objective of apple production.

Fruit from trees on Bud 9 had significantly higher fruit color, sunburn (Table 2), and firmness (Table 3) at harvest but lower leaf N (Table 1) than those on Nic 29 rootstock in both 2015 and 2016. Fruits from trees on Bud 9 also had higher SSC than did those from

Table 1. Effects of rootstock, tree architecture, and girdling on terminal shoot length, trunk cross-sectional areas above and below the girdled or scored points, and leaf nitrogen in 'Aztec Fuji' apple in 2015 and 2016.

	Terminal shoot length in June (cm)		TCSA above girdling or scoring (cm^2)		TCSA below girdling or scoring (cm^2)		Leaf nitrogen (% dry wt)	
Treatment	9 June 2015	18 June 2016	2015	2016	2015	2016	2015	2016
Rootstock								
Nic 29	34.7 a[z]	31.2 a	30.6 a	34.7 a	31.3 a	35.2 a	2.30 a	2.33 a
Bud 9	27.6 b	26.0 b	17.1 b	19.3 b	17.6 b	19.4 b	2.19 b	2.26 b
Tree architecture								
Central leader	32.8 a	33.3 a	22.9 a	26.4 a	23.4 a	26.6 a	2.29 a	2.27 a
Tall spindle	29.4 b	24.5 b	23.5 a	26.0 a	24.2 a	26.2 a	2.20 b	2.32 a
Girdling								
NOGD	34.4 a	35.1 a	22.3 b	24.6 b	22.3 b	24.6 b	2.30 a	2.30 b
BG15	29.2 b	27.4 b	24.5 a	27.2 a	25.1 a	27.3 a	2.16 b	2.41 a
SG15	29.9 ab	29.0 ab	22.8 b	24.9 b	24.1 ab	26.3 ab	2.28 a	2.32 b
BG1516		25.6 b		29.2 a		28.1 a		2.17 c
SG1516		27.5 b		25.2 b		26.2 ab		2.27 b

[z] Mean separation within columns in each group of treatments by least significant difference at 5% level.

BG15 = bark girdling in 2015; BG1516 = bark girdling in 2015 and 2016; NOGD = no girdling (control); SG15 = score girdling in 2015; SG1516 = score girdling in 2015 and 2016; TCSA = trunk cross sectional area.

Table 2. Effects of rootstock, tree architecture, and girdling on yield, fruit weight, color, and sunburn in 'Aztec Fuji' apple at harvest in 2015 and 2016.

	Yield per tree (kg)		Fruit wt (g)		Fruit color (1–5)[z]		Fruit sunburn (%)	
Treatment	2015	2016	2015	2016	2015	2016	2015	2016
Rootstock								
Nic 29	46.1 a[y]	47.3 a	238.4 a	246.6 a	3.97 b	3.81 b	13.9 b	18.7 b
Bud 9	25.3 b	45.8 a	229.1b	230.5 b	4.21 a	3.89 a	21.9 a	27.8 a
Tree architecture								
Central leader	38.8 a	43.4 b	235.7 a	242.7 a	4.04 a	3.78 a	18.7 a	20.5 a
Tall spindle	31.3 a	49.1 a	231.4 a	234.0 a	4.14 a	3.91 a	17.5 a	25.9 a
Girdling								
NOGD	36.2 a	41.6 b	213.5 b	223.3 b	3.92 b	3.61 b	19.0 ab	23.6 a
BG15	36.5 a	51.9 a	243.8 a	241.6 ab	4.22 a	3.98 ab	13.8 b	19.4 a
SG15	32.1 a	46.6 ab	240.0 a	236.0 ab	4.13 ab	3.71 ab	21.8 a	27.6 a
BG1516		45.0 ab		242.0 ab		4.06 a		27.8 a
SG1516		50.3 a		249.3 a		3.82 ab		17.9 a

[z] Fruit skin color rating: scale of 1 to 5, with 1 = 20% red, progressively to 5 = 100% red.

[y] Mean separation within columns in each group of treatments by least significant difference at 5% level. A significant interaction existed between rootstock and tree architecture for yield in 2016. No other interaction existed among any other treatments.

BG15 = bark girdling in 2015; BG1516 = bark girdling in 2015 and 2016; NOGD = no girdling (control); SG15 = score girdling in 2015; SG1516 = score girdling in 2015 and 2016.

