Effect of tree type and rootstock on the long-term performance of 'Gala', 'Fuji' and 'Honeycrisp' apple trees trained to Tall Spindle under New York State climatic conditions

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Abstract

In 2006, two 0.3 ha orchard trials were established at two sites (Dressel farm in Southeastern New York State and VandeWalle farm in Western New York State) to compare two tree types (feathered trees and bench-grafted trees) on five rootstocks [three Geneva® rootstocks (G.11, G.16, G.41) with one Budagovsky rootstock (B.9) and one Malling rootstock (M.9T337)] as controls. 'Gala' and 'Fuji' were used as scion cultivars at Dressel farm and 'Gala' and 'Honeycrisp' as the scions cultivars at VandeWalle farm. At each location, trees were planted at 3,262 trees ha^{-1}and trained to a Tall Spindle (TS) system. Location, tree type and rootstock interacted to affect tree growth, production and fruit quality of each scion cultivar. 'Gala' trees from VandeWalle (Western NY State) were more productive (33% more production) than those from Dressel Farm (Southern NY State), because they produced more fruits per cm^{-2} and fruit size was bigger. When comparing the two tree types (feathered and bench-grafted) at both locations and across all rootstocks (B.9, G.11, G.16, G.41, and M.9T337), feathered trees were similar in tree size after 11 seasons as bench-grafted ones, except for ‘Fuji’ at Dressel farm where bench-grafted trees were 27% smaller than feathered trees. The bench-grafted trees had lower cumulative yield per hectare, cumulative yield efficiency, and cumulative crop load than the fully feathered trees. Finally, when comparing all 10 tree type x rootstock combinations, for ‘Fuji’, feathered trees with G.11, for ‘Gala’, feathered trees with G.41, and for ‘Honeycrisp’, feathered trees with G.16 were the combinations with the highest cumulative yield, high yield efficiency and crop loads, low biennial bearing, and with slightly significant larger fruits.

Keywords: feathered tree, bench-grafted tree, Geneva® rootstocks, crop load, yield efficiency, soluble solids content, fruit red color

1. Introduction

The Tall Spindle (TS) apple (*Malus* × *domestica* Borkhausen) planting system is becoming the preferred planting system in several areas of the world. It is an amalgamation of the Slender Spindle, the Vertical Axis, the Super Spindle, and the Solaxe systems (Robinson et al., 2006). This system utilizes the concept of high tree densities from the Slender Spindle system, branch management from the Vertical Axis, Super Spindle and the Solaxe, but utilizes lower planting densities (~2,500-3,300 trees/ha) than the Super Spindle (Robinson et al., 2014). Currently, most of the new orchards in U.S are being planted to the Tall Spindle (TS) system (Robinson et al., 2011). A key component of this system is high-quality nursery trees that have lateral branches or shoots (feathers) and good tree growth (Dominguez, 2015).

With the development of high density orchard systems, several researchers have studied the impact of tree quality and the number of feathers (side branches) on the performance of maiden nursery trees. Wertheim and Joose (1972) showed that both the thickness of the stem and the number of lateral branches (feathers) of the maiden tree had a large influence on early yield. The greater the number of feathers at planting the greater the yield, especially in the second and third years. Thus, for high density systems that depend on significant 2^{nd} and 3^{rd} year yield, feathered trees have become an essential part of the success of these systems (Dominguez, 2015; Robinson, 2007). Currently, the ideal tree for high density plantings should have a minimum stem diameter of 15 mm, and 10-15 well positioned feathers with a maximum length of 40 cm and starting at a minimum height to 80 cm on the tree (Balkhoven-Baart et al., 2000; Robinson, 2007; Weis, 2004). However, the high investment cost of high density orchards is directly related to the number of trees per ha and the cost of each tree.

Worldwide growers are struggling with the availability of desired apple cultivars on the desired rootstock at an affordable price. Although most research has shown the value of highly feathered trees to improve yield in the early years of an orchard's life, some fruit growers have wondered if using less expensive trees such as bench-grafts (table grafted plants placed directly into the orchard with no stage in the nursery) could be a reasonable approach to reducing initial investment cost and thus reducing the risk of high density orchards and still achieve acceptable early yield.

There are no studies showing the long-term influence of tree type on yield and fruit quality. Therefore, the aims of this trial were:1) to investigate the long-term effectiveness of bench-grafted trees as an alternative to highly feathered trees in the most common high-density orchard system (Tall Spindle, TS) using two common dwarfing rootstocks (B.9 and M.9T337) and three new promising dwarfing rootstocks from the Geneva® breeding program (G.11, G.16, G.41), and 2) to determine the best rootstock for three popular apple cultivars with different growth habits (bench-grafted and feathered trees).

2. Material and Methods

2.1. Plant material, site description and experimental design

In the spring of 2006, two 0.3 ha orchard trials of two tree types and five apple rootstocks were established at two locations in New York State, USA (Dressel farm and VandeWalle farm).The two types of trees were: fully feathered nursery trees (2 years in the nursery), and bench-grafted trees (no time in the nursery but directly planted to the field after grafting). The feathered trees were propagated by Adams County Nursery, Aspers PA, USA and the bench-grafted trees were propagated by Wafler Nursery, Wolcott, NY. Virus free scion wood and rootstocks were used at both nurseries.' Gala' and 'Fuji' apple cultivars were used at the Dressel farm site and 'Gala' and 'Honeycrisp' were used as scion cultivars at the VandeWalle farm site. Rootstocks included three Cornell-Geneva rootstocks [('Geneva® 11' (G.11), 'Geneva® 16' (G.16), and ‘Geneva®41’ (G.41)], ‘Budagovsky 9’ (B.9), and ‘Malling 9’ (‘M.9 Dutch clone T337’) (Table 1). The planting system was the Tall Spindle (TS) and trees were spaced 0.91 m × 3.35 m (3,262 trees ha^{-1}).

The trial at Dressel farm was planted in Southeast New York State in New Paltz, USA (lat. 41º42’53.15”N, long. 74º06’39.78”W) on a Hoosic gravelly loam soil, and the trial at VandeWalle farm was planted in Western New York State, Alton, USA (lat. 43°13'12.58"N, long. 76°58'17.11"W) on a Williamson silt loam soil (https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx). In both trials, row orientation was north-south. The Dressel site had previously been planted to apple trees on seedling rootstock for 40 years and was not fumigated. The VandeWalle site had previously been planted to an apple tree nursery and was not fumigated before planting. The replant disease severity at both trial sites was not evaluated before planting but field fumigation trials in the same counties by Merwin et al. (2001) showed low replant disease pressure for similar soils.

Trees at both sites were irrigated each year through drip lines as needed. Average annual precipitation for the Dressel site was 1,000 mm and at the VandeWalle site annual rainfall averaged 990 mm during spring and summer months. Calcium nitrate fertilizer (338 – 394 kg ha^{-1}) was applied each year to all cultivars, whereas muriate of potash (KCl 338 kg ha^{-1}) was only applied to ‘Gala’. Foliar micronutrients and pesticides and insecticides were applied as necessary according to local recommendations at each site, following industry standards.

The design of the experiment at each location was a randomized complete block with a split-split plot, with three replications. Within each block the main plot was cultivar and the sub plot was tree type and the sub-sub plot was rootstock. Sub plots consisted of whole rows while rootstock sub-sub plots were composed of a row section 12m long with thirteen trees. The treatment design was a complete factorial of 2 cultivars, 2 tree types and 5 rootstocks with 20 treatment combinations of cultivar, tree type and rootstock.

2.2. Tree management

Feathered trees were produced by planting the rootstock liner (7mm diameter) in the nursery in the spring of 2004 and then chip budding a single scion bud in August of 2004. The scion bud remained dormant until spring of 2005 when it began to grow and the rootstock stem above the scion bud was removed and all other competing rootstock shoots. The nursery tree was irrigated and fertilized continuously to achieve very rapid growth in 2005. In mid-June of 2005 the growing tip was sprayed with 25 ml of Maxcel per liter of water (Valent BioScience Corporation, Illinois, USA) to induce lateral branching (Lordan et al., 2017a). Two additional sprays of 6-BA were applied at 14 day intervals to stimulate more lateral branching. This produced 7-8 feathers in the nursery. The trees were dug in the fall of 2005, headed at 2m height and stored in a temperature and humidity controlled tree storage chamber and then planted in the experimental plot in the spring of 2006. During the early years, feathered tree training was based on encouraging the further development of the leader to a height of 3.5m and the development of new branches to quickly fill the space assigned to the trees. In the first and second year, dormant pruning was minimal. The trees were developed by not heading the leader further at planting, removing one or two of the largest feathers, leaving the remaining feathers unpruned and tying down the feathers below horizontal (120° from vertical) soon after planting. In years 2 through 4, the leader was not headed. Beginning in year 3, limbs larger than 2 cm diameter were removed back to the trunk with an angled cut to develop replacement limbs. Each year one to two branches larger than 2 cm were removed. Tree height was limited to 3.5 m by cutting the top back to a small lateral branch at that height each spring. Only small lateral branches (<2 cm) were allowed to remain in the tree and they were each kept simple by removing sub-lateral branches to create a single axis for each branch. Once trees filled the allotted space, a balanced winter and summer pruning was developed to promote fruiting wood and moderate tree growth. The constant annual removal of larger limbs kept the trees to the size allotted by the tree spacing.

