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Long-term Performance of 'Delicious' Apple Trees Grafted on Geneva® Rootstocks and Trained to Four High-density Systems under New York State Climatic Conditions

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***Abstract*. We conducted a large (0.8 ha) field experiment of system × rootstock, using Super Chief Delicious apple as cultivar at Yonder farm in Hudson, NY, between 2007 and 2017. In this study, we compared six Geneva® rootstocks ('G.11', 'G.16', 'G.210', 'G.30', 'G.41', and 'G.935') with one Budagovsky ('B.118') and three Malling rootstocks ('M.7EMLA', 'M.9T337' and 'M.26EMLA'). Trees on each rootstock were trained to four high-density systems: Super Spindle (SS) (5382 apple trees/ha), Tall Spindle (TS) (3262 apple trees/ha), Triple Axis Spindle (TAS) (2243 apple trees/ha), and Vertical Axis (VA) (1656 apple trees/ha). Rootstock and training system interacted to influence growth, production, and fruit quality. When comparing systems, SS trees were the least vigorous but much more productive on a per hectare basis. Among the rootstocks we evaluated, 'B.118' had the largest trunk cross-sectional area (TCSA), followed by 'G.30' and 'M.7EMLA', which were similar in size but they did not differ statistically from 'G.935'. 'M.9T337' was the smallest and was significantly smaller than most of the other rootstocks but it did not differ statistically from 'G.11', 'G.16', 'G.210', 'G.41', and 'M.26EMLA'. Although 'B.118' trees were the largest, they had low productivity, whereas the second largest rootstock 'G.30' was the most productive on a per hectare basis. 'M.9' was the smallest rootstock and failed to adequately fill the space in all systems except the SS, and had low cumulative yield. The highest values for cumulative yield efficiency (CYE) were with 'G.210' for all training systems except for VA, where 'M.9T337' had the highest value. The lowest values were for all training systems with 'B.118' and 'M.7EMLA'. Regardless of the training system, 'M.7EMLA' trees had the highest number of root suckers. Some fruit quality traits were affected by training system, rootstock or system × rootstock combination.**

Apple orchard designs have gone through major changes during the past 2 decades. The needs for maximum use of land and water have mandated discovery of dwarf and efficient rootstocks and training systems and new cultivars to produce higher yield and top-quality fruit from a given unit of land. Large free-standing trees have been replaced by dwarfed trees that require trellis structures to support intensive planting systems. With cultivars that have high grower returns, the increase in tree planting density leads to a more rapid return of the high initial investment (Lordan et al., 2018c).

To obtain the uniformity required for profitable production, the commercial apple tree is a composite biological unit: a combination of rootstock, scion, and sometimes an interstem (Cornille et al., 2019). Rootstock is one of the most critical elements of any apple orchard, particularly in high-density systems where the economic risks and potential returns are the highest (Autio et al., 2017). The choice of rootstock influences productivity, precocity, yield, environmental and edaphic adaptability, cold tolerance, light interception, and disease and pest resistance (Fallahi et al., 2002; Lordan et al., 2018a; Reig et al., 2018, 2019a). In addition, roots are essential for anchorage and nutrient and water acquisition, and they harbor large bacterial and fungal communities that mediate

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interactions between the plant and the surrounding ecosystem (Thompson et al., 2019). Most successful high-density apple orchards are established using dwarfing rootstocks such as 'M.9', 'M.26EMLA', or 'B.9' (Webster, 1995), but these rootstocks lack winterhardiness, except for 'B.9', are susceptible to *Phytophthora* spp. root rot or fire blight bacterial disease (*Erwinia amylovora* Burill) or insect pests such as the woolly apple aphid (*Eriosoma lanigerum* Hausmann), have burr knots, poor anchorage or root suckers, are sensitive to apple replant disease or have brittle graft unions, which limits the establishment of new high-density plantings (Norelli et al., 2003; Robinson, 2007a; Russo et al., 2007). To overcome these challenges and provide sufficient growth control, enhanced precocity, higher yield, improved adaptability to environmental and edaphic conditions, and better fruit quality, apple rootstock breeding programs worldwide, such as the Bugadovsky, Pillnitz, and the Cornell-Geneva have been established (Autio et al., 2017; Robinson, 2007a). In particular, Geneva® series rootstocks have gained popularity with commercial growers for having greater yield efficiency, as well as greater tolerance to fire blight (*Erwinia amylovora*) and replant disease than the Malling rootstocks (Fazio et al., 2015; Russo et al., 2007).

Besides the rootstock and scion, the choice of the training system is critical for orchard profitability. A training system is a combination of planting density and tree pruning and training strategy. Over the past three decades, many new training systems for intensive apple orchards have been developed in the world (Gandev and Dzhuvinov, 2014). The common parameter in all of them is the objective of a growing system that is easy and inexpensive to implement, precocious, efficient, with the goal to improve the interception and distribution of light in the different parts of the crown for the purpose of optimizing yield and fruit quality, and last but not least, to be cost-effective and profitable (Alfonso et al., 2017; Gandev et al., 2016; Hampson et al., 2002). However, each cultivar has its own bearing habit, which will determine its suitability for different training systems (Lespinasse and Lauri, 1996) and no system is optimum for all conditions (Barritt, 1987).

Because there are many different factors that affect orchard profitability (Badiu et al., 2015; Bradshaw et al., 2016; Lordan et al., 2017, 2019a; Sojková and Adamičková, 2011; Weber, 2001), it is necessary to conduct long-term studies to find the best training system for each particular scion/rootstock combination, within the constraints imposed by local climate and economic conditions. However, there are few studies that offer direct long-term comparisons of different training systems with identical rootstocks, and successful commercial cultivars due to the expense and time commitment required (Lordan et al., 2018a; Reig et al., 2019a, 2019b). This experiment is another in our series of trials to investigate the interaction of four of the most promising high-density systems (SS, TS, TAS, and VA) and six of the most promising Geneva® rootstocks ('G.11', 'G.16', 'G.210', 'G.30', 'G.41', and 'G.935'), along with 'B.118', 'M.9T337', 'M.26EMLA' and 'M.7EMLA' as controls using the low-vigor, spur-type cultivar 'Super Chief Delicious' under New York State climatic conditions. We chose 'Delicious' for this experiment because of its commercial importance (in the top 10 apple cultivars produced in the United States, www.usapple.org) and because of its almost unique spur-type growth habit.