Table 3. Effects of rootstock, tree architecture, and girdling on fruit firmness, soluble solids, starch degradation pattern, and russet in 'Aztec Fuji' apple at harvest in 2015 and 2016.

	Fruit firmness (Newton)		Soluble solids concn (% Brix)		Starch pattern (1–6)[z]		Fruit russet (%)	
Treatment	2015	2016	2015	2016	2015	2016	2015	2016
Rootstock								
Nic 29	71.2 b[y]	71.9 b	13.5 b	13.3 a	4.12 a	5.79 a	21 a	13 a
Bud 9	78.4 a	72.6 a	15.0 a	13.3 a	4.16 a	5.86 a	20 a	14 a
Tree architecture								
Central leader	73.1 b	72.3 a	13.9 b	13.4 a	4.23 a	5.84 a	21 a	10 b
Tall spindle	76.8 a	72.1 a	14.7 a	13.2 a	4.05 a	5.82 a	20 a	17 a
Girdling								
NOGD	73.2 b	70.7 b	13.6 b	13.3 a	4.30 a	5.80 ab	17 a	15 ab
BG15	76.2 a	71.3 b	14.5 a	12.5 b	4.17 b	5.93 a	23 a	18 a
SG15	75.3 ab	72.2 ab	14.6 a	13.6 a	3.94 b	5.81 ab	21 a	11 ab
BG1516		74.3 a		13.9 a		5.71 b	21 a	11 ab
SG1516		72.3 ab				5.93 a	20 a	10 b

[z]Fruit starch degradation pattern (SDP): with 1 = least starch hydrolysis, progressively to 6 = most starch hydrolysis, using Bartram et al.'s chart (1993).
[y]Mean separation within columns in each group of treatments by least significant difference at 5% level. No interaction existed among any treatments.
BG15 = bark girdling in 2015; BG1516 = bark girdling in 2015 and 2016; concn = concentration; NOGD = no girdling (control); SG15 = score girdling in 2015; SG1516 = score girdling in 2015 and 2016.

trees on Nic 29 in 2015 (Table 3). In the present study, lower leaf N and higher light penetration through the smaller and more open canopy (data not shown) are likely reasons for a better fruit color but higher sunburn in the fruits from trees on Bud 9 rootstock. Also, higher firmness of fruit in the trees on Bud 9 at harvest (Table 3) is partially due to their smaller size (Table 2). Negative correlations between fruit size and fruit firmness and between leaf N and fruit color were previously reported in 'Stark Spur Golden Delicious' apple on various rootstocks (Fallahi et al., 1985). Rootstock did not affect fruit russet (Table 3), bitter pit, or water core at harvest in either 2015 or 2016 (data not shown).

Tree architecture effect. Trees with a CL architecture had longer terminal shoots in both 2015 and 2016 (Table 1) and higher leaf N concentration in 2015 than did those with a TS system (Table 1). Trees with a CL system had a higher number of permanent terminal shoots, resulting in stronger growth compared with trees with TS system. Trees with a TS system only had side branches that temporarily remained as fruiting branches on the tree for three to five seasons. These branches were cut when their diameters reached about two-thirds of the diameter of the main leader, leaving 10- to 12-cm stubs for initiating new branches. This practice resulted in shorter terminal growth in the trees with a TS system. Nevertheless, tree architectures did not affect the tree size in either 2015 or 2016 because trees receiving CL and TS had similar TCSA above and below the point of girdling and scoring (Table 1).

Trees with TS training had significantly higher yield only in 2016 (Table 2). Also, fruit from trees with TS training had significantly higher fruit firmness and SSC in 2015 and higher fruit russet in 2016 than did those with a CL training system (Tables 3).

Girdling effect. Bark girdling, practiced in May of 2015 only (BG15) or both 2015 and 2016 (BG1516), significantly reduced growth of terminal shoots and increased TCSA in both 2015 and 2016 (Table 1). Score girdling also tended to reduce the terminal growth and increase TCSA of the treated trees as compared with the NOGD trees, although differences were not significant (Table 1). Accumulation of starch and other nutrients on both sides of girdled area may have increased TCSA (Noel et al., 1970; Schechter et al., 1994).