Bench-grafted trees were developed by grafting a 2-bud scion to the rootstock in February 2006 and then callusing the grafted trees for 2 months at 10°C. Subsequently in early April the grafted trees were planted directly into the experimental plot. The newly-planted trees were protected with a 30cm long rectangular tube of wax-covered cardboard and a 120cm long bamboo tree stake. As the scion buds developed the most vigorous one was selected and retained while all others were removed. The new shoot was tied to the bamboo tree stake at monthly intervals. By the end of the first year these trees had a height of ~1.5m. In years 2-6 the leaders were not headed and lateral branching was induced by treating with 50 ml of Maxcel per liter of water at two weeks after bud-break in the second year. In the third year, lateral branches were tied down below horizontal (120° from vertical) about 1 month after bud break. Thereafter the bench-grafted trees were managed as described in the feathered tree TS section.

Feathered trees were defruited manually in the first year (2006) at both locations, and then allowed to crop from 2007 to 2016. In 2007 trees were hand thinned at 50 days after bloom. Every year after 2007 trees were chemically thinned by spraying them with 1.2 L ha^{-1} of Carbaryl (Sevin 4L -Bayer Crop Science, Research Triangle Park, NC) at petal fall plus 2.4 L ha^{-1} of Carbaryl and 25 ml of 6-Benzyladenine per liter of water (Maxcel - Valent BioScience Corporation, Illinois, USA) at 8-10 mm fruit size. Bench-grafted trees had no flowers in the first year (2006) and were manually defruited in the second year (2007). Thereafter they were chemically thinned similarly to the feathered trees each year. Hand thinning was conducted on both tree types as a touch up practice at the end of June – early July each year. Trees were supported by a 3-wire trellis (2.75 m tall).

2.3. Horticultural assessments

Trees were evaluated through eleven years (season 2016) after planting. From the second year (2007) onward we recorded at harvest: fruit number and weight (kg $tree^{-1}$). Average fruit size (g) was calculated from the total number of fruits and total yield per tree. At the end of the experiment (Oct. 2016), tree circumference was recorded at 30 cm above the graft union, and the trunk cross-sectional area (TCSA, cm^2) was then calculated. Cumulative yield (CY), cumulative yield efficiency (CYE, kg/cm^2) and cumulative crop load (CCL, fruit number/cm^2) of each scion-rootstock-tree type combination were computed from 2007 to 2016. Root suckers were removed each year, and during the last two years of the study (2015 and 2016) they were counted and removed thereafter.

Partitioning index (PI) was calculated as the ratio of cumulative yield and the TCSA difference between the last year of the study and the second year after planting. We calculated alternate bearing index (AI) according to the formula suggested by Racsko (2007) from the third year after planting (2008) to the eleventh year after planting (2016):$AI = 1/(n - 1) \times \{|(a_2 - a_1)| / (a_2 + a_1) \ldots + |(a_{(n)} - a_{(n-1)})| / (a_{(n)} + a_{(n-1)})\}$where n: number of years, and a1, a2,…, a(n-1), and: yield (kg $tree^{-1}$). This index ranges from 0 to 1, with 0= no alternation and 1= complete yield alternation.

2.4. Fruit quality assessments

From year 3 to year 11, at each harvest, 50 representative fruits were randomly hand-picked at commercial maturity stage for each scion-rootstock-planting system combination. Fruit red color was measured in years 5-11 by grading fruit for fruit color using a commercial electronic MAF RODA Pomone (MAF Industries, Travers, CA) fruit grader with a camera system for evaluating red color. Fruits were classified according to the fruit quality grades used in the United States (USDA, 2002). A random sub-sample of 10 fruits was then evaluated for flesh firmness (FF) and soluble solids content (SSC). FF was measured on two paired sides of each fruit, by removing 1 mm thick disk of skin from each side of the fruit, and using a pressure texture (EPT, Lake City Technical Products, USA) equipped with an 8 mm tip. The two readings were averaged for each fruit and data were expressed in Newtons (N). SSC of juice extracted from 10 fruits was measured with a digital refractometer (Atago PR-101, Tokyo, Japan) and was expressed as °Brix.

2.5. Statistical analysis

Because of the use of different cultivars at each location, data were analyzed separately for each location using linear mixed effect models. The models included replicate as a random effect, and the balanced factorial treatments of 2 cultivars, 2 tree types and 5 rootstocks as fixed factors. The significance of cultivar, rootstock, tree type and their interactions were tested by analysis of variance (ANOVA). We evaluated the main and interaction effects of treatment on trunk cross-sectional area, cumulative yield, cumulative yield efficiency, cumulative crop load, number of suckers, partitioning index, and alternative bearing index. Separately a mixed model including treatment as fixed factor, and year nested to replicate and replicate as random factors was built to determine treatment effect on flesh firmness, soluble solids content and percentage of red skin color. Mean separation was determined by Tukey HSD test with a *P* value of 0.05 using the JMP statistical software package (Version 12, SAS Institute Inc., Cary, North Carolina).The effect of location was evaluated with linear mixed effect models using only data from ‘Gala’ which was common at both locations. Mean separation was determined by t Student test with a *P* value of 0.05. The effect of cultivar was evaluated with linear mixed effect models and mean separation was determined by t Student test with a *P* value of 0.05.

3. Results

3.1. Factors affecting agronomic and fruit quality traits

The main effect factors of cultivar, rootstock and tree type and their interactions affected agronomic and fruit quality traits at each location separately (Table 2). ANOVA results at Dressel farm showed a significant cultivar effect on tree vigor (TCSA), cumulative crop load (CCL), fruit weight (FW), cumulative root suckers (CRS), alternate bearing index (AI) and all fruit quality traits (FF, flesh firmness; SSC, soluble solids content; SRC, percentage of skin red color). At VandeWalle farm, in addition to the significant effects observed at Dressel farm with the exception of CRS, there was a significant effect of cultivar on cumulative yield (CY) and cumulative yield efficiency (CYE). At Dressel farm, rootstock had a significant effect on TCSA, CRS and SSC, whereas at VandeWalle farm rootstock had a significant effect on TCSA, CYE, CCL, partition index (PI), CRS, and AI (Table 2). Tree type significantly affected TCSA, CY, CCL, PI, and FW at Dressel farm, whereas at VandeWalle farm tree type affected CY, PI, FW and AI (Table 2). The interaction of cultivar and rootstock interaction was significant for FW at Dressel farm, and for PI and AI at VandeWalle farm (Table 2). At Dressel farm, the interaction of cultivar and tree type was significant for CCL, AI and SRC, whereas at VandeWalle farm the interaction was significant only for SRC (Table 2). The interaction between rootstock and tree type was significant for CRS at Dressel farm, and for CYE, CCL, PI and AI at VandeWalle farm (Table 2). Finally, the triple interaction (cultivar x rootstock x tree type) was significant only for CYE, CCL, PI and AI at VandeWalle farm (Table 2).

3.2. Location effect

Over the 11 years of this experiment, site affected all aspects of ‘Gala’ tree performance, with the exception of tree size and partitioning index (PI) (Table 3). ‘Gala’ trees from VandeWalle were less biennial and more productive, but with more root suckers than those from Dressel. In particular, trees from VandeWalle farm produced 165 tons per ha more than those from Dressel farm, approximately 33% more production. This bigger production was related to the greater yield efficiency at VandeWalle’s and to the larger fruit size (4% more) than those from Dressel. In addition, and despite the bigger size fruits from VandeWalle farm were firmer and redder than those from Dressel farm.

3.3. Cultivar effect

At Dressel farm, ‘Gala’ trees were smaller, had higher cumulative crop load and partitioning index, were less biennial and had fewer suckers than ‘Fuji’ trees. ‘Gala’ fruits were smaller, firmer and with more red color than those from ‘Fuji’ (Table 4). Cumulative yield was equal for ‘Fuji’ and ‘Gala’ at Dressel farm. Despite this, fruit size of ‘Fuji’ was larger with higher soluble solids but with less red color than ‘Gala’ fruits. At VandeWalle farm, ‘Honeycrisp’ trees were smaller and less productive and more biennial than ‘Gala’ trees (Table 4). Cumulative yield and cumulative crop load of ‘Gala’ were greater than for ‘Honeycrisp’ at VandeWalle farm. Fruits of ‘Honeycrisp’ were larger, firmer, with more soluble solids and less red color than ‘Gala’.

3.4. Main effect of tree type

With some variables there was a significant interaction between tree type - rootstock (at Dressel farm: root suckers, at VandeWalle farm: cumulative yield efficiency, cumulative crop load, partitioning index and alternate bearing); however, to understand general trends we here present the main effects of tree type and will later present and discuss the significant interactions.

When comparing the two tree types (feathered and bench-grafted) at both locations and across all rootstocks (B.9, G.11, G.16, G.41, and M.9T337), feathered trees were similar in tree size after 11 seasons as bench-grafted ones, except for ‘Fuji’ at Dressel farm where bench-grafted trees were 27% smaller than feathered trees (Tables 5-8). Feathered trees were more productive than bench-grafted for all cultivars and most rootstocks (Tables 5-8), and had the highest partitioning index values. Feathered trees had the largest fruit size only with ‘Fuji’ and ‘Gala’ from Dressel farm. Yearly yield differences between tree types started in the second year after planting when the feathered trees had a significant crop but the bench-grafted had none (Fig.1). In general, feathered trees had higher annual yield compared to bench-grafted trees, with the exception of 2011 with ‘Fuji’ at Dressel’s farm and 2012 and 2014 with ‘Honeycrisp’ at VandeWalle farm.