Material and Methods

Plant material, site description, and experimental design. In the spring of 2007, a 0.8-ha orchard trial of 10 apple rootstocks and four training systems were established at Yonder farm in Hudson, NY. 'Delicious' (Super Chief strain) apple cultivar was used. Rootstocks included six named Cornell-Geneva rootstocks [Geneva® 11 ('G.11'), Geneva® 16 ('G.16'), Geneva® 210 ('G.210'), Geneva® 30 ('G.30'), Geneva® 41 ('G.41'), and Geneva® 935 ('G.935')], one Budagovsky series clone ('B.118'), and three Malling series clones ('M.7EMLA', 'M.9T337', and 'M.26EMLA') to serve as controls (Table 1). The four planting systems were SS (trees spaced at 0.6 m × 3.0 m, 5382 trees/ha), TS (trees spaced 0.9 m × 3.3 m, 3262 trees/ha), TAS (trees spaced 1.2 m × 3.6 m, 2243 trees/ha), and VA (trees spaced 1.5 m × 4.0 m, 1656 trees/ha). Nonfeathered standard nursery trees (2 years in nursery cultivation) were used in this study and were propagated using all virus-free plant material by the authors at the New York State Agricultural Experiment Station in Geneva, NY.

The trial was established in eastern New York State, Town of Hudson, Columbia County (lat. 41°42′53.15″N, long. 74°06′39.78″W) on a Hoosic gravelly loam soil. Row orientation was north-south. Previously it has been planted to apple trees on seedling rootstock for 30 years and was not fumigated. The replant disease severity was not evaluated before planting. Trees were irrigated each year through drip lines as needed. Average annual precipitation was ≈1000 mm during spring and summer months. Calcium nitrate fertilizer (338–394 $kg \cdot ha^{-1}$) was applied each year. Foliar micronutrients and pesticides and insecticides were applied as necessary according to local recommendations following industry standards.

The experiment was a randomized complete block design with a split plot, with three replications. Within each block the main plot was training system and the sub-plot was rootstock. Each main plot (system) consisted of five adjacent rows 24 m long with each row composed of two rootstock sub-plot row sections 12 m long with 19 trees for SS, 13 trees for TS, 10 trees for TAS, and 8 trees for VA. The treatment design was a complete factorial of four systems, and 10 rootstocks with 40 combinations (Table 2).

Tree management. SS trees were developed by leaving the leader unheaded at planting. A single shoot near the top of the leader was allowed to grow each year by eliminating competitor branches. Beginning in year 2, limbs larger than 2 cm diameter or that had a narrow crotch angle were removed back to the trunk with an angled cut to develop flatter replacement limbs. Each year one to two lateral branches were removed. Lateral branches were each kept simple by removing sub-lateral branches to create a single axis for each branch. Beginning in year 4, lateral branches that exceeded 60 cm in length were shortened to 60 cm by cutting to a spur. Tree height was limited to 3.3 m by cutting the leader to a lateral spur or weak branch each year.

TS trees were developed by leaving the leader unheaded at planting. A single shoot near the top of the leader was allowed to grow each year by eliminating competitor branches. Beginning in year 2, limbs larger than 2 cm diameter or that had a narrow crotch angle were removed back to the trunk with an angled cut to develop flatter replacement limbs. Each year one to two branches larger than 2 cm were removed. Lateral branches were each kept simple by removing sub-lateral branches to create a single axis for each branch. In years 2 through 4, the leader was not headed. Beginning in year 5, lateral branches that exceeded 90 cm in length were shortened to 90 cm by cutting to a spur. Tree height was limited to 3.5 m by cutting the leader to a lateral spur or weak branch each year.

VA trees were developed by leaving the leader unheaded at planting. A single shoot near the top of the leader was allowed to grow each year by eliminating competitor branches. In years 2 through 6, the leader was not headed. In year 3, four to five lower scaffold branches were tied down to horizontal. Beginning in year 4, large diameter limbs above the bottom tier of scaffolds (>4 cm) were removed back to the trunk with an angled cut to develop replacement limbs. Each year two to three large branches were removed. Lateral branches were not shortened but kept simple by removing sub-lateral branches to create a single axis for each branch. Tree height was limited to 4.5 m by cutting the leader to a lateral spur or weak branch each year.

TAS trees were developed by heading the leader at 50 cm above the soil at planting. Three shoots were developed as equal diameter leaders from below the heading cut. Each of the leaders was tied to the vertical trellis in the second year with a spacing of 40 cm between the leaders. A single shoot near the top of the leader was allowed to grow each year by eliminating competitor branches. Beginning in year 3, lateral limbs larger than 2 cm diameter or that had a narrow crotch angle were removed back to the each of the three main leaders with an angled cut to develop flatter replacement limbs. Each year one to two lateral branches were removed. Lateral branches were each kept simple by

Table 1. Apple rootstocks evaluated in this study and their descriptions.

Rootstock	Type	Parentage	Class of rootstock (vigor)	Origin
B.118	Semi dwarf	Moscow Pear × mixture of M8 or M9 pollen	M.7	Michurinsk State Agrarian, Russia
G.11	Dwarf	M.26 × 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.210	Semi dwarf	Ottawa 3 × Robusta 5	M.7	Cornell University-USDA (USA)
G.30	Semi dwarf	Robusta 5 × M.9	M.7 to MM.106	Cornell University-USDA (USA)
G.41	Dwarf	M.27 × Robusta 5	M.9	Cornell University-USDA (USA)
G.935	Dwarf	Ottawa 3 × Robusta 5	M.26 to M.7	Cornell University-USDA (USA)
M.7EMLA	Semi dwarf	Unknown	M.7	East Malling (UK)
M.9T337	Dwarf	Unknown	M.9	East Malling (UK)
M.26EMLA	Dwarf	M.16 × M.9	M.26	HRI-East Malling (UK)

USDA = U.S. Department of Agriculture.

Table 2. Statistical significance of planting system, rootstock, and the interaction of planting system and rootstock on tree performance and fruit quality of 'Delicious' apple trees over 11 years in Hudson, NY.