Girdling had a major impact on several quality attributes. Yield per tree was unaffected by girdling treatments in 2015 (Table 2). This was expected because flowers of the 2015 crop were initiated, and fruits of this season were already set before we applied our girdling treatments in May 2015. Nevertheless, trees receiving BG15 or SG1516 had significantly higher yield than did those with NOGD or BG1516 in 2016 season (Table 2). This is because bark girdling or scoring in these trees resulted in higher flower bud initiation, and thus fruit set, leading to higher yield in 2016. In 2016, trees receiving BG1516 had similar yield to trees with NOGD and slightly (but not significantly) lower yield than those with BG15 (Table 2). The repeat of bark girdling in 2016 on the same tree that were bark girdled in 2015 could have resulted in additional fruit drop in 2016, and this area deserves further study. In 2018 (3 years after the initial treatments), trees on Nic 29 and Bud 9, with either a TS or CL training and receiving BG15 treatment had higher yield than those without any girdling or scoring.

Bark girdling or scoring in 2015 (BG15 or SG15) significantly increased fruit weight (size) in the same year (2015) (Table 2). Similar to our results, Nguyen and Yen (2012) reported that a simple S-shape scoring increased fruit size in 'Wax' apple. In our study, however, girdling or scoring only in 2015 did not have a "carryover" effect and did not affect the next year's fruit size in 2016 (Table 2). When score girdling was repeated in 2016 in addition to 2015 (SG1516), fruit size was significantly increased in 2016 (Table 2). Fruit size was also larger when bark girdling was practiced in both 2015 and 2016 (BG1516); however, the difference was not significant when compared with fruit size from NOGD trees (Table 2). On the basis of our 2-year data, we conclude that bark girdling in one year is sufficient to increase fruit size of the current year and the yield in the following year. However, if both fruit size and higher yield are the critical objectives of fruit production, annual bark scoring should be practiced in each year.

Applications of BG15 and BG1516 treatments significantly increased fruit color in 2015 and 2016, respectively (Table 2). Score girdling in each year (SG15 or SG1516) also tended to increase the fruit color in the same year but effects were not significant (Table 2). This result agrees with a previous study in 'Red Delicious' apple (Schechter et al., 1994). However, BG15 or SG15 did not have any effects on the fruit red color in 2016. Trees receiving BG15 or BG1516 had significantly lower leaf N (Table 1), which caused the improved fruit color in these trees (Table 2). Better color in the fruit from trees with lower leaf N was reported in a previous report (Fallahi et al., 1985), which can be due to lower chlorophyll content in the skin of these fruits.

Bark girdling in each year, increased fruit firmness of the same year but had no significant effect on the firmness of fruit in the following year. The physiological mechanism between girdling and firmness is not clear. However, it is well documented that leaves are much stronger sinks for Ca than are fruits (Amiri et al., 2014). Thus, it is possible that vegetative growth reduction in the trees with bark girdling in this study (Table 1) resulted in more Ca partitioning in the fruit of these trees, leading to higher fruit firmness. Scoring also tended to increase the fruit firmness in the same year, but this effect was not as strong as that of bark girdling (Table 3).

Trees with a bark girdling needed about 6 weeks and those with a scoring needed about 3 weeks to heal. Many apple growers, particularly in the humid regions, are concerned that girdling or scoring during early growing season might introduce fire blight bacteria through the wounded areas. Although we did not observe any sign of fire blight incident in these experimental trees, one can postpone the girdling or scoring to late June or early July when the pressure of fire blight inoculum is reduced in the orchard. However, this practice should be tested in each apple-growing region before it is widely recommended to growers. It is extremely important to allow sufficient time for the girdling or scoring wounds to heal to avoid freeze damage.

Schechter et al. (1994) reported that levels of nutrients, including N in leaves on girdled nonfruiting limbs were generally lower than those in the other treatments. The impact of girdling in their nonfruiting 'Sturdeespur Delicious' agreed with our results in fruiting 'Aztec Fuji' apples. The impact of girdling on nutrient partitioning in apple fruit tissue on different rootstocks deserves further study. Because girdling had a positive impact on fruit firmness in our study (Table 3), we suggest that the impact of girdling in popular cultivars such as 'Honeycrisp' apple, which has a tendency for insufficient Ca uptake and is susceptible to storage disorders, be studied.

From our 2-year study, we conclude that frequency of girdling and scoring practices may have major long-term effects on tree performance. Thus, this subject with additional measurements and treatments that we used in our study, deserves to be further investigated over several seasons to understand the long-term impacts of girdling and scoring on biennial bearing and other fruit quality attributes.

Literature Cited

Agusti, M., I. Andreu, M. Juan, V. Almela, and L. Zacarias. 1998. Effects of ringing branches on fruit size and maturity of peach and nectarine cultivars. J. Hort. Sci. Biotechnol. 73:537–540.