Bench-grafted trees for all cultivars suffered more biennial bearing than the feathered ones for all cultivars (Tables 5-8), with the exception of ‘Fuji’. Flesh firmness was affected by tree type only in ‘Gala’ trees from both Dressel and VandeWalle farms (Tables 6 and 7). Fruits from feathered trees were firmer. Tree type affected the soluble solids content only on ‘Fuji’ and ‘Gala’ from Dressel farm (Tables 4 and 5). Bench-grafted trees had sweeter fruits. Finally, red fruit color was also affected by tree type, but only in ‘Fuji’ and ‘Honeycrisp’ where fruits from bench-grafted trees were redder than fruits from feathered trees(Tables 5-8).

3.5. Main effect of rootstock

Among rootstocks (B.9, G.11, G.16, G.41, and M.9T337) there were no differences in final tree size for any cultivar except for ‘Honeycrisp’ where G.16 was significantly larger than all other stocks. G.11 and B.9 were smaller than all other stocks (Tables 5-88). There were no significant differences in cumulative yield among rootstocks with any cultivar except ‘Fuji’ where trees on G.11, G.16 and M.9T337 had the highest yield and B.9 the lowest (Tables 5-8). Yearly, few differences were observed among rootstocks, but each cultivar responded differently (Fig. 2). Comparing locations with ‘Gala’, more yearly differences in yield were observed among rootstocks at VandeWalle farm than at Dressel farm where rootstocks only differed in yield one year. Yield efficiency did not differ among rootstocks with ‘Fuji’ or ‘Gala’ at Dressel farm. At VandeWalle farm, G.11 had the highest yield efficiency for ‘Gala’, whereas B.9 and G.11 had the highest yield efficiency for ‘Honeycrisp’ while G.16 had the lowest yield efficiency for both cultivars. Cumulative crop load was affected by rootstock only with ‘Honeycrisp’ from VandeWalle farm (Tables 5- 8) where M.9T337 had the highest value. No differences among rootstocks were observed for partitioning index and fruit weight (Tables 5- 8). The greatest root suckering came from M.9T337 with ‘Fuji’ and ‘Gala’ from Dressel farm, and from B.9 with ‘Gala’ and B.9 and G.16 with ‘Honeycrisp’ at VandeWalle farm (Tables 5, 6, 7and 8). There were significant differences in biennial bearing among rootstocks with ‘Fuji’ at Dressel farm, and ‘Gala’ from VandeWalle farm (Tables 5, 6, 7 and 8). However, the differences were small. In the case of ‘Fuji’ at Dressel farm, the greatest bienniality was with G.41while with ‘Gala’ trees at VandeWalle farm, G.11 had the highest bienniality. Finally, with regards to fruit quality, flesh firmness was affected by rootstock only for ‘Honeycrisp’ from VandeWalle farm (Tables 5- 8). ‘Honeycrisp’ fruits from G.11, G.16 and M.9T337 were firmer than those from B.9 and G.41. Soluble solids content and red skin color were affected by rootstock only for ‘Gala’ from Dressel farm (Tables 5-8). ‘Gala’ fruits from B.9 and G.16 trees were sweeter and redder than those from the other rootstocks.

3.6. Interaction of tree type and rootstock (treatment) effect

When comparing all 10 tree type x rootstock combinations, the feathered tree of 'Fuji' on G.16 produced the largest trees, followed by those on G.11 (Tables 5- 8). The smallest trees were with feathered trees on B.9 and bench-grafted trees on G.41. With 'Honeycrisp' the largest trees were the bench-grafted on G.16, whereas the smallest were with feathered trees on B.9 and bench-grafted trees on G.11. There were significant differences in tree size with 'Gala' only at Dressel farm. The largest trees were feathered trees on G.16, whereas the smallest trees were bench-grafted trees on B.9.

For 'Fuji', the highest cumulative yield was observed for feathered trees on G.11, whereas the lowest yield was with bench-grafted trees on B.9. For 'Gala' at both sites, the highest yield was for feathered trees with G.41, whereas at Dressel farm the lowest yield was for bench-grafted tree on M.9T337 and at VandeWalle farm the lowest yield was for bench-grafted trees with G.16. For 'Honeycrisp' the highest yield was with feathered trees on G.16 followed by M.9T337, whereas the lowest ones were for bench-grafted trees on G.11 and G.41.

In this study, most feathered trees produced fruits from the second year (2007) onwards while the bench-grafted produced no fruit until the fourth year at Dressel farm and from the third year at VandeWalle farm (Fig.3). In the fourth season (2009), large significant differences were observed among these combinations. The very large crop in 2009 resulted in the first biennial yield response at Dressel farm with a severe decline in 'Fuji' yield in 2010. Yield was reduced in 2012 due to a spring frost which affected 'Fuji' the most, but also reduced 'Gala' yield. At VandeWalle farm the biennial bearing patterns were also apparent in 2010 and 2012 but to a much lesser extent.

There were no significant differences in cumulative yield efficiency and cumulative crop load among tree type × rootstock combinations for both cultivars at Dressel farm (Tables 5and 6). At VandeWalle farm, 'Gala' yield efficiency and cumulative crop load were highest for feathered trees on G.11 and bench-grafted trees on M.9T337 (Table 7). This last combination had the highest cumulative crop load for 'Gala'. For 'Honeycrisp', the highest yield efficiency and cumulative crop load values were for feathered trees with B.9 (Table 8). The lowest yield efficiency values for both cultivars were for bench-grafted trees on G.16.

For 'Fuji' and 'Honeycrisp' the highest partitioning index values were for feathered trees on B.9 and M.9T337, whereas 'Gala' feathered trees on G.11 had the highest values at VandeWalle farm (Tables 5-8). There were no significant differences in partitioning index with 'Gala' at Dressel farm.

There were significant differences in fruit size among tree type × rootstock combinations only for 'Fuji' and 'Gala' from VandeWalle farm (Tables 5,6, 7and 8). 'Fuji' feathered trees on M.9T337 had the largest fruits, whereas 'Gala' bench-grafted trees on B.9 and M.9T337 had the largest ones.

Cumulative number of root suckers was highest from bench-grafted trees on M.9T337 for 'Fuji' and bench-grafted trees on B.9 for 'Gala' and 'Honeycrisp' (Tables 5-8). Bench-grafted trees on G.41 showed the lowest values for all cultivars.

Differences in cumulative biennial bearing among tree type × rootstock combinations were only observed with 'Fuji' from Dressel farms, and 'Gala' and 'Honeycrisp' from VandeWalle farm (Tables 5, 6, 7and 8). With 'Fuji', the highest biennial bearing values were for feathered trees on G.41 and M.9T337, whereas for 'Gala' the highest values were for bench-grafted trees on G.11. For 'Honeycrisp' the highest values were for bench-grafted trees on 'M.9'.

In terms of fruit quality, there were no significant differences in flesh firmness, soluble solids concentration and red skin color among tree type x rootstock combinations, with the exception of 'Fuji' from Dressel farm in the case of fruit firmness and red skin color and 'Gala' from Dressel farm in the case of soluble solids concentration (Tables 5- 8). For 'Fuji', fruits from feathered trees on B.9 and bench-grafted trees on G.11 were firmer compared to the rest of the combinations, whereas fruits from bench-grafted trees on G.16 were the reddest colored. With 'Gala' from Dressel farm, bench-grafted trees on G.16 had the sweetest fruits while feathered trees on G.11 had the lowest soluble solids.

4. Discussion

Dwarfing rootstocks such as M.9T337, B.9 or the fire blight (*Erwinia amylovora* Burill) resistant dwarfing rootstocks from Geneva® (G.11, G.16 and G.41) have been compared in other long-term trials (Autio et al., 2017; Lordan et al., 2017b; Robinson et al., 2011). However this is the first experiment that has compared the long-term performance of these rootstocks with different initial tree types and three popular cultivars, 'Gala', Fuji' and 'Honeycrisp' in a Tall Spindle (TS) system.

4.1. Location effect

As expected, 'Gala' orchard performance varied between sites. The location effect on orchard performance has been reported in previous apple rootstock studies (Marini et al., 2012; Autio et al., 2013, 2017). Indeed, among the variables we evaluated, only TCSA and PI did not differ significantly between sites when both tree types and all rootstocks were compared. The adaptation of 'Gala' cultivar to different soil and climatic conditions could explain these differences. In addition, it is worth mentioning that 'Gala' apples from Dressel farm (Hudson Valley region) were, in general, less firm, less red, and sweeter. The lower crop load and resulting larger fruit size could explain these differences but also the warmer climate in growing season could also cause the larger fruit size. The reduced red color can also be mainly by the color limiting climatic conditions from Hudson Valley region. Climatic conditions near harvest for the two sites were different. At Dressel farm, minimum and maximum temperatures and solar radiation from August 1 to September 15, (5-year average (2012–2016) were 17.5 °C, 28.5 °C and 18.6 MJm−2 while at VandeWalle farm, minimum and maximum temperatures and solar radiation averaged 13.8 °C, 25.7 °C and 10.9 MJm−2. The higher temperatures (day and night) during summer and early fall with not enough cool nights limited red color development at Dressel farm compared to VandeWalle farm (Reig et al., 2019).

4.2. Main effect of tree type

Over 11 years, the effect of tree type (feathered or bench-grafted) with a TS system did not vary for each of the three cultivars in terms of fruit production. The cumulative yield advantage for the feathered trees was substantial, whereas the percentage of red color in the skin of the bicolor cultivars, 'Fuji' and 'Honeycrisp', diminished around 10% by using feathered trees. The beneficial effect of planting well-feathered trees diminishes with the tree age, but their yield advantage in the first few years provides larger income and greatly shortens the investment period (Gąstoł and Poniedziałek, 2003). Therefore, the final benefit of feathered trees can only be positive if the increased production and yields gained using feathered trees allows an earlier return of investment and greater long-term profitability (Sadowski et al. 2007). On the other hand, the lower cumulative fruit production of bench-grafted trees observed after 11 years of study could be offset by reduced initial cost of the bench-grafted tree. Our results clearly showed that the feathered trees have higher early yield and that yield of bench-grafted is delayed 1-2 years, as an average. Robinson et al. (2007) reported that when orchards do not produce significant quantities of fruit until year four or five, often the carrying costs from the extremely high investment of the TS orchard overwhelms the potential returns and negates the benefit of the high tree density on profitability.

