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Long-Term Impacts of Tree Architectures and Branch Configurations on Tree Growth, Yield, Fruit Quality Attributes, and Leaf Minerals in "Aztec Fuji" Apple

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Abstract

Canopy and branch architectures in high-density orchards can be crucial in production and fruit quality. The influence of two canopy orientations (Upright and Tilted) in combination with two arm (branch) architectures (Shortened or Overlapped) on tree growth, yield components, fruit quality, and leaf mineral nutrients in an "Aztec Fuji" apple (*Malus domestica* Bork.) high-density orchard was studied over five years. Tilted trees with shortened arm configuration (TilShArm) always had significantly larger trunk cross-sectional area (TCSA) than Upright trees with an Overlapped arm configuration (UpOverArm) every year from 2012 to 2016. Trees with a TilShArm system had more cumulative fruit per tree than those with an Upright orientation. Trees with a tilted canopy (TilShArm and TilOverArm) tended to have higher yield per tree and yield per hectare than those with an upright system. Trees with a TilShArm system were more precocious and had more yield per tree than those with an upright canopy orientation in 2012. When values were polled over five years, trees with an upright canopy-shortened arm system (UpShArm) treatment had a lower biennial bearing index (BBI) than those with an upright canopy-overlapped system (UpOverArm). Trees receiving an arm shortening (UpShArm or TilShArm) configuration often had larger fruits than those with overlapped arms (UpOverArm and TilOverArm). Fruit from trees receiving an UpOverArm had higher fruit firmness than those from trees with other canopy-branch arrangements at harvest due to their smaller size. Fruit from trees with a TilShArm and TilOverArm had significantly higher water core and bitter pit but lower sunburn than trees with an upright canopy (UpShArm and UpOverArm). Leaves from trees with an UpOverArm canopy-branch configuration had the lowest leaf Ca but the highest leaf K and Fe concentrations among all treatments.

Keywords

Branch Training, High-Density Orchard, Quality Attributes, Tree Architecture

1. Introduction

Establishing high-density apple (*Malus domestica* Borkh) orchards to meet the increasing demands is essential, and scientists have focused on using suitable rootstocks in high-density systems for high-quality fruit [1]-[5]. Combining a suitable rootstock and training system in a high-density orchard can also result in precocity, better spray coverage, and better light penetration through the tree canopy [6]-[8]. In addition to using a suitable rootstock and design, a modern high-density should also facilitate the application of modern machinery and mechanization [9].

The Tall Spindle (T.S.) training system has become extremely popular because trees trained in this system start prodcing fruiit two or three years after planting [10]. Today, many orchards are trained according to the T.S. system in New York [10] and the Pacific Northwest [11]. Pomologists have focused on comparing the T.S. system with other training systems [12] and manipulating the T.S. system to improve production and control tree growth [11]. Clements [12] reported that apple trees with T.S. had the highest production per hectare, followed by those with vertical axis and central leader.

Manipulation in branching is practiced for improving yield and quality in high-density apple orchards [11]-[14]. Mahdavi *et al.* [13] reported that a partial scoring or girdling above the bud increased branching along the apple tree trunk where nursery trees were poorly branched. In their report, the addition of Promalin [(GA_{4+7}) and 6-benzyl adenine (6-BA); Valent BioSciences (Biostimulants), Libertyville, IL, USA] to the scoring or girdling cuts had an additive effect on induction of branches. Girdling can impair the health of trees and vines if callusing is slow, and girdling needs to be practiced carefully [11]. In a recent report, Fallahi *et al.* [15] reported that tipping "Fuji" apple lateral arms resulted in higher yield and lower biennial bearing index than in a T.S. system.

Limited information exists on the impact of canopy orientation in combination with branch configurations. Therefore, this experiment aimed to study the effect of two canopy orientations in combination with two branch configurations on tree growth, yield, fruit quality attributes, and leaf mineral concentrations of the "Aztec Fuji" apple in a high-density orchard over five years from 2012 to 2016.