Variable	Experimental factor	DF	F value	*P*
TCSA	Training system (T)	3	13.1	<0.0001
	Rootstock (R)	9	23.9	<0.0001
	T × R	27	1.7	0.0325
Y	Training system (T)	3	36.4	<0.0001
	Rootstock (R)	9	5.9	<0.0001
	T × R	27	1.3	0.2105
ECY	Training system (T)	3	42.4	<0.0001
	Rootstock (R)	9	3.1	0.0027
	T × R	27	1.4	0.1231
MCY	Training system (T)	3	36.3	<0.0001
	Rootstock (R)	9	11.3	<0.0001
	T × R	27	2.0	0.0082
TCY	Training system (T)	3	22.7	<0.0001
	Rootstock (R)	9	3.0	0.0035
	T × R	27	1.4	0.1224
CYE	Training system (T)	3	12.1	<0.0001
	Rootstock (R)	9	8.5	<0.0001
	T × R	27	2.1	0.0058
CCL	Training system (T)	3	11.8	<0.0001
	Rootstock (R)	9	8.2	<0.0001
	T × R	27	2.3	0.0027
FW	Training system (T)	3	5.5	0.0018
	Rootstock (R)	9	5.4	<0.0001
	T × R	27	2.3	0.0029
No. root suckers	Training system (T)	3	0.7	0.5301
	Rootstock (R)	9	23.4	<0.0001
	T × R	27	0.5	0.9727
ABI	Training system (T)	3	6.2	0.0007
	Rootstock (R)	9	2.4	0.0183
	T × R	27	15	0.0445
FF	Training system (T)	3	8.5	<0.0001
	Rootstock (R)	9	6.7	<0.0001
	T × R	27	1.4	0.0862
SSC	Training system (T)	3	15.5	<0.0001
	Rootstock (R)	9	5.1	<0.0001
	T × R	27	1.9	0.0040
SRC	Training system (T)	3	0.9	0.4156
	Rootstock (R)	9	0.9	0.4444
	T × R	27	1.5	0.0808

ABI = alternate bearing index; CCL = cumulative crop load; CYE = cumulative yield efficiency; ECY = early cumulative yield (2009–12); FF = flesh firmness; FW = fruit weight; MCY = mature cumulative yield (2013–17); SRC = skin red color; SSC = soluble solids content; TCSA = trunk cross-sectional area; TCY = total cumulative yield; Y = average yield per tree (2009–17).

removing sub-lateral branches to create a single axis for each branch. Beginning in year 4, lateral branches that exceeded 50 cm in length were shortened to 50 cm by cutting to a spur. Tree height was limited to 4 m by cutting the leader to a lateral spur or weak branch each year.

Trees were defruited chemically and then manually in the first 2 years (2007 and 2008), and then allowed to crop from 2009 to 2017. Every year, trees were chemically thinned by spraying them with 1.2 $L \cdot ha^{-1}$ of Sevin (Bayer Crop Science, Research Triangle Park, NC) at petal fall plus 2.4 $L \cdot ha^{-1}$ of Sevin and 5.1 $kg \cdot ha^{-1}$ of Maxcel (Valent BioScience Corporation, Libertyville, IL) at 10- to 12-mm fruit size. Hand thinning was conducted as a touch-up practice at the end of June to early July each year.

VA trees were supported by a steel conduit pipe (3 m with 0.3 m in the ground) at each tree and the conduit pipes were supported by a single wire trellis (2.3 m high) (Robinson and Hoying, 1999). SS, TS, and TAS systems were supported by a 3-wire trellis (2.7 m tall).

Horticultural assessments. Trees were evaluated through 11 years (2007–17) after planting. From the third year (2009) onward we recorded at harvest: fruit number and weight (kg/tree). Average fruit size (g) was calculated from the total number of fruits and total yield per tree. At the end of the experiment (Oct. 2017), tree circumference was recorded at 30 cm above the graft union, and the TCSA (cm^2) was then calculated. Total cumulative yield (TCY) of each rootstock-planting system combination was calculated from 2009 to 2017. Early cumulative yield (from 2009 to 2012) and mature cumulative yield (from 2013 to 2017) were also calculated. CYE (kg/cm^2) was calculated by dividing TCY (kg) by final TCSA (cm^{-2}) and cumulative crop load (CCL, fruit number/cm^2) was calculated by dividing cumulative fruit number per tree by final TCSA. Root suckers were removed each year, and during the last year of the study (2017) they were counted and then removed.

We calculated alternate bearing index (ABI) according to the formula suggested by Racsko (2007) from the third year after planting (2009) to the 11th year after planting (2017): $AI = 1/(n-1) \times \{|(a2 - a1)| / (a2 + a1) \ldots + |[a(n) - a(n-1)]| / [a(n) + a(n-1)]\}$, where n is number of years, and a1, a2,…, a(n–1), and: yield (kg/tree). This index ranges from 0 to 1, with 0 = no alternation and 1 = complete yield alternation.

Fruit quality assessments. From year 5 to year 11, at each harvest, 50 representative fruits were randomly hand-picked at commercial maturity stage from each scion-rootstock-system combination. Fruit red color was measured 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, Kelowna, British

Columbia, Canada) 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 (PR-101; Atago, Tokyo, Japan) and was expressed as °Brix.

Statistical analysis. Data were analyzed using linear mixed effect models. The first model included replicate as a random effect, the combination of the 10 rootstocks and four training systems (treatments) as a fixed factor, and was built to evaluate the effect of treatment on TCSA, early, mature and TCY, CYE, CCL, fruit weight, number of suckers, and ABI. Separately, a mixed model including treatment as a fixed factor, and year and replicate as cross random factors was built to determine treatment effect on FF, SSC, and percentage of red skin color. The main effects of training system and rootstock were evaluated with linear mixed effect models. Mean separation was determined by Tukey's honestly significant difference test with a P value of 0.05 using the JMP statistical software package (Version 12; SAS Institute Inc., Cary, NC).

To further interpret the results, we evaluated the regression relationship between some variables and tree plant density (one of the two components of an orchard system). The relationship of CCL and CYE was explored by linear regression. Individual training system × rootstock means were plotted to identify training system × rootstock combinations that gave more or less yield than expected at a given crop load. The effect of tree planting density using four training systems and 10 rootstocks was evaluated for TCSA, TCY, CYE, and CCL by regression analysis. Quadratic regression was reported if the quadratic term was significant, and linear relationship was reported if only the linear term was significant but not the quadratic.