4.3. Main effect of rootstock

One of the most critical elements of any high-density apple orchard is the rootstock (Autio et al., 2017; Reig et al., 2018). After 11 years in our study, rootstock effect on tree size was only observed in the low vigor cultivar 'Honeycrisp', whereas rootstock effect on fruit production and fruit size was, in general, minimal except with 'Fuji' where there was a 1.7 fold difference between the lowest yielding rootstock and the highest yielding rootstock. This lack of differences in cumulative yield among rootstocks with the other cultivars could be explained by the few significant yearly differences among rootstocks in yield for each cultivar. Our data confirms that all 5 of the rootstocks we compared have been selected for very good yield potential and perform well in the humid climate of New York State.

Kosina (2010) suggested that production of suckers might be affected by the scion cultivar, but sucker production is also influenced by climate (Marini et al., 2006). These both statements agree with our results. 'Fuji' and 'Gala' trees on M.9T337 from Dressel farm had the greatest root suckering, whereas 'Gala' and 'Honeycrisp' trees on B.9 from VandeWalle farm had the highest ones.

4.4. Interaction of tree type and rootstock (treatment) effect

Comparing all tree type and rootstocks combinations, in general, feathered trees with G.16 were the biggest ones, with the exception of 'Gala' at VandeWalle farm where, although there were no significant differences among the 10 combinations, the trend of G.16 having the greatest TCSA was apparent. G.16 feathered trees were significantly more vigorous than B.9 and M.9T337 trees for 'Fuji' and 'Honeycrisp'. This supports the findings of Lordan et al. (2018) who also reported G.16 being larger than M.9T337 or B.9. In the case of bench-grafted trees, this trend was only observed in 'Honeycrisp'. M.9T337 was similar in tree size to G.16 with feathered 'Gala' trees from both locations, which is in agreement with Reig et al. (2019). G.16 tree size was previously reported to be similar to M.9T337 size with 'Jonagold', but slightly more vigorous with 'Gala' (Robinson et al., 2003). These results confirm the importance of testing tree type × rootstock combination for each particular cultivar.

Cumulative production is by far the most important indicator of successful economic performance of orchards (Lordan et al., 2018). In this study, all treatments related to feathered trees produced fruits from the second year after planting (2007) onwards. Only bench-grafted trees from VandeWalle farm started to produce fruits from the third year (2008). Bench-grafted trees are produced without time in the field nursery while feathered trees typically have two years in the orchard. This helps to explain why they have lower cost per unit but as a result they crop 1-2 years later. Similar to tree size, cumulative yield was related to tree type and rootstock for each cultivar and location. Higher cumulative yields of 'Fuji' were on G.11 feathered trees, whereas with 'Gala' highest yields were on G.41 feathered trees, and with 'Honeycrisp' on G.16 feathered trees.

B.9 rootstock is known to be sensitive to apple replant disease (Robinson et al., 2003). This fact could help to explain the lower yield performance of 'Fuji' B.9 bench-grafted trees which were inferior to the rest of the treatments. This study was carried out in replant sites without fumigation. This was by design since soil fumigation is not available to New York State growers due to regulatory concerns. Therefore, these results confirm the importance of testing rootstock and tree type performance for each cultivar and location.

Regarding yield efficiency, an effect of treatment was only observed at VandeWalle farm, but with only small differences between treatments. The highest values for 'Gala' were on G.11 and M.9T337 feathered trees, whereas for 'Honeycrisp' the highest values were on B.9 feathered trees. On both cultivars, G.16 bench-grafted trees had the lowest values. Autio et al. (2017) reported no difference in yield efficiency on 5-year-old tall spindle 'Honeycrisp' trees grafted with both B.9 and M.9T337, among other rootstocks, and grown at 13 different sites across the USA. Crop load is one of the most important factors affecting fruit size. In general, the treatment with the highest crop load value had the highest yield, independent of cultivar.

Crops in the early years must be carefully managed to prevent biennial bearing. As expected after 11 years, 'Gala' showed less alternate bearing (lower index values) than 'Fuji' and 'Honeycrisp'. Regarding tree type, feathered trees, despite promoting early yield on all cultivars, did not affect the biennial bearing except with 'Fuji', where biennial bearing was lower for feathered trees. 'Fuji' trees at Dressel farms grafted on B.9 had less biennial bearing, whereas 'Gala' on G.41 and M.9T337 at VandeWalle farm had less biennial than other stocks.

Fruit quality (flesh firmness, soluble solids content and percentage of red color) were, in general, only affected by tree type and rootstock with ‘Fuji’ and ‘Gala’ from Dressel farm. Despite these differences, the sugar content values were within the commercial harvest criteria, but ‘Fuji’ and ‘Gala’ fruits had less red color than the commercial harvest criteria. As abovementioned, the reduced red color can be explained by the color limiting climatic conditions from Hudson Valley region, which include high temperatures (day and night) during summer and early fall with insufficient cool nights to enhance red color in some years (Reig et al., 2019).

5. Conclusions

In general, for all three cultivars, feathered trees were more productive and efficient than the bench-grafted trees while also producing excellent fruit quality, although there was a small reduction in the percentage of skin red color, especially on ‘Fuji’ and ‘Honeycrisp’. For ‘Fuji’ feathered trees on G.11, for ‘Gala’ feathered trees on G.41, and for ‘Honeycrisp’ feathered trees on G.16 were the combinations with the highest cumulative yield, high yield efficiency and crop load, low biennial bearing and with slightly significant larger fruits.

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Table 1. Apple rootstock descriptions

Rootstock	Vigor Class	Parentage	Tree size	Origin
B.9	Dwarf	M.8 x Red Standard	M.9	State Research Institute of Horticulture, Mitschurinsk, (Russia)
G.11	Dwarf	M.26 x Robusta 5	M.9	Cornell University-USDA (USA)
G.16	Dwarf	Ottawa 3 × Malus floribunda	M.9 to M.26	Cornell University-USDA (USA)
G.41	Dwarf	M.27 x Robusta 5	M.9	Cornell University-USDA (USA)
M.9T337	Dwarf	Unknown	M.9	East Malling (UK) Dutch clone of M.9

Table 2. Mixed model analysis to evaluate the effect of cultivar, rootstock, tree type and all interactions on agronomic and fruit quality traits.

Variable	DF	SS	F value	P	Variable	DF	SS	F value	P
Dressel farm					*VandeWalle farm*				
TCSA					**TCSA**				
Cultivar (C)	1	1340.72	12.54	0.0010	Cultivar (C)	1	649.64	7.89	0.0076
Rootstock (R)	4	2343.47	5.48	0.0013	Rootstock (R)	4	1351.84	4.11	0.0070
Tree type (T)	1	1212.53	11.34	0.0017	Tree type (T)	1	290.27	3.53	0.0677
C x R	4	455.33	1.06	0.3862	C x R	4	201.90	0.61	0.6556
C x T	1	273.60	2.56	0.1173	C x T	1	211.20	2.57	0.1171
R x T	4	953.74	2.23	0.0824	R x T	4	446.86	1.36	0.2659
C x R x T	4	614.98	1.44	0.2387	C x R x T	4	433.65	1.32	0.2802
CY					**CY**				
Cultivar (C)	1	1933.47	0.14	0.7086	Cultivar (C)	1	234202.53	82.64	<0.0001
Rootstock (R)	4	62094.55	1.14	0.3525	Rootstock (R)	4	22005.96	1.94	0.1223
Tree type (T)	1	214849.54	15.74	0.0003	Tree type (T)	1	64429.75	22.73	<0.0001
C x R	4	66648.00	1.22	0.3169	C x R	4	18018.22	1.59	0.1959
C x T	1	30465.07	2.23	0.1428	C x T	1	1395.68	0.49	0.4869
R x T	4	51545.06	0.94	0.4483	R x T	4	8474.47	0.75	0.5655
C x R x T	4	76536.63	1.40	0.2504	C x R x T	4	9586.39	0.85	0.5047
CYE					**CYE**				
Cultivar (C)	1	5.16	2.66	0.1106	Cultivar (C)	1	3.79	6.20	0.0171
Rootstock (R)	4	3.86	0.50	0.7379	Rootstock (R)	4	29.18	11.94	<0.0001
Tree type (T)	1	1.73	0.89	0.3502	Tree type (T)	1	1.06	1.74	0.1945
C x R	4	5.53	0.71	0.5881	C x R	4	3.12	1.27	0.2959
C x T	1	3.95	2.04	0.1612	C x T	1	2.12	3.46	0.0701
R x T	4	2.54	0.33	0.8584	R x T	4	8.77	3.59	0.0136
C x R x T	4	7.29	0.94	0.4509	C x R x T	4	11.35	4.65	0.0036
CCL					**CCL**				
Cultivar (C)	1	23805.40	5.73	0.0214	Cultivar (C)	1	588018.42	116.65	<0.0001
Rootstock (R)	4	26550.62	1.60	0.1934	Rootstock (R)	4	76359.51	3.79	0.0105
Tree type (T)	1	56984.64	13.71	0.0006	Tree type (T)	1	3869.01	0.77	0.3862
C x R	4	7704.82	0.46	0.7621	C x R	4	12949.84	0.64	0.6355
C x T	1	23195.85	5.58	0.0230	C x T	1	1369.09	0.27	0.6051
R x T	4	21348.75	1.28	0.2920	R x T	4	87257.47	4.33	0.0053
C x R x T	4	3592.77	0.22	0.9280	C x R x T	4	130823.36	6.49	0.0004
PI					**PI**				
Cultivar (C)	1	69.71	2.67	0.1101	Cultivar (C)	1	4.37	0.65	0.4246
Rootstock (R)	4	99.98	0.96	0.4418	Rootstock (R)	4	305.97	11.38	<0.0001
Tree type (T)	1	227.08	8.69	0.0053	Tree type (T)	1	3971.34	590.85	<0.0001
C x R	4	142.70	1.36	0.2629	C x R	4	98.45	3.66	0.0124
C x T	1	36.31	1.39	0.2454	C x T	1	4.16	0.62	0.4360
R x T	4	5.80	0.06	0.9940	R x T	4	185.19	6.89	0.0003
C x R x T	4	53.86	0.52	0.7251	C x R x T	4	135.28	5.03	0.0022
FW					**FW**				
Cultivar (C)	1	12647.65	86.65	<0.0001	Cultivar (C)	1	119126.70	1046.49	<0.0001
Rootstock (R)	4	337.44	0.58	0.6803	Rootstock (R)	4	475.69	1.04	0.3964