2. Materials and Methods

2.1. Orchard Establishment and General Cultural Practices

"Aztec Fuji" trees on *Budagovsky* 9 (Bud 9) rootstocks (C & O Nursery, Wenatchee, WA) were planted in single rows with a 0.914 × 3.66 m spacing either in a 60˚ V-shape Tatura Trellis system (Tilted) or in an Upright architecture with a north-south orientation in spring of 2010. We started the experiment in 2010 and maintained the structure of canopies and arm configurations throughout the study. However, for this portion of study, only results of 2012 - 2016 are reported. In trees with an Upright or Tilted orientation, branches were arranged in two configurations: Shortened Arm (TipArm) and Overlapped Arm (OverArm). Therefore, we had four treatments in this study consisting of an Upright Shortened Arm (UpShArm), an Upright Overlapped Arm (UpOverArm), a Tilted Shortened Arm (TilShArm), and a Tilted Overlapped Arm (TilOverArm). Details on the formation of these systems will be described later. "Snow Drift" crab apple (Malus × "Snowdrift") on M.26 EMLA rootstock (C & O Nursery, Wenatchee, WA) was planted in each row as the pollinizer between every 10 "Aztec Fuji" trees. Trees were planted just before the supporting system was installed. Besides branch configuration treatments, general cultural practices, including fruit thinning and pest and disease control, were like those recommended for commercial orchards in the Pacific Northwest [16] and in a previous report by Fallahi *et al.* [15].

Trees were irrigated with a drip system twice a week at 100% of daily crop evapotranspiration (ETc) for mature apples [17] but adjusted for the ground shading area (G.S.), as described by Allen *et al.* [18] and Fallahi *et al.* [3].

Nitrogen as UAN 32 (urea and ammonium nitrate, 32% N) was applied twice, each at 30 g/tree (total of 60 g N/tree/year) via fertigation in late May. 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 150 g of formulation to each tree-planting hole only once when planting. Micronutrients, particularly iron and zinc, were sprayed twice each year in spring and once in early summer. Calcium (Ca) was sprayed three times with cover sprays during early spring to early summer every year.

2.2. Support System and Branch Configurations

In the Tilted canopy architecture, two 4.9-m pressure-treated poles were installed at opposite directions in a tilted position at an angle of 30º with the vertical at every 7.31-m spacing on the row, with about 91.4 cm of the pole buried in the ground and 4 m above the ground. Seven rows of 4.96-mm^2 gauge galvanized wires were installed on the poles on each side the Tatura (Tilted) walls to support the trees. On each Tilted wall system (Tatura), the first wire was installed 61 cm from the ground. The other six wires were installed 45.7 cm apart from each other in such a way that the last wire was installed at 3.31 m from the ground level (**Figure 1**). At the time of planting, trees on each side of the Tatura wall were planted to the east or west directions, alternately, at an angle 30˚ with the vertical. Trees were secured to the Tatura support system (**Figure 2**). Tips of the tree leaders were minimally (about 3 cm) removed to eliminate meristems that were damaged during shipping. Tree leaders were maintained at approx—3.75 m in height (**Figure 2**).

Figure 1. Branch Configurations for Tilted Wall (top) and Upright Canopy (bottom), at full bloom, May 14, 2011.

The installation and tree planting in the Upright canopy architecture were generally similar to those in the Tilted system with two exceptions: 1) only one support post was installed at every 7.31-m spacing in an upright position, and 2) all trees were planted upright (**Figure 1** and **Figure 2**).

Each block consisted of both Tilted and Upright architecture systems. Each block of the Tilted canopy architecture consisted of 16 trees with a 0.914 × 3.66 m spacing (91.4 cm × 366 cm spacing), with eight trees on each side of the Tatura wall. Trees with an Upright system were planted in solid rows in the same orchard and at the same spacing. They received the same branch configuration system as those in the Tilted architecture, but they were planted in an upright position. Data were collected from four trees in the mid-portion of each plot in both Tilted and Upright systems to avoid border effects.