Results and Discussion

Statistical analysis showed that training system and rootstock affected tree growth, productivity, yield efficiency, fruit size, ABI, FF, and fruit SSC but not fruit red color (Table 2). Training system and rootstock interaction significantly affected tree size, mature cumulative yield per hectare, CYE, CCL, fruit weight, ABI, and fruit soluble solids, but not for yield per tree, early and TCY, number of root suckers, fruit firmness, or fruit red color (Table 2). To help readers understand our results, we first present the main effects of training system and rootstock for all variables before presenting the interaction effects for those variables, where the interaction was significant.

Main effect of training system. The training system had an important influence on most of the agronomic and fruit quality traits evaluated. SS trees were the least vigorous (Table 3). SS trees were 26%, 28%, and 30% smaller than TS, TAS, and VA trees, respectively, likely because the number of trees per ha in SS was more than 40% higher than the rest of the training systems. A reduction of overall tree size with increasing tree density has been reported previously (Hampson et al., 2004; Reig et al., 2019a; Robinson, 2007b).The pruning regimen, which involved the annual removal of large branches (>2 cm diameter), is a dwarfing process, and may have contributed to the smaller tree size of SS. In addition, greater root competition for water and nutrients at closer plant spacings may also have contributed (Reig et al., 2019a).

In terms of yield precocity, most system by rootstock combinations produced fruits from the third leaf (2009) after planting onward (Fig. 1). In general, yield increased gradually in all training systems and rootstock combinations until 2015, showing a small decline in 2016 because of the higher crop produced in 2015. Early cumulative yield (ECY), defined as the sum of yield over the first 4 cropping years (2009–12 = years 3–6), was greatest with the SS system and least for the TAS and VA systems. In general, the SS system doubled the ECY compared with TAS and VA systems. From an economic perspective, early production is essential to increase profitability, especially for high-density systems, which have high investment costs. Second year production helps to repay the capital investment more quickly and increases the profitability over time. Lordan et al. (2019a) reported that high early return from high early yields coupled with high fruit prices from a high in-demand new cultivar can dramatically improve profitability when planting high density. Overall, our results of early cropping support the findings of Robinson (2007b) that there was a strong effect of increasing tree density on limiting tree growth but there is always a cost in growth from cropping the trees in the second year (Dominguez, 2015). This reduction in growth can be minimized with proper irrigation, nutrient management, and crop load management. In scenarios with high fruit prices, repayment of the entire initial investment can be achieved in a very short time period (8–9 years) (Lordan et al., 2019a); however, under poor price conditions and lower than expected yield, orchard life would have to be 20+ years to be profitable. Therefore, high-density systems can be the most profitable systems, but only with good yields and high fruit prices (Lordan et al., 2019a). Thus, those systems with high early and high maximum yield will likely be the most profitable. Mature cumulative yield (MCY), defined as the sum of yield over the 5 mature cropping years (2003–17 = years 7–11), was also greatest with the SS system and least for the TAS and VA systems. This result indicates that the early advantage of the SS could persist for the entire 20-year life of an orchard.

When comparing systems across all rootstocks, the SS system had the lowest yield per tree but the highest TCY per ha, but medium to high CYE and crop load (Table 3). The lowest production per ha was on trees trained as TAS, although it did not differ statistically from VA. The TS system produced intermediate yields between SS and VA. In fact, TS trees produced 21% more than VA trees, in agreement with previous studies (Mitre et al., 2011; Reig et al., 2019a). As expected, and coinciding with other studies (Reig et al., 2019a; Robinson et al., 2006), the increase in planting density resulted in less yield per tree, but increased yield per ha.

The lowest density system (VA) had the highest CYE and CCL, whereas TS and TAS had the opposite results (Table 3).

The SS system had the smallest fruit size and was similar to the TS and VA systems, whereas the TAS system had the largest fruit (Table 3). The influence of training system on fruit weight is not always clear. Depending on the cultivar, the rootstock, and the training systems evaluated, some recent studies reported influence of training system on fruit weight (Arsov et al., 2016; D'Abrosca et al., 2017) and others did not (Reig et al., 2019a).

Alternate bearing (ABI) was greatest with TAS system and least with both SS and TS systems (Table 3). In general, the effect of system on ABI was small, all of them had values close to 0. TCSA and ABI had a low but significant and positive correlation (r = 0.38, $P \leq 0.0001$) in agreement with other

Table 3. Effect of training system on horticultural traits from 2009 to 2017, root suckers (2017), and fruit quality (FF, SSC, and SRC) from 2011 to 2017.

Training system	Tree density (trees/ha)	Final TCSA (cm^{-2})	Y (kg/tree)	ECY ($t·ha^{-1}$)	MCY ($t·ha^{-1}$)	TCY ($t·ha^{-1}$)	CYE ($kg·cm^{-2}$ TCSA)	CCL (no. fruit/cm^2 TCSA)	FW (g)	No. root Suckers	ABI	FF (N)	SSC (°Brix)	SRC (%)
Super Spindle	5,382	20.1 b[z]	9.6 c	99.2 a	358.8 a	458 a	5.4 b	30 ab	216.5 b	7.6 a	0.18 b	60.7 a	13.1 b	61.8 a
Tall Spindle	3,262	27.0 a	13.4 b	75.9 b	306.6 b	383 b	4.7 b	23 c	223.3 ab	7.5 a	0.18 b	60.2 a	13.2 b	62.4 a
Triple Axis Spindle	2,243	28.1 a	15.0 b	44.3 c	247.6 c	292 c	4.9 b	25 bc	227.4 a	7.6 a	0.23 a	59.9 ab	13.2 b	63.2 a
Vertical Axis	1,656	28.8 a	18.5 a	43.6 c	226.5 c	270 c	7.1 a	36 a	222.6 ab	10.2 a	0.20 b	59.1 b	13.5 a	62.8 a

[z]Means followed by the same letter in each column are not significantly different at $P \leq 0.05$ according to Tukey's honestly significant difference test.
ABI = alternate bearing index; CCL = cumulative crop load; ECY = early cumulative yield (2009–12); CYE = cumulative yield efficiency; FF = flesh firmness; FW = fruit weight; MCY = mature cumulative yield (2013–17); SRC = skin red color; SSC = soluble solids content; TCSA = trunk cross-sectional area; TCY = total cumulative yield (2009–17); Y = average yield per tree (2009–17).