Tree type (T)	1	3987.39	27.32	<0.0001	Tree type (T)	1	6449.73	56.66	<0.0001
C x R	4	358.30	0.61	0.6552	C x R	4	231.45	0.51	0.7299
C x T	1	876.50	6.00	0.0186	C x T	1	31.54	0.28	0.6015
R x T	4	488.83	0.84	0.5095	R x T	4	85.75	0.19	0.9431
C x R x T	4	192.55	0.33	0.8563	C x R x T	4	154.82	0.34	0.8493

Table 3. Location means for trunk-cross sectional area, yield, yield efficiency, fruit size, crop load, partition index, root suckers and alternative bearing of 'Gala' apple trees from 2007 to 2016, except root suckers (2015 and 2016 only) and fruit quality (FF, SSC and SRC) from 2008 and 2016.

Location	Final TCSA (cm^{-2})	CY ($t\ ha^{-1}$)	CYE ($kg\ cm^{-2}$ TCSA)	CCL (# fruit cm^{-2} TCSA)	PI ($kg\ cm^{-2}$ TCSA)	FW (g)	CRS	AI	FF (N)	SSC (ºBrix)	SRC (%)
Means for 'Gala' trees of both tree types and all rootstocks											
Dressel farm	34.5 a	341.5 b	3.1 b	188.2 b	11.6 a	156.3 b	4.5 b	0.37 a	60.0 b	13.3 a	54.5 b
VandeWalle farm	30.4 a	506.8 a	5.5 a	388.5 a	13.2 a	163.5 a	10.2 a	0.23 b	63.6 a	12.8 b	72.3 a
P ≤ 0.05	***ns***	***<0.0001***	***<0.0001***	***<0.0001***	***ns***	***0.0134***	***0.0006***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***

Means followed by the same letter in each column are not significantly different at $P \leq 0.05$ according to t Student Test. *Abbreviations:* AI, alternative bearing index; CCL, cumulative crop load; CRS, cumulative root suckers; CY, cumulative yield; CYE, cumulative yield efficiency; FF, flesh firmness; FW, fruit weight; PI, partition index; SRC, skin red color; SSC, soluble solids content; TCSA, trunk cross sectional area.

Table 4. Cultivar means at Dressel farm and VandeWalle farm for trunk-cross sectional area, yield, yield efficiency, fruit size, crop load, partition index, root suckers and alternative bearing of high density apple trees from 2007 to 2016, except root suckers (2015 and 2016 only) and fruit quality (FF, SSC and SRC) from 2008 to 2016.

Cultivar	Final TCSA (cm^{-2})	CY ($t\ ha^{-1}$)	CYE (kg cm^{-2} TCSA)	CCL (# fruit cm^{-2} TCSA)	PI (kg cm^{-2} TCSA)	FW (g)	CRS	AI	FF (N)	SSC (ºBrix)	SRC (%)
Dressel farm											
Fuji	44.7 a	356.8 a	2.5 a	149.9 b	9.6 a	188.0 a	6.7 a	0.51 a	54.1 b	13.5 a	30.7 b
Gala	34.4 b	342.4 a	3.1 a	188.2 a	11.6 a	158.6 b	4.4 b	0.37 b	59.6 a	13.3 b	54.3 a
$P \leq 0.05$	***0.0049***	***ns***	***ns***	***0.0356***	***ns***	***<0.0001***	***0.0200***	***<0.0001***	***<0.0001***	***0.0402***	***<0.0001***
VandeWallefarm											
Gala	30.4 a	506.8 a	5.5 a	388.5 a	13.2 a	163.5 b	10.2 a	0.23 b	63.6 a	12.8 a	72.8 a
Honeycrisp	23.9 b	381.9 b	5.0 a	190.5 b	12.7 a	252.6 a	10.4 a	0.38 a	59.9 b	12.4 b	49.5 b
$P \leq 0.05$	***0.0149***	***<0.0001***	***ns***	***<0.0001***	***ns***	***<0.0001***	***ns***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***

Means followed by the same letter in each column are not significantly different at $P \leq 0.05$ according to t Student Test. *Abbreviations:* AI, alternative bearing index; CCL, cumulative crop load; CRS, cumulative root suckers; CY, cumulative yield; CYE, cumulative yield efficiency; FF, flesh firmness; FW, fruit weight; PI, partition index; SC, skin red color; SSC, soluble solids content; TCSA, trunk cross sectional area.

Table 5. Horticultural and fruit quality traits for ‘Fuji’ at Dressel farm (New Paltz, NY). Trunk-cross sectional area, yield, yield efficiency, fruit size, crop load, partitioning index, and alternative bearing index of high density apple trees from 2007 to 2016, except root suckers (2015 and 2016 only) and fruit quality (FF, SSC and SRC) from 2008 to 2016.

Experimental Factor	Final TCSA (cm^{-2})	CY (t ha^{-1})	CYE (kg cm^{-2} TCSA)	CCL (# fruit cm^{-2} TCSA)	PI (kg cm^{-2} TCSA)	FW (g)	CRS	AI	FF (N)	SSC (ºBrix)	SRC (%)
Tree type											
Feathered tree	50.8 a	391.3 a	2.5 a	160.6 a	10.7 a	198.7 a	6.4 a	0.52 a	55.2 a	13.3 b	28.7 b
Bench-graft tree	37.3 b	314.4 b	2.6 a	136.5 a	8.3 b	175.1 b	6.7 a	0.49 a	53.1 a	13.6 a	32.9 a
P ≤ 0.05	***0.0255***	***0.0196***	***ns***	***ns***	***0.0155***	***<0.0001***	***ns***	***ns***	***ns***	***0.0398***	***0.0005***
Rootstock											
B9	34.6 a	245.6 b	2.5 a	160.4 a	10.2 a	188.6 a	8.0 ab	0.43 b	54.6 a	13.7 a	32.9 ab
G11	54.6 a	426.5 a	2.3 a	128.8 a	8.9 a	191.9 a	5.4 ab	0.50 ab	55.9 a	13.4 ab	27.9 b
G16	51.2 a	386.1 a	2.2 a	142.0 a	8.6 a	190.5 a	5.7 ab	0.47 ab	52.7 a	13.6 a	33.9 a
G41	42.8 a	333.9 ab	2.7 a	129.6 a	8.2 a	180.8 a	0.9 b	0.58 a	52.2 a	13.2 b	27.9 b
M9	38.6 a	377.2 a	3.0 a	181.2 a	11.9 a	189.6 a	12.5 a	0.56 ab	55.1 a	13.4 ab	30.2 ab
P ≤ 0.05	***ns***	***0.0040***	***ns***	***ns***	***ns***	***ns***	***0.0018***	***0.0353***	***ns***	***0.0046***	***0.0022***
Tree type x Rootstock											
Feathered tree B9	32.6 d	287.5 bc	2.8 a	191.1 a	12.9 a	198.2 ab	3.6 bcd	0.40 b	56.6 a	13.7 a	30.8 abc
Bench-graft tree B9	37.0 cd	196.5 c	2.1 a	127.1 a	7.4 b	175.7 bc	12.5 ab	0.45 ab	52.1 ab	13.8 a	35.1 ab
Feathered tree G11	60.8 ab	471.9 a	2.4 a	144.1 a	9.9 ab	196.6 ab	9.1 abcd	0.51 ab	54.6 ab	13.1 a	27.2 bc
Bench-graft tree G11	48.9 abcd	373.8 ab	2.2 a	110.8 a	7.9 b	183.9 abc	1.7 cd	0.48 ab	57.1 a	13.7 a	28.9 abc
Feathered tree G16	63.9 a	440.0 ab	2.1 a	152.5 a	9.3 ab	198.4 ab	6.5 abcd	0.45 ab	55.4 ab	13.6 a	32.5 ab
Bench-graft tree G16	34.8 cd	310.6 abc	2.2 a	126.8 a	7.6 b	178.3 bc	4.8 abcd	0.49 ab	42.3 b	13.7 a	35.8 a
Feathered tree G41	57.1 abc	367.7 abc	1.9 a	110.8 a	8.4 b	192.3 ab	0.5 d	0.60 a	54.8 ab	13.1 a	25.0 c
Bench-graft tree G41	28.9 d	293.0 abc	3.5 a	145.8 a	7.9 b	165.9 c	1.2 cd	0.55 ab	49.5 ab	13.2 a	31.5 abc
Feathered tree M9	39.3 bcd	370.6 ab	2.9 a	192.5 a	12.7 a	204.2 a	11.1 abc	0.63 a	54.5 ab	13.3 a	28.4 abc
Bench-graft tree M9	35.5 bcd	382.3 ab	3.1 a	164.8 a	10.7 ab	168.4 c	14.4 a	0.46 ab	55.9 ab	13.5 a	33.0 ab
P ≤ 0.05	***0.0268***	***0.0012***	***ns***	***ns***	***0.0418***	***<0.0001***	***0.0006***	***0.0371***	***0.0221***	***ns***	***0.0002***

Means followed by the same letter in each column are not significantly different at $P \leq 0.05$ according to Tukey HSD Test. *Abbreviations:* AI, alternative bearing index; CCL, cumulative crop load; CRS, cumulative root suckers; CY, cumulative yield; CYE, cumulative yield efficiency; FF, flesh firmness; FW, fruit weight; PI, partition index; SRC, skin red color; SSC, soluble solids content; TCSA, trunk cross sectional area.