All trees were forced to induce seven pairs of bilateral cordon arms at every 45.7 cm point along the main trunk. If an arm did not exist in the exact desired place,

Figure 2. Support System and Branch Configurations in Tilted Wall (top) and Upright Canopy (bottom), Before Bloom on April 4, 2014.

a 3 - 4-cm patrial cut (scoring) was made perpendicular to the main trunk through the bark cambium layer at about 6 - 7 mm above an outward-going bud, using a sharp scoring knife and applying Promalin at 500 ppm. These arms were trained in a north-south orientation and fastened to the wires at a 90˚ angle about the main trunk during the late dormant season in early March and continued throughout the season. Other branches or feathers were eliminated. Trees in each plot received one of the following branch configurations:

1. Short Arm systems (UpShArm and TilShArm). All arms in this system were on the same plane. Arms in trees with a ShArm system were shortened on each side of the tree and maintained halfway between the two adjacent trees growing in the same orientation in March of every year (Figure 2 bottom photo). Thus, the arm length on each side of the trees with a ShArm was 45.7 cm in upright trees and 91.4 cm in tilted trees. Branches were guided and fastened to the wires and excessive branches were eliminated and others were shortened, if needed, during the growing season. But shortening of the main arms was done only once a year in March.

2. Overlapped Arm system (OverArm). Training trees with an OverArm branch configuration (UpOverArm and TilOverArm) were identical to those with a ShArm system, except that each arm remained uncut until it reached the main trunk of the next tree on the same plane. Thus, the arms of the two adjacent trees on the same side of the wall or plane would "overlap" in an OverArm system (Figure 2 top photo). Therefore, each side of the OverArm was 91.4 cm in trees with an Upright canopy and 182.8 cm in trees with an OverArm and growing on the same plane (orientation) in the Tilted canopy architecture.