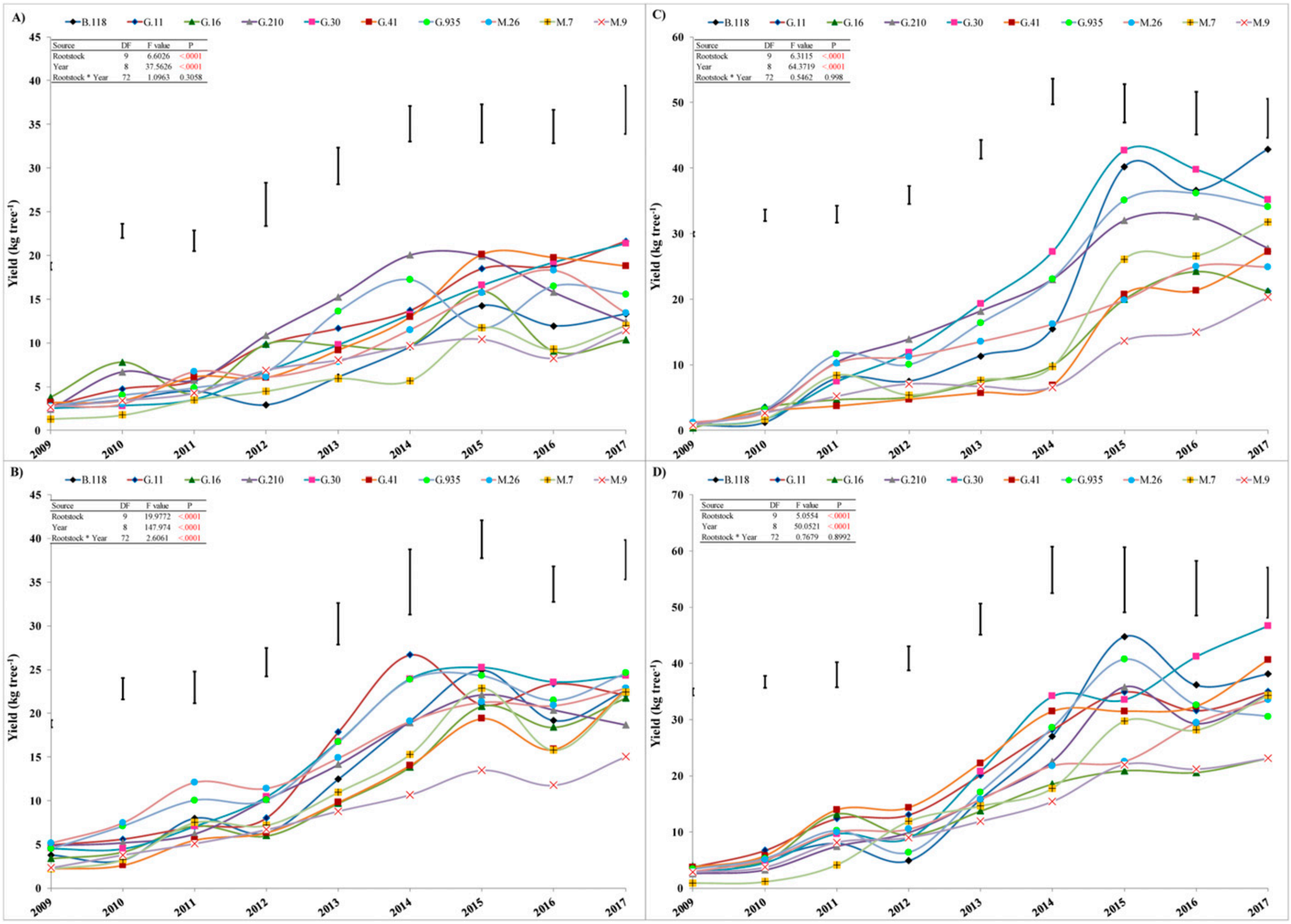

Fig. 1. Annual yields (kg/tree) of 'Delicious' apple trees on 10 rootstocks and trained to four systems (**A**, super spindle; **B**, tall spindle; **C**, triple axis spindle; **D**, vertical axis) over 11 years in Hudson, NY. Vertical bars indicate least significant difference test ($P \leq 0.05$).

studies (Barritt et al., 1997; Lordan et al., 2019b), which suggested that vigor control is not always related to the suppression of alternate bearing.

Among fruit quality traits (FF, SSC, and SRC), training system affected FF and SSC. The most vigorous trees, those from VA system, had lesser firmness and sweeter fruits compared with those from SS, TS, and TAS (Table 3), which is in agreement with Reig et al. (2019a). A positive correlation exists among yield, light interception, and tree density (Palmer et al., 1992), and between light penetration and SSC (Campbell and Marini, 1992; Jung and Choi, 2010). The amount of light available at the spur affects photosynthesis and determines fruit quality (Dussi et al., 2005).

Main effect of rootstock. Tree vigor in commercial apple orchards is largely controlled by the choice of rootstocks. Among the rootstocks we evaluated, 'B.118' had the largest TCSA, followed by 'G.30' and 'M.7EMLA', which were similar in size but they did not differ statistically from 'G.935' (Table 4). 'M.9T337' was the smallest and was significantly smaller than most of the other rootstocks but it did not differ statistically from 'G.11', 'G.16', 'G.210', 'G.41', and 'M.26EMLA'. Other authors have found after 10 years that 'McIntosh', 'Fuji', and 'Golden Delicious' trees on 'G.41' were similar in size and yield efficiency to those on 'M.9T337' (Autio et al., 2011, 2017; Czynczyk and Bielicki, 2012; Marini et al., 2012). In agreement with our results, others have reported 'G.935' was similar in tree size with 'M.26EMLA' on 'Fuji' and 'McIntosh' (Autio et al., 2011) and 'Gala' (Autio et al., 2013). In contrast to our results, other studies (Czynczyk and Bielicki, 2012; Lordan et al., 2017) reported lower 'G.11' vigor compared with 'M.9T337' when grafted with 'Golden Delicious Reinders' and 'Honeycrisp' under Poland and New York climatic conditions, respectively. Another unexpected result was that 'G.210' was significantly smaller than we would anticipate, because in other studies with 'Gala' and 'Honeycrisp', it was similar in size to 'G.30' and 'M.7EMLA' (Autio et al., 2013, 2017).