Table 6. Horticultural and fruit quality traits for ‘Gala’ at Dressel farm (New Paltz, NY). Trunk-cross sectional area, yield, yield efficiency, fruit size, crop load, partitioning index, and alternative bearing index of high density apple trees from 2007 to 2016, except root suckers (2015 and 2016 only) and fruit quality (FF, SSC and SRC) from 2008 to 2016.

Experimental Factor	Final TCSA (cm^{-2})	CY ($t\ ha^{-1}$)	CYE ($kg\ cm^{-2}$ TCSA)	CCL (# fruit cm^{-2} TCSA)	PI ($kg\ cm^{-2}$ TCSA)	FW (g)	CRS	AI	FF (N)	SSC (ºBrix)	SRC (%)
Tree type											
Feathered tree	36.9 a	423.8 a	3.6 a	238.7 a	14.4 a	160.6 a	4.3 a	0.33 b	61.8 a	13.1 b	55.5 a
Bench-graft tree	39.5 a	259.1 b	2.7 a	137.7 b	8.9 b	151.9 b	4.6 a	0.41 a	57.4 b	13.5 a	53.1 a
$P \le 0.05$	***ns***	***0.0002***	***ns***	***0.0009***	***0.0139***	***0.0051***	***ns***	***0.0052***	***0.0035***	***0.0002***	***ns***
Rootstock											
B9	41.4 a	345.9 a	4.0 a	229.3 a	15.9 a	152.2 a	7.4 a	0.35 a	63.2 a	13.5 a	55.8 a
G11	35.5 a	361.8 a	3.2 a	190.0 a	12.2 a	156.2 a	0.9 b	0.38 a	61.0 a	13.1 a	50.8 a
G16	42.8 a	345.0 a	2.8 a	184.0 a	10.6 a	155.6 a	5.3 ab	0.39 a	58.2 a	13.5 a	54.7 a
G41	36.5 a	360.9 a	3.0 a	142.1 a	11.4 a	156.2 a	1.3 b	0.36 a	57.9 a	13.1 a	55.7 a
M9	34.9 a	293.7 a	2.7 a	195.3 a	8.0 a	161.3 a	7.5 a	0.37 a	58.2 a	13.2 a	55.8 a
$P \le 0.05$	***ns***	***ns***	***ns***	***ns***	***ns***	***ns***	***0.0004***	***ns***	***ns***	***ns***	***ns***
Tree type x Rootstock											
Feathered tree B9	26.2 bc	322.1 abc	3.8 a	289.7 a	16.8 a	158.9 a	5.4 ab	0.32 a	62.7 a	13.4 ab	57.6 a
Bench-graft tree B9	20.0c	369.7 abc	4.3 a	169.0 a	15.0 a	145.4 a	9.4 a	0.38 a	63.8 a	13.6 ab	52.6 a
Feathered tree G11	35.8 abc	471.2 ab	3.9 a	255.3 a	16.3 a	155.3 a	1.6 b	0.34 a	61.8 a	13.0 b	52.5 a
Bench-graft tree G11	35.3 abc	252.5 abc	2.3 a	124.7 a	8.1 a	156.9 a	0.2 b	0.41 a	59.9 a	13.3 ab	49.2 a
Feathered tree G.16	43.9 a	408.0 abc	2.9 a	222.3 a	13.1 a	160.9 a	4.2 ab	0.32 a	62.4 a	13.2 ab	55.1 a
Bench-graft tree G.16	41.6 ab	282.3 abc	2.7 a	145.7 a	8.2 a	150.3 a	6.4 ab	0.46 a	54.8 a	13.8 a	54.3 a
Feathered tree G41	43.2 a	528.2 a	3.7 a	152.0 a	15.1 a	162.8 a	0.9 b	0.35 a	60.9 a	12.9 b	56.3 a
Bench-graft tree G41	29.7 abc	203.6 bc	2.4 a	132.3 a	7.7 a	149.6 a	1.7 b	0.37 a	55.0 a	13.4 ab	54.2 a
Feathered tree M9	35.4 abc	399.7 abc	3.6 a	274.0 a	10.5 a	165.1 a	9.4 a	0.29 a	61.5 a	12.9 b	55.2 a
Bench-graft tree M9	34.4 abc	187.7 c	1.9 a	116.7 a	5.6 a	157.6 a	5.5 ab	0.45 a	54.9 a	13.5 ab	57.1 a
$P \le 0.05$	***0.0016***	***0.0044***	***ns***	***ns***	***ns***	***ns***	***0.0017***	***ns***	***ns***	***0.0032***	***ns***

Means followed by the same letter in each column are not significantly different at $P \le 0.05$ according to Tukey HSD Test. *Abbreviations:* AI, alternative bearing index; CCL, cumulative crop load; CRS, cumulative root suckers; CY, cumulative yield; CYE, cumulative yield efficiency; FF, flesh firmness; FW, fruit weight; PI, partition index; SRC, skin red color; SSC, soluble solids content; TCSA, trunk cross sectional area.

Table 7. Horticultural and fruit quality traits for 'Gala' at VandeWalle farm (Alton, NY). Trunk-cross sectional area, yield, yield efficiency, fruit size, crop load, partitioning index, and alternative bearing index of high density apple trees from 2007 to 2016, except root suckers (2015 and 2016 only) and fruit quality (FF, SSC and SRC) from 2008 to 2016.

Experimental Factor	Final TCSA (cm^{-2})	CY ($t\ ha^{-1}$)	CYE ($kg\ cm^{-2}$ TCSA)	CCL (# fruit cm^{-2} TCSA)	PI ($kg\ cm^{-2}$ TCSA)	FW (g)	CRS	AI	FF (N)	SSC (ºBrix)	SRC (%)
Tree type											
Feathered tree	34.5 a	544.4 a	5.5 a	385.3 a	21.1 a	153.8 b	9.3 a	0.19 b	64.3 a	12.9 a	72.6 a
Bench-graft tree	26.4 a	469.2 b	5.6 a	391.8 a	5.3 b	173.1 a	11.1 a	0.27 a	63.0 b	12.7 a	72.1 a
P ≤ 0.05	***ns***	***0.0006***	***ns***	***ns***	***<0.0001***	***<0.0001***	***ns***	***0.0062***	***0.0027***	***ns***	***ns***
Rootstock											
B9	24.8 a	472.9 a	5.8 ab	401.8 a	15.1 a	169-0 a	19.5 a	0.23 ab	63.6 a	12.8 a	73.4 a
G11	23.7 a	500.4 a	6.5 a	435.4 a	17.9 a	161.3 a	7.9 b	0.33 a	63.7 a	12.8 a	73.8 a
G16	37.5 a	483.4 a	3.9 b	343.2 a	9.1 a	157.6 a	6.8 b	0.23 ab	64.8 a	12.8 a	72.5 a
G41	28.8 a	523.7 a	5.6 ab	325.3 a	12.9 a	163.9 a	4.9 b	0.19 b	63.1 a	12.6 a	70.9 a
M9	37.4 a	553.4 a	5.8 ab	436.9 a	10.9 a	165.8 a	11.9 ab	0.17 b	63.1 a	12.9 a	71.9 a
P ≤ 0.05	***ns***	***ns***	***0.0138***	***ns***	***ns***	***ns***	***0.0035***	***0.0025***	***ns***	***ns***	***ns***
Tree type x Rootstock											
Feathered tree B9	24.6 a	499.6 abc	6.3 ab	440.2 ab	25.0 ab	161.3 bcd	14.9 ab	0.20 bc	64.1 a	12.8 a	74.9 a
Bench-graft tree B9	25.1 a	446.2 bc	5.4 ab	363.4 ab	5.3 e	176.7 a	24.3 a	0.27 abc	63.1 a	12.8 a	71.8 a
Feathered tree G11	24.9 a	556.6 ab	6.9 a	478.1 ab	29.8 a	152.5 d	8.2 ab	0.30 ab	64.0 a	12.9 a	71.9 a
Bench-graft tree G11	22.4 a	444.2 bc	6.1 ab	390.6 ab	6.1 e	170.1 ab	7.6 ab	0.36 a	63.4 a	12.6 a	75.3 a
Feathered tree G.16	42.1 a	528.7 abc	3.8 b	285.9 b	14.5 cd	147.8 d	7.1 ab	0.20 bc	65.4 a	13.0 a	73.0 a
Bench-graft tree G.16	32.9 a	438.7 c	4.1 b	390.6 ab	3.8 e	167.3 abc	6.6 ab	0.27 abc	64.1 a	12.5 a	71.8 a
Feathered tree G41	29.3 a	587.1 a	6.2 ab	416.3 ab	21.1 bc	154.4 cd	6.8 ab	0.13 c	63.9 a	12.7 a	70.5 a
Bench-graft tree G41	28.2 a	460.3 bc	5.0 ab	234.2 b	4.6 e	173.4 ab	3.0 b	0.26 abc	62.3 a	12.6 a	71.4 a
Feathered tree M9	51.6 a	550.1 abc	4.3 b	295.9 b	14.9 c	153.4 cd	9.5 ab	0.13 c	64.2 a	12.8 a	72.7 a
Bench-graft tree M9	23.1 a	556.8 ab	7.4 a	578.1 a	6.8 de	178.2 a	14.4 ab	0.20 bc	62.6 a	12.9 a	71.1 a
P ≤ 0.05	***ns***	***0.0007***	***0.0004***	***0.0115***	***<0.0001***	***<0.0001***	***0.0251***	***0.0002***	***ns***	***ns***	***ns***