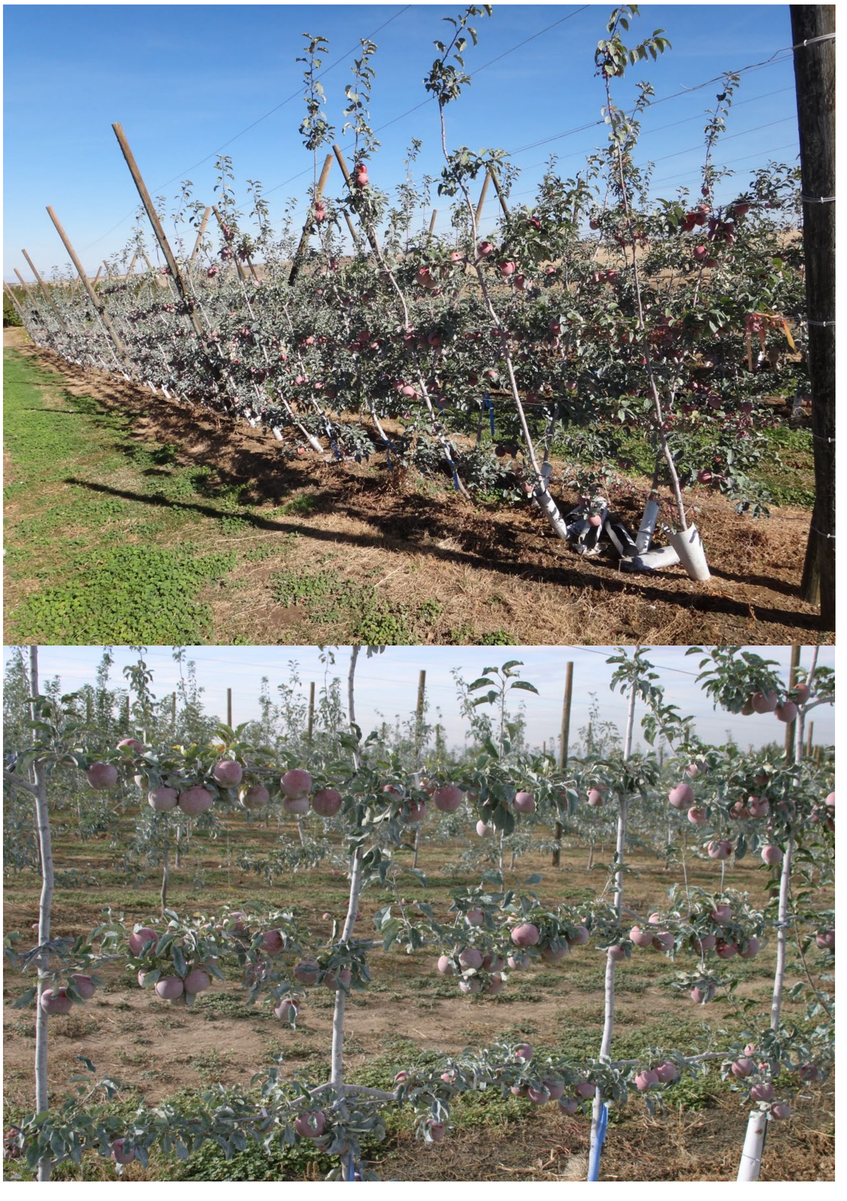

Figure 3. Tilted Wall (top) and Upright Canopy (Bottom) at Harvest Time, October 17, 2012.

In both Upright and Tilted tree architectures, raisers (shoot and suckers) that arose from each lateral arm were cut short to keep them at about 12 cm during the growing season to create a spur structure (**Figures 1-4**), like the system described by Goodwin [19].

2.3. Tree Growth, Yield, Quality Attributes, and Leaf Minerals

Tree trunk diameter was measured using a digital caliper in early November each year, and trunk cross-sectional area (TCSA) was calculated. Yield per tree was recorded at harvest time, and twenty fruits were randomly sampled from each tree on October 17 - 20 each year. Ten fruits were used to assess quality attributes at harvest, and the other ten were kept in plastic containers in a regular atmosphere and stored at ˚C for 120 days. In this study, only quality attributes for harvest time are reported. Methods for quality assessment were similar to those in our earlier reports [11] [15].

Figure 4. Tileted Wall Overlapped (TilOverArm) Configuration (Top) and UpOverArm Structure (Bottom) at Harvest on November 1, 2016.

2.4. Leaf and Mineral Nutrient Measurements

Thirty leaves per tree were sampled randomly from the middle of the current season shoots in mid-August each year. Leaves were then washed and dried in a forced-air oven at 65˚C. Nitrogen (N) concentration was determined by combusting the dry leaf tissue using a LECO Protein/Nitrogen Analyser (Model FP-528; LECO *et al.*, MI, USA). Leaf tissue was analyzed for potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) by dry-ashing at 500˚C, digestion with 10% (v/v) nitric acid, and atomic absorption spectrophotometry (Perkin-Elmer B1100; Norwalk, CT, USA), generally as described in details by Chaplin and Dixon [20] and Fallahi *et al.* [3].

2.5. Experimental Designs and Statistics

The experimental design in each year was completely randomized with four four-tree replications (a total of 16 trees per treatment). 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, USA), with GLM, and Least Significant Difference test (LSD) compared means) at $P \leq 0.05$.

3. Results and Discussion

3.1. Canopy and Arm Formation, Tree Growth, Yield Components, and Biennial Bearing

The figures for support systems, formation of the canopy and arm configurations for different stages of tree growth are shown in **Figures 1-4**. Spurs and fruits in trees with all canopy-arm configurations were developed along wires in perfectly regular "window patterns" during early years of this study (**Figures 1-3**). However, the regular window patterns in different combinations canopy-arm combinations became more irregular as trees grew because spurs and fruits were produced farther from the primary branches in the older trees (**Figure 4**).

Results for yield, growth, fruit quality, and leaf minerals are reported in **Tables 1-4**. Yield per tree in all tree canopy-branch configurations steadily increased between the "on years" of 2012, 2014, and 2016 and between the "off years" of 2013 and 2015 (**Table 2**).