In terms of yield precocity, most rootstocks produced fruits from the third leaf (2009) after planting onward (Fig. 1). However, ECY (2009–12) was very different among rootstocks with the greatest early yield with 'M.26EMLA' and 'G.16' rootstocks and least for the 'M.7EMLA'. MCY (2003–17) was more different among rootstocks than ECY; however, 'M.7EMLA' continued to have low MCY. 'M.9T337' followed by 'G.16' and 'M.7EMLA' rootstocks had the lowest MCY values, whereas 'G.30' had the highest one. This result indicates that the early advantage of some rootstocks may not persist for the entire 20-year life of an orchard.

Among rootstocks, trees on 'G.30' had the highest yield per tree and TCY per ha, and medium to high CYE, in agreement with the results reported by Fuller et al. (2011); whereas 'M.9T337', 'M.7EMLA', and 'G.16' had the lowest yield per tree and TCY per ha (Table 4). In contrast, 'M.9T337' together with the rest of the rootstocks, except for 'B.118' and 'M.7EMLA', had the highest CYE (Table 4), in agreement with those results reported by other authors (Autio et al., 2017; Chávez-González et al., 2011; Czynczyk and Bielicki, 2012; Fuller et al., 2011). Dwarfing rootstocks have been shown to have a dramatic effect on CYE (tree productivity/tree size), which determines the optimal spacing to capture light energy and convert it to fruit (Autio et al., 2013; Fallahi et al., 2018). CCL was affected by rootstock. 'G.210', 'G.16', 'M.9T337', and 'M.26EMLA' had the highest value, but they did not differ statistically from the rest of the rootstocks except for 'B.118' and 'M.7EMLA' (Table 4).

Rootstock significantly influenced fruit size. 'Delicious' fruits from 'G.11' and 'G.41' were larger compared with those from the other rootstocks (Table 4), whereas fruits from 'G.16', 'G.935', 'M.26', 'M.9', and 'G.210' were significantly smaller. Reig et al. (2019a) reported small 'Gala' fruits from 'G.16' when compared with 'B.9', 'G.11', 'G.41', and 'M.9T337' rootstocks. Czynczyk and Bielicki (2012) also reported larger 'Golden Delicious Reinders' fruits from trees on 'G.41'. Lordan et al. (2017) reported larger 'Honeycrisp' fruits on 'G.41' and 'G.11'.

The production of root suckers in this study was influenced by rootstock, which is consistent with many other studies (Czynczyk and Bielicki, 2012; Reig et al., 2018; Robinson et al., 2011a). The greatest root suckering was with 'M.7EMLA', followed by 'M.9T337' (Table 4). The relatively high root suckering from 'M.7EMLA', independent of the system or cultivar, agrees with other rootstock studies (Kumar and Chandel, 2017; Reig et al., 2018; Robinson et al., 2011a).

Among rootstocks, alternate bearing was greatest with 'B.118' and 'M.7EMLA' and least with the rest of them (Table 4). However,

Table 4. Main effect of rootstock on horticultural traits from 2009 to 2017, root suckers (2017), and fruit quality (FF, SSC, and SRC) from 2011 to 2017.

Rootstock	Final TCSA (cm^{-2})	Y (kg/tree)	ECY ($t \cdot ha^{-1}$)	MCY ($t \cdot ha^{-1}$)	TCY ($t \cdot ha^{-1}$)	CYE ($kg \cdot cm^{-2}$ TCSA)	CCL (no. fruit/cm^2 TCSA)	FW (g)	No. root suckers	ABI	FF (N)	SSC (°Brix)	SRC (%)
B.118	44.1 a[z]	15.2 ab	53.1 ab	303.3 abcd	356 abc	3.0 c	15.1 c	226.5 abc	1.7 c	0.24 a	61.4 a	13.5 a	63.4 a
G.11	21.3 cd	15.2 ab	72.1 ab	308.5 abc	381 ab	6.3 a	30.4 a	235.1 a	0.8 c	0.18 ab	58.9 bc	13.5 a	60.9 a
G.16	20.4 cd	12.2 bc	77.6 a	231.2 de	309 bcd	6.8 a	35.2 a	215.4 c	7.7 c	0.19 ab	60.8 a	13.2 abc	64.4 a
G.210	22.1 cd	15.2 ab	75.2 ab	318.9 ab	394 ab	6.7 a	36.7 a	217.5 c	5.7 c	0.19 ab	60.3 ab	13.1 bc	62.1 a
G.30	32.8 b	17.5 a	64.7 ab	362.9 a	428 a	5.3 ab	27.1 ab	220.3 bc	4.7 c	0.21 ab	60.4 ab	13.2 abc	61.5 a
G.41	20.6 cd	14.0 ab	59.5 ab	286.7 bcd	346 abc	5.8 a	28.2 ab	233.8 ab	1.0 c	0.19 ab	58.3 c	13.3 ab	62.3 a
G.935	27.8 bc	16.5 ab	73.0 ab	333.8 ab	407 a	5.1 abc	29.3 a	216.7 c	3.9 c	0.21 ab	59.8 abc	12.9 c	63.3 a
M.26	22.1 cd	13.8 abc	80.5 a	277.0 bcd	358 abc	6.4 a	33.7 a	217.0 c	1.2 c	0.18 ab	60.2 ab	13.1 abc	62.9 a
M.7	33.5 b	12.1 bc	46.8 b	239.8 cde	287 cd	3.2 bc	16.6 bc	223.6 abc	36.6 a	0.23 ab	61.0 a	13.3 ab	61.8 a
M.9	15.5 d	9.5 c	55.1 ab	186.8 e	242 d	6.8 a	34.1 a	218.9 c	19.2 b	0.17 b	58.9 bc	13.2 abc	62.8 a

[z]Means followed by the same letter in each column are not significantly different at $P \leq 0.05$ according to Tukey's honestly significant difference test.
ABI = alternate bearing index; CCL = cumulative crop load; ECY = early cumulative yield (2009–12); CYE = cumulative yield efficiency; FF = flesh firmness; FW = fruit weight; MCY = mature cumulative yield (2013–17); SRC = skin red color; SSC = soluble solids content; TCSA = trunk cross-sectional area; TCY = total cumulative yield (2009–17); Y = average yield per tree (2009–17).