Means followed by the same letter in each column are not significantly different at $P \leq 0.05$ according to Tukey HSD Test. *Abbreviations:* AI, alternative bearing index; CCL, cumulative crop load; CRS, cumulative root suckers; CY, cumulative yield; CYE, cumulative yield efficiency; FF, flesh firmness; FW, fruit weight; PI, partition index; SRC, skin red color; SSC, soluble solids content; TCSA, trunk cross sectional area.

Table 8. Horticultural and fruit quality traits for 'Honeycrisp' at VandeWalle farm (Alton, NY). Trunk-cross sectional area, yield, yield efficiency, fruit size, crop load, partitioning index, and alternative bearing index of high density apple trees from 2007 to 2016, except root suckers (2015 and 2016 only) and fruit quality (FF, SSC and SRC) from 2008 to 2016.

Experimental Factor	Final TCSA (cm^{-2})	CY ($t\ ha^{-1}$)	CYE (kg cm^{-2} TCSA)	CCL (# fruit cm^{-2} TCSA)	PI (kg cm^{-2} TCSA)	FW (g)	CRS	AI	FF (N)	SSC (ºBrix)	SRC (%)
Tree type											
Feathered tree	24.2 a	409.8 a	5.4 a	177.7 a	21.1 a	241.6 b	10.9 a	0.33 b	60.2 a	12.4 a	47.6 b
Bench-graft tree	23.5 a	353.9 b	4.7 a	203.3 a	4.3 b	263.7 a	10.0 a	0.44 a	59.8 a	12.4 a	51.2 a
P ≤ 0.05	***ns***	***0.0007***	***ns***	***ns***	***<0.0001***	***<0.0001***	***ns***	***0.0203***	***ns***	***ns***	***0.0037***
Rootstock											
B9	20.1 c	368.2 a	5.7 a	208.9 ab	14.6 a	256.1 a	14.1 a	0.36 a	59.4 ab	12.4 a	50.4 a
G11	19.8 c	362.5 a	5.6 a	192.1 ab	14.0 a	253.0 a	6.8 b	0.47 a	60.6 a	12.3 a	50.1 a
G16	30.9 a	416.1 a	4.1 b	188.5 ab	10.2 a	250.7 a	13.0 a	0.29 a	60.7 a	12.5 a	48.8 a
G41	24.6 b	361.8 a	4.5 ab	139.1 b	10.3 a	255.2 a	8.6 ab	0.33 a	58.1 b	12.5 a	48.3 a
M9	23.7 b	400.7 a	5.2 ab	224.0 a	14.2 a	248.2 a	9.7 ab	0.45 a	60.7 a	12.2 a	48.9 a
P ≤ 0.05	***<0.0001***	***ns***	***0.0081***	***0.0355***	***ns***	***ns***	***0.0485***	***ns***	***0.0011***	***ns***	***ns***
Tree type x Rootstock											
Feathered tree B9	18.8 d	386.2 ab	6.4 a	224.6 a	24.6 a	244.0 a	11.7 ab	0.40 bcd	59.8 a	12.3 a	49.5 a
Bench-graft tree B9	21.5 cd	350.3 ab	4.9 ab	193.2 ab	4.6 c	268.1 a	16.6 a	0.33 bcd	59.1 a	12.5 a	51.4 a
Feathered tree G11	21.2 cd	393.3 ab	5.7 ab	140.9 ab	23.0 ab	242.3 a	5.8 ab	0.50 ab	61.2 a	12.5 a	48.4 a
Bench-graft tree G11	18.5 d	331.8 b	5.6 ab	243.4 a	5.0 c	263.2 a	7.9 ab	0.45 abc	60.3 a	12.3 a	51.7 a
Feathered tree G.16	31.7 a	445.3 a	4.3 ab	186.0 ab	16.6 ab	242.3 a	15.1 ab	0.20 d	59.9 a	12.4 a	45.7 a
Bench-graft tree G.16	30.2 ab	386.8 ab	3.9 b	191.1 ab	3.8 c	259.2 a	10.9 ab	0.39 bcd	61.4 a	12.6 a	51.9 a
Feathered tree G41	25.4 bc	389.5 ab	4.7 ab	114.9 b	17.0 ab	239.9 a	12.5 ab	0.27 cd	59.9 a	12.4 a	46.1 a
Bench-graft tree G41	23.9 cd	334.2 b	4.4 ab	163.3 ab	3.6 c	270.4 a	4.6 b	0.40 bcd	56.4 b	12.5 a	50.5 a
Feathered tree M9	23.9 cd	434.9 ab	5.6 ab	222.3 ab	24.1 ab	238.6 a	9.3 ab	0.27 cd	60.4 a	12.3 a	47.7 a
Bench-graft tree M9	23.6 cd	366.5 ab	4.7 ab	225.8 a	4.2 c	257.8 a	10.1 ab	0.63 a	61.1 a	12.1 a	50.2 a
P ≤ 0.05	***<0.0001***	***0.0199***	***0.0131***	***0.0096***	***<0.0001***	***ns***	***0.0365***	***<0.0001***	***ns***	***ns***	***ns***

Means followed by the same letter in each column are not significantly different at $P \leq 0.05$ according to Tukey HSD Test. *Abbreviations:* AI, alternative bearing index; CCL, cumulative crop load; CRS, cumulative root suckers; CY, cumulative yield; CYE, cumulative yield efficiency; FF, flesh firmness; FW, fruit weight; PI, partition index; SRC, skin red color; SSC, soluble solids content; TCSA, trunk cross sectional area.

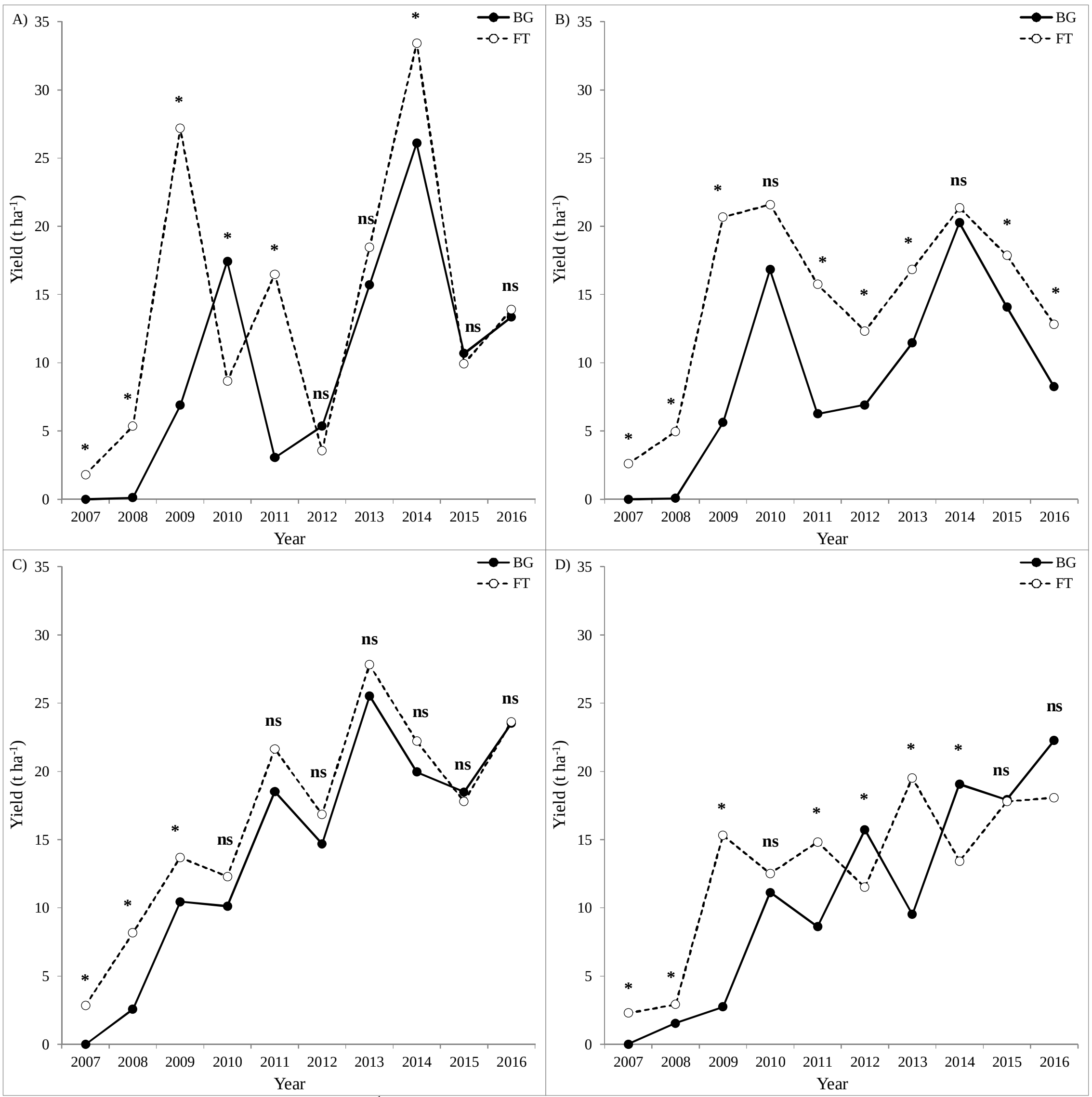

Figure 1. Annual yields (t ha^{-1}) of feathered trees (FT) and bench-graft trees (BG) for 'Fuji' (A) and 'Gala' (B) at Dressel farm, and 'Gala' (C) and 'Honeycrisp' (D) at VandeWalle farm. * represents statistical significance at $P \leq 0.05$.