Tilted trees with a shortened arm configuration (TilShArm) always had larger TCSA than Upright trees with an overlapped arm configuration (UpOverArm) every year from 2012 to 2016. Since trees in all treatments had a diameter of about 1.27 cm at the time of planting in 2010, the TCSA differences between TilShArm and UpOverArm systems must have started between 2010 and 2012 because trees with TilShArm already had larger TCSA than those with an UpOverArm system in 2012 (**Table 1**). Trees with UpShArm, TilShArm, and TilOverArm had statistically similar TCSA every year (**Table 1**).

There were differences among treatments for fruit number per tree, yield per tree, and yield per hectare, and these differences had approximately the same

Table 1. The impact of canopy and branch configurations on tree growth and number fruit per tree in "Aztec Fuji" apple in five years of 2012 to 2016.

	Trunk cross sectional area (cm^2) 2012 - 2016					Number of Fruit per tree over 2012 - 2016					
Treatment[z]	2012	2013	2014	2015	2016	2012	2013	2014	2015	2016	Cum. 2012 - 16
UpShArm	9.34a[y]	11.83ab	12.89ab	14.76ab	17.45ab	18b	26ab	66c	102a	119b	331b
UpOverArm	8.19b	10.19b	10.62b	12.67b	14.73b	35a	15b	63c	67b	143ab	323b
TilShArm	9.37a	12.93a	13.98a	17.95a	21.05a	36a	33a	117a	63b	181a	430a
TilOverArm	9.02a	11.52ab	12.10ab	14.77ab	17.08b	33a	24ab	95b	75ab	161ab	388ab

[z]Treatment: UpShArm = Upright canopy with Shortened arm; UpOverArm = Upright canopy with overlapped arm; TilShArm = Tilted canopy with Shortened arm; TilOverArm = Tiled canopy with overlapped arm.
[y]Mean and Significance denotations: Mean values within each column of tree Spacing or Training in each year followed by the different letters are significant at 5% and those followed by the same letters are not different at 5%, using least significant difference test.

Table 2. The impact of canopy orientation and branch configuration on yield per tree, yield per hectare, biennial baring index, and fruit weight in "Aztec Fuji" apple from 2012 to 2016.

	Yield per tree (kg)						5-yr cum.[z]		Fruit weight (g)					
Treatment[z]	2012	2013	2014	2015	2016	5-year cum.	Yield (kg·ha^{-1})	BBI[z] (5-yr avg.)	2012	2013	2014	2015	2016	5-y5 cum[z].
UpShArm	4.65c[y]	7.30a	15.6bc	21.10a	24.54c	73.15bc	218,719bc	0.271b	255.4a	222.7a	231.5a	214.9a	214.5bc	227.8a
UpOverArm	6.46b	2.79b	13.53c	13.31b	27.33bc	63.45c	189,712c	0.459a	191.5c	186.4b	212.0b	202.9a	193.1c	197.1c
TilShArm	8.20a	5.74ab	26.08a	13.90b	42.49a	96.82a	289,484a	0.483b	230.3ab	225.6a	225.0ab	228.1a	240.3a	230.0a
TilOverArm	7.08ab	5.11ab	20.11b	15.54ab	35.35ab	83.19ab	248,748ab	0.392ab	218.4b	207.7ab	211.5b	210.8a	220.9ab	213.9b

[z]Treatment: UpShArm = Upright canopy with Shortened arm; UpOverArm = Upright canopy with overlapped arm; TilShArm = Tilted canopy with Shortened arm; TilOverArm = Tiled canopy with overlapped arm; yr = year; avg. = average; 5-yr avg. = average of values over 5 years, from 2012 to 2016; cum = cumulative; BBI = biennial bearing index = BBIY1Y2 = biennial bearing between year 1 and year 2 = absolute (yield per tree in year 1 − yield per tree year 2)/(yield per tree year 1 + yield per tree year 2).
[y]Mean values within each column followed by different letters are significant at 5%, using Least Significant Difference test.

Table 3. The impact of canopy and branch configurations on fruit internal and external quality attributes in "Aztec Fuji" apple from 2012 to 2016.