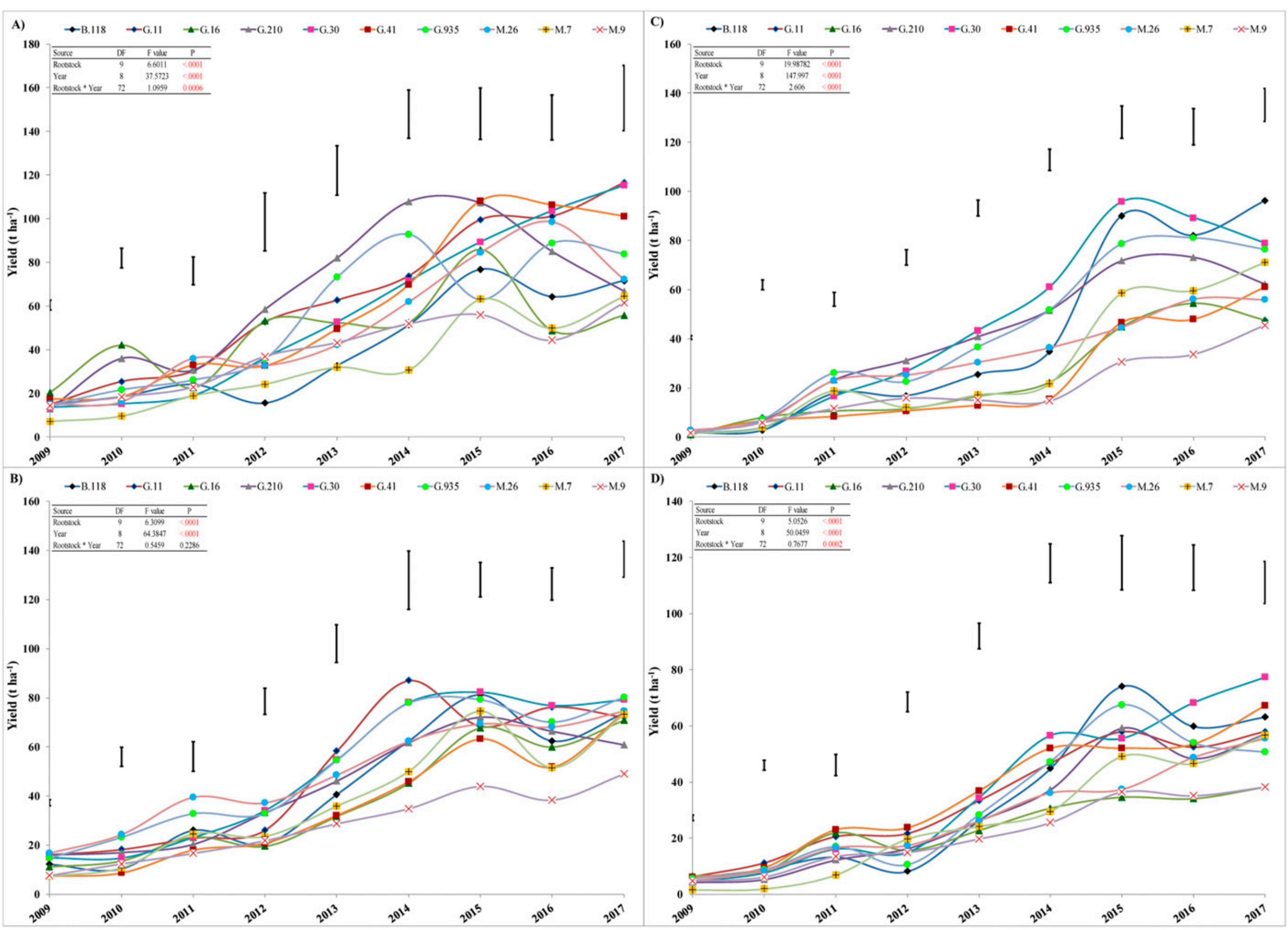

Fig. 2. Annual yields ($t \cdot ha^{-1}$) of 'Delicious' apple trees on 10 rootstocks and trained to four systems (**A**, super spindle; **B**, tall spindle; **C**, triple axis spindle; **D**, vertical axis) over 11 years in Hudson, NY. Vertical bars indicate least significant difference test ($P \leq 0.05$).

in general, ABI values were very low (<0.3). ABI can be visualized in Figs. 1 and 2, which show the annual yields per tree and annual yield per ha for each rootstock and training system. The exact physiological pathway that controls alternate bearing is not yet known and may involve timing of flower initiation, the availability of carbohydrate and nutrient resources, and the hormonal status of the tree when meristems are ready to change from vegetative to reproductive modes (Lordan et al., 2019b). Rootstocks from a diverse genetic background have been recently implicated in the ability to influence alternate bearing of some cultivars, perhaps through the induction of different hormone levels (Lordan et al., 2017) or by changes in crop load and carbohydrate storage (Reig et al., 2019a).

With regard to fruit quality, FF and SSC were affected by rootstock. 'Delicious' fruits from most of the rootstocks had similar SSC, except for those from 'G.935', which had slightly lower fruit SSC (Table 4). 'G.41' had the softest fruits with high SSC values, whereas fruits from 'B.118' and 'M.7EMLA' were the firmest with also high SSC values.

Interaction of training system and rootstock (treatment) effect. Training system and rootstock interacted to give differing effects of rootstock on tree size depending on the system. The interaction was likely caused by the differing slopes of the response of tree size to increasing tree planting (the main component of different systems) density among rootstocks. With some rootstocks, like 'B.118', 'M.7EMLA', and 'G.30', there was a strong negative effect on tree size with increasing tree planting density, whereas with other rootstocks there was little effect of tree planting density on tree size (Fig. 3).