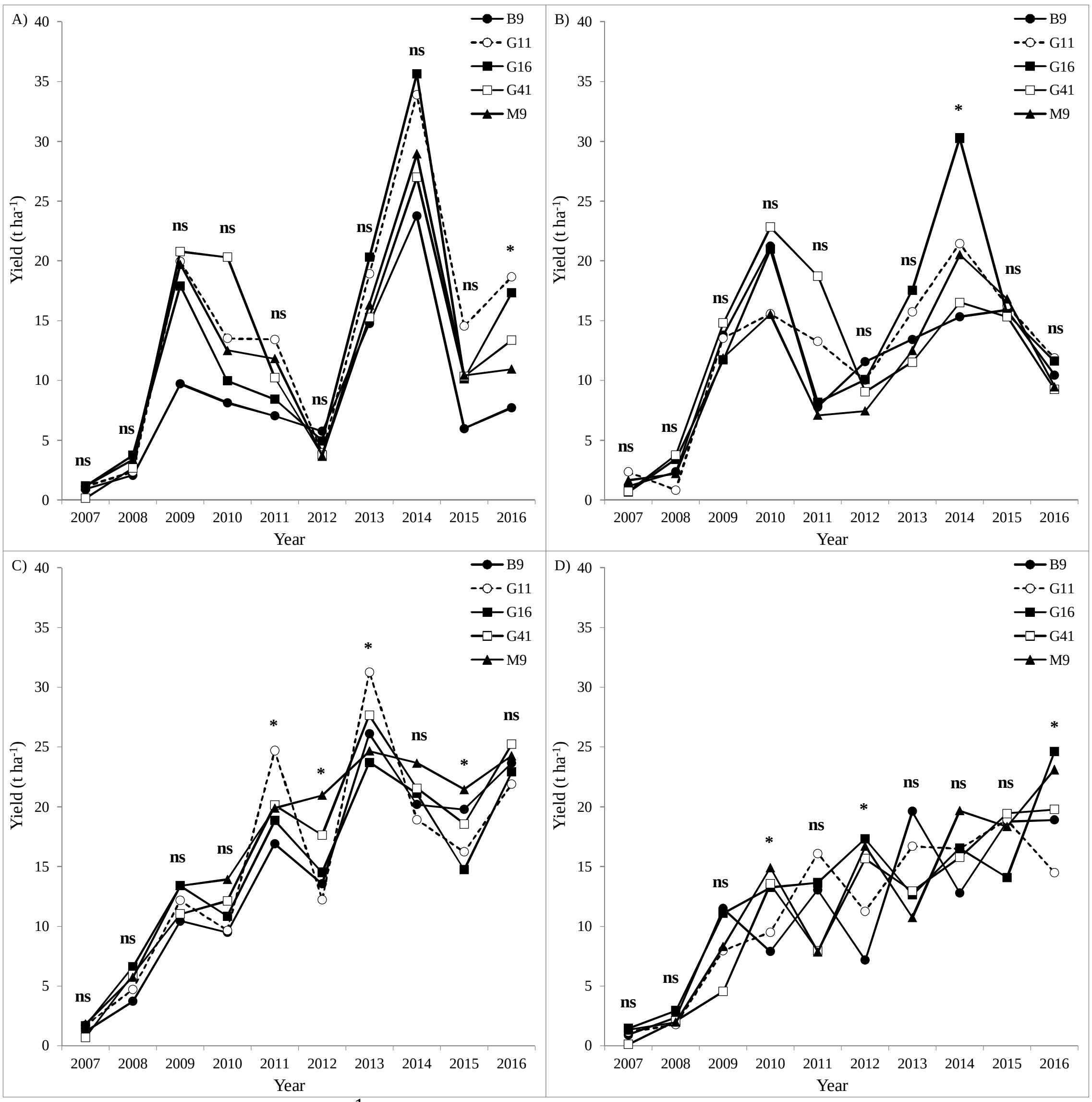

Figure 2. Annual yields (tha^{-1}) of 5 rootstocks ('B.9', 'G.11', 'G.16', 'G.41' and 'M.9') for 'Fuji' (A) and 'Gala' (B) at Dressel farm and 'Gala' (C) and 'Honeycrisp' (D) at VandeWalle farm. * represents statistical significance at $P \leq 0.05$.

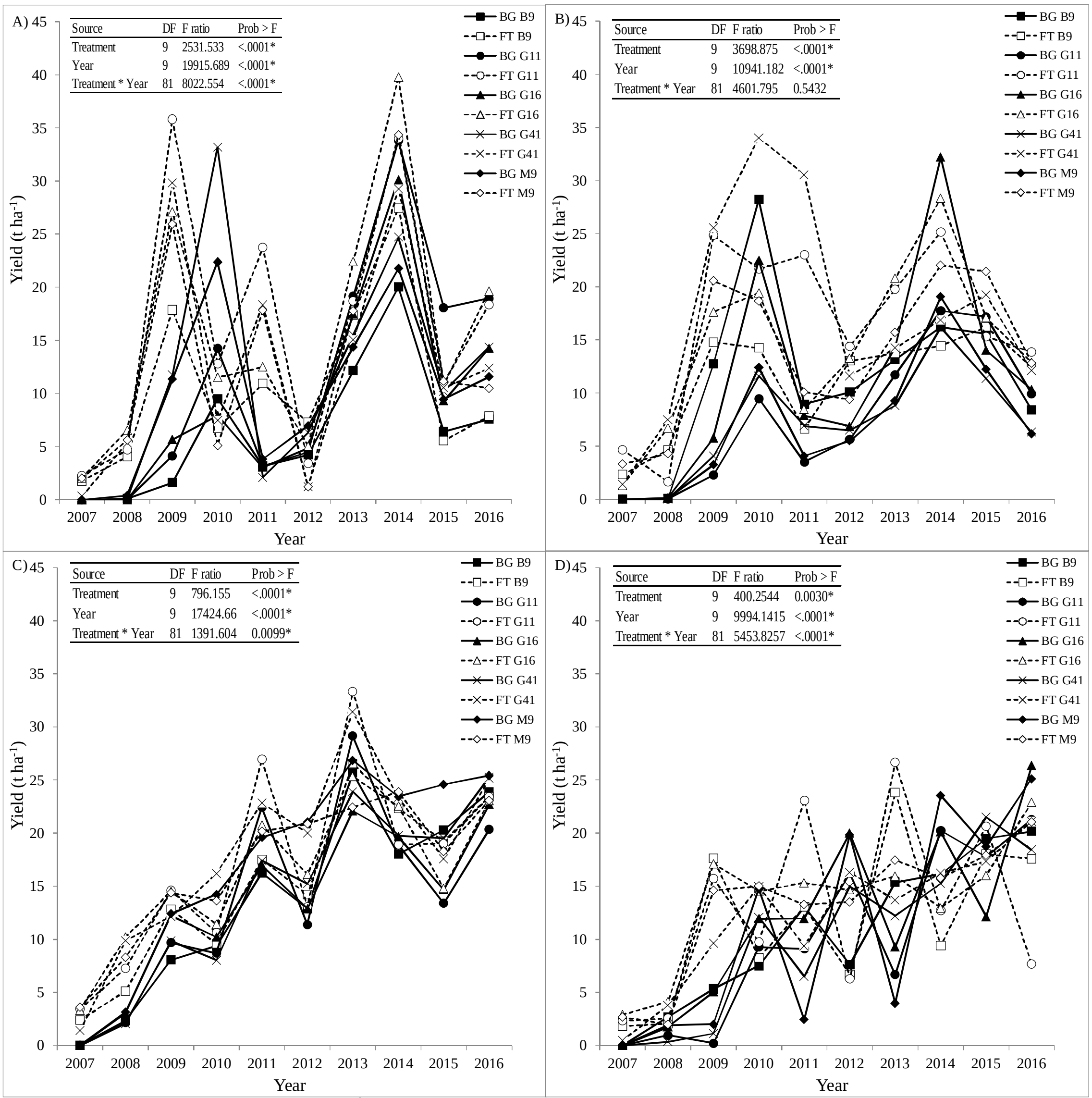

Figure 3. Annual yields (tha^{-1}) for feathered trees and bench-graft trees trained to a Tall Spindle systemon 5 rootstocks (‘B.9’, ‘G.11’, ‘G.16’, ‘G.41’ and ‘M.9’) for ‘Fuji’ (A) and ‘Gala’ (B) at Dressel Farm and ‘Gala’ (C) and ‘Honeycrisp’ (D) at VandeWalle farm.