	Fruit Firmness at harvest (N)						External and internal quality attributes at harvest, averaged over 2012 - 16.				
Treatment[z]	2012	2013	2014	2015	2016	5-yr[z] avg.	Water core (%)	Bitter pit (%)	Sunburn (%)	SDP[z] (1 - 6)	SSC[z] (°Brix)
UpShArm	80.9a[y]	83.9b	74.5ab	78.3b	76.8a	78.9b	18b	12b	29.4a	4.08a	15.6a
UpOverArm	81.9a	90.3a	75.1a	82.1a	77.5a	81.4a	12c	11b	29.6a	4.07a	15.8a
TilShArm	77.9b	88.9ab	72.1b	81.3ab	71.8b	78.4b	27a	17a	18.0b	4.27a	15.5a
TilOverArm	78.0b	87.7ab	72.6ab	81.0ab	73.4b	78.6b	24a	14a	21.7b	4.23a	15.8a

[z]Treatment: UpShArm = Upright canopy with Shortened arm; UpOverArm = Upright canopy with overlapped arm; TilShArm = Tilted canopy with Shortened arm; TilOverArm = Tiled canopy with overlapped arm; yr = year; avg. = average; 5-yr avg. = average of values over 5 years, from 2012 to 2016; SDP = Starch Degradation Pattern ranging from 1= least starch degradation, progressively to 6 = complete starch degradation; SSC = soluble solids concentration.
[y]Mean values within each column followed by different letters are significant at 5%, using Least Significant Difference test.

Table 4. The impact of canopy and branch configurations on leaf weight and mineral concentrations in "Aztec Fuji" apple over 5 years from 2012 to 2016.

Treatments[z]	Leaf fresh weight (g/leaf)	Leaf dry weight (g/leaf)	Leaf dry weight (%)	N (% dwt[z])	Ca (% dwt)	Mg (% dwt)	K (% (dwt)	Fe (ppm)	Zn (ppm)	Cu (ppm)	Mn (ppm)
UpShArm	0.596a[y]	0.244ab	41.1b	2.33a	1.73ab	0.355a	1.30b	90.0b	39.6a	7.45a	96.8a
UpOverArm	0.552b	0.234b	42.1a	2.32a	1.66c	0.318bc	1.46a	93.2a	39.9a	7.79a	90.5a
TilShArm	0.613a	0.254a	41.5ab	2.31a	1.78a	0.339ab	1.17c	86.2c	36.9b	7.85a	81.7b
TilOverArm	0.585a	0.246a	41.8ab	2.33a	1.71bc	0.303c	1.16c	87.5c	40.7a	7.48a	77.5b

[z]Treatment: UpShArm = Upright canopy with Shortened arm; UpOverArm = Upright canopy with overlapped arm; TilShArm = Tilted canopy with Shortened arm; TilOverArm = Tiled canopy with overlapped arm; dwt = dry weight.
[y]Mean values within each column followed by different letters are significant at 5%, using Least Significant Difference test.

patterns as their TSCAs. Thus, in general, trees with a tilted orientation (TilShArm and TiltOverArm), particularly trees with a TilShArm, had a relatively higher number of fruits per tree than those with an Upright orientation, and the difference was significant in 2014 (**Table 1**). Furthermore, trees with a tilted canopy (TilShArm and TilOverArm) tended to have (and sometimes significantly) higher yield per tree and yield per hectare than those with an Upright system 4 of 5 years (**Table 2**). The higher yield per tree in trees with a TiltShArm system compared to those with an UpOverArm was significant in 3 of 5 years, resulting in a significantly higher cumulative year in trees with TilShArm (**Table 2**).

Since the within-row spacing between trees was the same in different canopy orientations (91.4 cm), the total yield per hectare followed a similar pattern as yield per acre in all treatments in all years (data not shown). Therefore, trees with a TilShArm had the highest five-year cumulative yield per hectare, while trees with an UpOverArm had the lowest among all treatments (**Table 2**).