Agustí, M.N., J.M. Gariglio, V. Almela, C. Mesejo, and A. Martínez-Fuentes. 2005. Effect of branch scoring on fruit development in loquat. J. Hort. Sci. Biotechnol. 80:370–374.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements (FAO Irrig. Drain. Pap. 56). FAO, Rome, Italy.

Amiri, M., E. Fallahi, and M. Seyfi. 2014. Influence of rootstock on mineral uptake and scion growth of 'Golden Delicious' and 'Royal Gala' apples. J. Plant Nutr. 37(1):16–29.

Autio, W.R. 1991. Rootstock affect ripening and other qualities of 'Delicious' apples. J. Amer. Soc. Hort. Sci. 116:378–382.

Autio, W.R. and D.W. Greene. 1994. Effects of growth retarding treatments on apple tree growth, fruit maturation and fruit abscission. J. Hort. Sci. 69:653–664.

Autio, W.R., R.A. Hayden, W.C. Micke, and G.R. Brown. 1996. Rootstock affects ripening, color, and shape of 'Starkspur Supreme Delicious' apples in the 1984 NC-140 cooperative planting. Fruit Var. J. 50:45–53.

Autio, W., T.L. Robinson, B. Black, S. Blatt, D. Cochran, W. Cowgill, C. Hampson, E. Hoover, G. Lang, D. Miller, I. Minas, R. Parra, and M. Stasiak. 2017a. Bugadovsky, Geneva, Pillnitz, and Malling apple rootstocks affect 'Honeycrisp' performance over the first years of the 2010 NC-140 'Honeycrisp' apple rootstock trial. J. Amer. Pomol. Soc. 71(3):149–166.

Autio, W., T.L. Robinson, B. Black, R. Crassweller, E. Fallahi, M. Parker, R.P. Quezada, and D. Wolfe. 2017b. Budagovsky, Geneva, Pillnitz, and Malling apple rootstocks affect 'Fuji' performance over the first five years of the 2010 NC-140 'Fuji' apple rootstock trial. J. Amer. Pomol. Soc. 71(3):167–182.

Bartram, R.D., W. Bramlage, E.M. Kupferman, K.L. Olsen, M.E. Patterson, and J. Thompson. 1993. Apple maturity program handbook. USDA–ARS Tree Fruit Research Station, Wenatchee, WA.

Chun, I.J., E. Fallahi, W.M. Colt, B. Shafii, and R.R. Tripepi. 2001. Effects of rootstocks and microsprinkler fertigation on mineral concentrations, yield, and fruit color of 'BC-2 Fuji' apple. J. Amer. Pomol. Soc. 55:197–205.

Clements, J. 2011. 'Mini' Apple Orchard Systems Trial: A Comparison of central-leader, vertical-axis, and tall-spindle apple orchard systems on three different rootstocks. Fruit Notes 76:10–13.

Davie, S.J., P.J.C. Stassen, M. van der Walt, and B. Snijder. 1995. Girdling avocado trees for improved production. S. Afr. Avocado Growers' Assoc. Yearbook. 18:51–53.

Day, K.R. and T.M. DeJong. 1990. Girdling of early season 'Mayfire' nectarine trees. J. Hort. Sci. 65:529–534.

Fallahi, E., D.G. Richardson, M.N. Westwood, and M.H. Chaplin. 1985. Relationships among mineral nutrition, ethylene and post-harvest physiology in apples on six rootstocks. Scientia Hort. 25(2):163–175.

Fallahi, E., W.M. Colt, and B. Fallahi. 2001a. Optimum ranges of leaf nitrogen for yield, fruit quality, and photosynthesis in 'BC-2 Fuji'. Apple. J. Amer. Pomol. Soc. 55:68–75.

Fallahi, E., I.J. Chun, G.H. Neilsen, and W.M. Colt. 2001b. Effects of three rootstocks on photosynthesis, leaf mineral nutrition, and vegetative growth of 'BC-2 Fuji' apple trees. J. Plant Nutr. 24:827–834.

Fallahi, E., B. Fallahi, B. Shafii, and B. Morales. 2007a. Water use, tree growth, and leaf mineral nutrients of young 'Fuji' apples as influenced by different irrigation systems. Acta Hort. 721:63–70.