The length of the Total Potential Fruiting Zone (TPFZ) on each side of the arms in two adjacent trees on the same side of the tree wall in a TilShArm or TilOverArm configuration was 182.8 cm. However, the TPFZ in the trees with an UpShArm or UpOverArm configuration TPFZ was 91.4 cm. The lower TCSA, fruit per tree, and yield per tree in trees with an UpOverArm system are likely related to the length of TPFZ and leaf size. The TPFZ in trees with an UpShArm and an UpOverArm was similar (91.4 cm on each side of the arm). Also, the TPFZ in trees with tilted canopies (TilShArm and TilOverArm) was 182.8 am. However, leaves in trees with an UpOverArm were smaller (lighter) than trees with other canopy-arm arrangements (**Table 4**).

We believe that trees with an UpOverArm treatment had a denser canopy, leading to less light penetration, photosynthesis, and carbohydrate partitioning and, hence, smaller leaves, TCSA, number of fruit per tree, and yield per tree than those with other types of canopy-arm configurations. Trees with a TilShArm system had situations opposite to those with an UpOverArms system, with larger leaves, more light penetration, and more carbohydrate transportation, leading to a higher yield.

It is paramount to remember that all fruits on the TPFZ in trees in all canopy-arm configurations (UpDhArm, UpOverArm, TilShArm, and TilOverArm) were thinned to a 15-cm spacing. Therefore, the longer TPFZ, larger leaves, a higher carbohydrate partitioning, and a higher number of fruits per tree, particularly in the TiltTipArm system (**Table 1**), rather than thinning practices, were the main reasons for their higher yield per tree (**Table 2**).

Trees with a TilShArm system were more precocious and had more yield per tree than those with an upright canopy orientation in 2012 (**Table 2**). When values were polled over five years, trees with an UpShArm treatment had significantly lower BBI than those with an UpOverArm system and relatively lower BBI than all other tree canopy-branch combinations (**Table 2**). Therefore, plating trees with a TilShArm is recommended if the main objective is precocity (early production). Also, planting trees according to an UpShArm system is recommended when low biennial bearing is the primary purpose of apple production.

3.2. Impacts of Canopy and Branch Configurations on Fruit Quality

Trees receiving an arm-shortening treatment (UpShArm and TilShArm) often had larger fruits than those with overlapped arms (UpOverArm and TilOverArm) (**Table 2**). Mokhles and Hirst [21] intensively studied the relationship between spur and shoot leaves in apples. In their report, bourse shoot defoliation and fruiting treatments inhibited spur flower formation but in different patterns from year to year. They suggested that bourse leaves play a significant role in producing and transporting flower formation signals. Lakso and Goffinet [22] reported that leaves of extension shoot support the growth of the shoot with carbohydrates until at least 10 - 12 leaves have developed. After that, the most basal leaves on the shoot can export carbohydrates to the fruit. After shoot growth stops, all leaves on the shoot can export their carbohydrate to the fruit. Because of this finding, they suggest that very light pruning that gives many shoots that stop growth quite early will support early fruit growth better than heavy heading cuts that give more long, vigorous extension shoots that compete with the fruit for longer times. We created that scenario by shortening the arms in the UpShArm and TilShArm canopy-branch architectures. We observed that shortening the arms induced considerable side shoots, bouse shoots, and spur structure along the arms (**Figure 1** and **Figure 2**). These shorter side shoots and bouse shoots can transport more carbohydrates to the fruit, as Lakso and Goffinet [22] suggested, resulting in larger fruit sizes in trees with UpShArm and TilShArm systems **(Table 2**).

Fruit from trees receiving an UpOverArm had higher fruit firmness than those from trees with other canopy-branch configurations at harvest due to their smaller size, and the differences were often significant (**Table 3**). Fallahi *et al.* [23] also reported a strong negative correlation between fruit size and firmness in the "Starkspur Golden Delicious" apple, which agrees with our study. Smaller fruits have more compacted flesh and, hence, higher firmness.