Fallahi, E., R. Ratnaprabha, R. Tripepi, B. Shafii, and B. Fallahi. 2007b. Tree growth, yield, fruit quality, and mineral partitioning as affected by rootstock and irrigation methods. Intl. J. Fruit Sci. 7:3–24.

Fallahi, E., B. Fallahi, and B. Shafii. 2013. Irrigation and rootstock influence on water use, tree growth, yield, and fruit quality at harvest at different ages of trees in 'Pacific Gala' apple. HortScience 48:588–593.

Fallahi, E., A. Tehranifar, and A. Gharaghani. 2017. Cluster management to improve berry quality in young 'Alborz' table grape in the Intermountain West Region, USA. Intl. J. Fruit Sci. 17(4):349–357.

Fernandez-Escobar, R., R. Martin, P. Lopez-Rivares, and M. Paz Suarez. 1987. Girdling as a means of increasing fruit size and earliness in peach and nectarine cultivars. J. Hort. Sci. 62:463–468.

Furr, J.R., P.C. Reece, and G. Hrnciar. 1945. Nitrogen absorption of ringed orange trees in sand culture. Proc. Amer. Soc. Hort. Sci. 46:51–54.

Greene, D.W. and W.J. Lord. 1983. Effects of dormant pruning, summer pruning, scoring and growth regulators on growth, yield and fruit quality of 'Delicious' and 'Cortland' apple trees. J. Amer. Soc. Hort. Sci. 108:590–595.

Hennerty, M.J. and C.G. Forshey. 1971. Effects of defruiting, scoring, defoliation and shading on carbohydrate content of 'Golden Delicious' apple trees. J. Hort. Sci. 46:153–161.

Hoying, S.A. and T.L. Robinson. 1992. Effects of chain saw girdling and root pruning of apple trees. Acta Hort. 322:167–172.

Lordan, J., P. Francescatto, L.I. Dominguez, and T.L. Robinson. 2018. Long-term effects of tree density and tree shape on apple orchard performance, a 20-year study—part 1, agronomic analysis. Scientia Hort. 238:303–317.

Noel, A.R.A. 1970. The girdled tree. Bot. Rev. 36:162–195.

Nguyen, M.T. and C.R. Yen. 2012. Effect of s-girdling on fruit growth and fruit quality of wax apple. Intl. J. Agr. and Biosys. Eng. 6(12):1064–1069.

Proebsting, E. 1994. Strategy development for managing drought, p. 39–50. In: K.M. Williams and T.W. Ley (eds.). Tree fruit irrigation. Good Fruit Grower, Yakima, WA.

Raffo, M.D., P. Calvo, V. De Angelis, L. Mañueco, S. Ziaurriz, and F. Menni. 2011. Effects of trunk girdling, on fruit productions, fruit size, and tree vigor on 'Bartlett' pears in Rio Negro and Neuquén Valley, Argentina. Acta Hort. 909:645–650.

Reig, G., J. Lordan, G. Fazio, M.A. Grusak, S. Hoying, L. Cheng, P. Francescatto, and T.L. Robinson. 2018. Horticultural performance and elemental nutrient concentrations on 'Fuji' grafted on apple rootstocks under New York climatic conditions. Scientia Hort. 227:22–37.

Reynolds, A.G. and C. de Savigny. 2004. Influence of girdling and gibberellic acid on yield components, fruit composition, and vestigial seed formation of 'Sovereign Coronation' table grapes. HortScience 39:541–544.

Schechter, I., J.T.A. Proctor, and D.C. Elfving. 1994. Apple fruit removal and limb girdling affect fruit and leaf characteristics. J. Amer. Soc. Hort. Sci. 119:157–162.

Schumacher, R.F., F. Fankhauser, and W. Stadler. 1986. Influence of growth regulators, ringing and root cutting on apple quality and physiological disorders. Acta Hort. 179:731–742.

Steyn, W.J., S.F. Ungerer, and K.I. Theron. 2008. Scoring and girdling, but not GA, increase yield without decreasing return bloom in 'Triumph' persimmon. HortScience 43:2022–2026.

Wargo, J.M., I.E. Merwin, and C.B. Watkins. 2004. Nitrogen fertilization, midsummer trunk girdling, and AVG treatments affect maturity and quality of 'Jonagold' apples. HortScience 39:493–500.

Washington State University. 2018. Washington State University Tree Fruit Research and Extension Center. 10 July 2018. <http://www.tfrec.wsu.edu>.