In general, fruit from trees with a Tatura system (TilShArm and TilOverArm had significantly higher water core and bitter pit but lower sunburn than trees with an upright canopy (UpShArm and UpOverArm) (**Table 3**). Fruit firmness values in trees with TiltShArm and TilOverArm canopies were lower than those with an upright canopy at harvest (**Table 3**). The lower fruit firmness, meshed with their higher water core and bitter pit in the fruit from trees with a tilted canopy, suggests that a tilted canopy could enhance fruit maturity compared to the upright canopy in the "Aztec Fuji" apple. This observation suggests that planting trees at an angle (tilted orientation) may advance fruit maturity in "Aztec Fuji" apple compared to those trained in an Upright. Tree canopy-branch configurations did not significantly affect soluble solids concentration and starch degradation pattern over the years (**Table 3**).

3.3. Impacts of Canopy and Branch Configurations on Leaf Mineral Nutrients

Leaves from trees with an UpOverArm canopy-branch configuration had significantly lower fresh weight and relatively lower dry weights but a higher percentage of dry weight than those from trees with other treatments (**Table 4**). Among all treatments, these trees also had the lowest leaf Ca but the highest leaf K and Fe concentrations (**Table 4**). Trees with an Upright orientation (UpShArm and UpOverArm) had higher leaf K and Fe concentrations than those with a tilted canopy (TilShArm and TilOverArm). Potassium has a higher affinity than other minerals to translocate from the leaf into fruit tissue when the crop is heavier [3]. Trees with UpOverArm and UpOverArm configurations had lower yields (**Table 2**), which resulted in a higher K accumulation in the leaf (**Table 4**).

A high level of K and K/Ca ratio in the fruit tissue can alarmingly increase bitter pit, particularly in "Honeycrisp" apples [24]. Despite considerable interest in studying the relationships between fruit mineral concentration and bitter pit incidences, less attention is paid to the relationships between leaf tissues and fruit minerals and bitter pits in "Honeycrisp". However, It is reported that leaf K is strongly and positively related to the fruit K in "Stark Spur Golden Delicious" [25]. If high K in the leaf also reflects high K in the fruit tissue in "Honeycrisp", growers should remember that planting "Honeycrisp" trees in an upright canopy can increase K compared to planting in a tilted orientation, and this might be a potential issue that should be considered. Leaf Fe concentration and crop load could have a mechanism similar to yield-leaf K, which deserves further study. Canopy-branch configuration did not affect Leaf N and Cu (**Table 4**).

3.4. General Comments

At first, it seems difficult to practice and teach workers how to tarin trees to these canopy and branch configurations. However, after one learns about the ultimate shape and basic physiology behind the practice, it becomes a routine. Modern orchard designs, combined with new rootstocks and branch configurations, create a much more complex biosystem in fruit physiology than before. Additionally, any alteration of the tree or branches such as bark girdling and scoring can influence some mineral concentrations, phytopigments, proline, and chlorophyll index [26], and may add to the complexity of the modern orchard biosystems. Therefore, further studies to understand the impacts of these complex systems on mineral partitioning, yield, and fruit quality attributes are of paramount importance.

4. Conclusion

Tree canopy orientation and branch configurations will have a major influence on some yield, fruit quality, and leaf mineral nutrients in "Aztec Fuji". Tilted trees with a TilShArm always produced bigger trees (larger TCSA) than those with an UpOverArm every year. Trees with a TilShArm system had more fruit per tree than those with an Upright orientation. Trees with a tilted canopy (TilShArm and TilOverArm) tended to have higher yield per tree and yield per hectare than those with an upright system. Averaging values over the five years revealed that UpShArm treatment had a lower BBI than those with an UpOverArm. Shortening arms (UpShArm or TilShArm) resulted in larger fruits than those with overlapped arms (UpOverArm and TilOverArm). Overlapping branches in an Upright planting led to the production of smaller and thus, firmer fruit than those from trees with other canopy-branch arrangements. Fruit from trees with a tilted canopy had higher watercore and bitter pit but lower sunburn than trees with an upright canopy (UpShArm and UpOverArm). Trees with an upright canopy and overlapped arms had the lowest leaf Ca but the highest leaf K and Fe concentrations among all treatments. As a general conclusion, shortening branches in both upright and tilted canopies is preferred than overlapping branches for many quality factors.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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