When comparing all 10 rootstocks for each training system, 'B.118' produced the largest trees regardless of system but 'M.7EMLA', which produced the second largest trees with VA and TAS, produced quite small trees with the SS system. Previous rootstock studies reported that trees grafted on 'G.30' and 'G.210' rootstocks were intermediate between the dwarfing 'M.26EMLA' and the semidwarfing 'M.7EMLA' (Denardi et al., 2016; Reig et al., 2018; Robinson and Hoying, 2004; Robinson et al., 2011a), which agrees with our results for the TAS and VA systems but when 'M.7EMLA' was planted at the high density of SS it was smaller than 'G.30'. The smallest trees were generally on 'M.9T337' in all systems but 'G.16' was the smallest with SS. The similarity of tree size of 'M.9T337' and 'G.16' in all four training systems is consistent with studies by Robinson et al. (2003) and Reig et al. (2019a) with 'Jonagold', 'Honeycrisp', and 'Gala'. However 'G.41' and 'G.11' were slightly larger than 'M.9T337' in this study but were similar to 'M.9T337' in earlier studies. This may be because of the weak, spur-type growth habit of 'Super Chief Delicious', which results in excessively small trees with 'M.9T337' but more acceptable tree size with 'G.11' and 'G.41'. When comparing two intermediate vigor rootstocks, 'G.935' and 'M.26EMLA' were similar at the lowest density of VA but 'M.26EMLA' was much smaller than 'G.935' at higher densities (TS and SS). Other studies (Autio et al., 2013, 2017) have indicated the two rootstocks were similar in size but they only evaluated them at an intermediate planting density. Our data indicate that the interaction of rootstock and planting system must be considered in interpreting rootstock performance results and that rootstock dwarfing level obtained in a rootstock trial is only valid for that tree density.

In this study with 'Delicious', the interaction of rootstock and system on yield per tree and TCY were not significant but rather

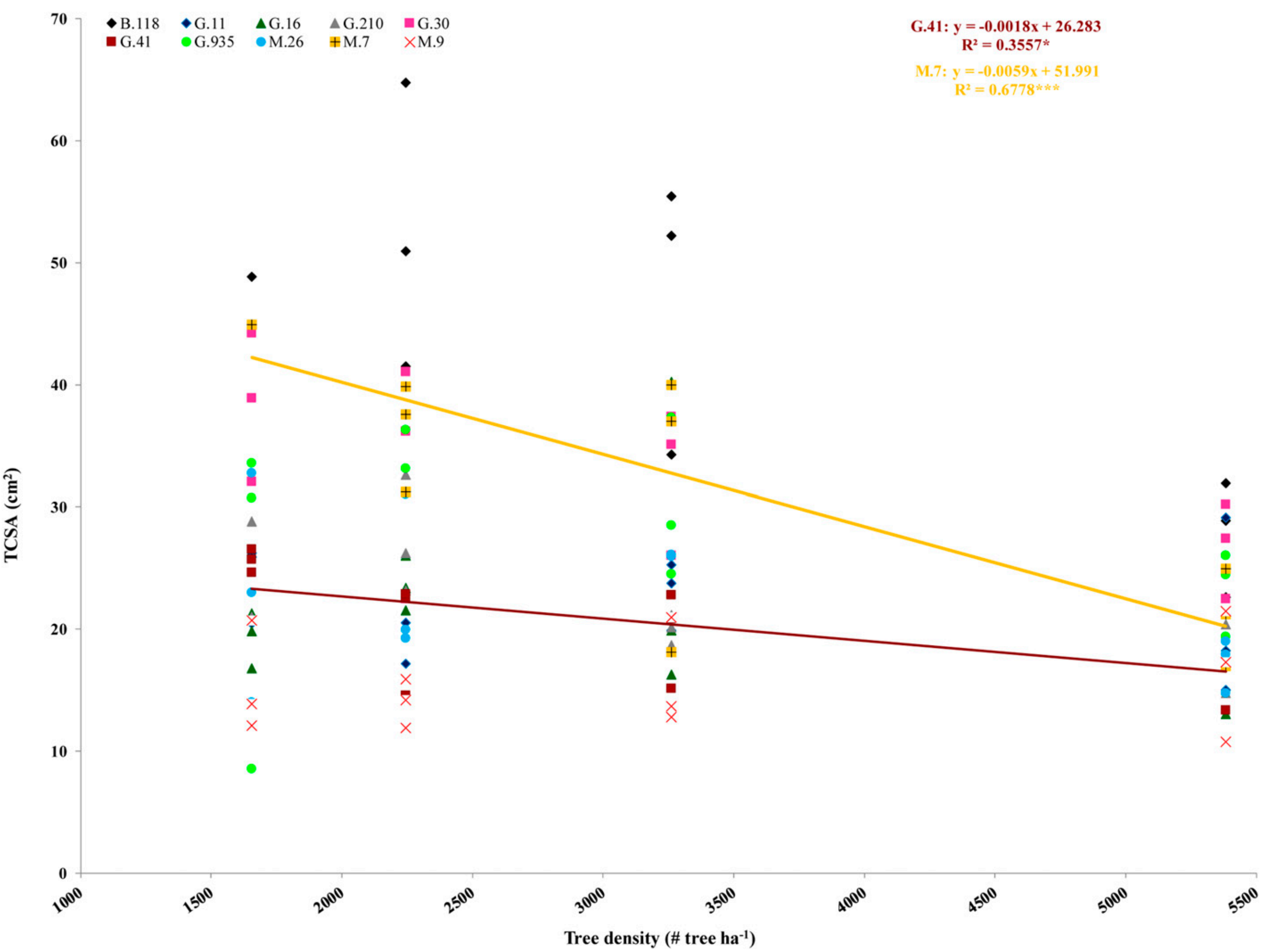

Fig. 3. Regression of tree planting density with final trunk cross-sectional area (TCSA) of 'Delicious' apple trees after 11 years in Hudson, NY. $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

Table 5. Interaction of training system × rootstock on horticultural traits of ‘Delicious’ apple trees from 2009 to 2017, root suckers (2017), and fruit quality (FF, SSC, and SRC) from 2011 to 2017 in Hudson, NY.

Training system	Rootstock	Tree density (trees/ha)	Final TCSA (cm^{-2})	Y (kg/tree)	ECY ($t \cdot ha^{-1}$)	MCY ($t \cdot ha^{-1}$)	TCY ($t \cdot ha^{-1}$)	CYE ($kg \cdot cm^{-2}$ TCSA)	CCL (no. fruit/cm^2 TCSA)	FW (g)	No. root Suckers	ABI	FF (N)	SSC (°Brix)	SRC (%)
SS	B118	5,382	27.8 a[z]	7.6 cde	73.1 a	296.8 bcd	370 bc	2.5 b	13.0 b	220.0 abc	1.2 c	0.19 a	62.3 a	13.4 a	63.4 a
	G11	5,382	20.8 ab	12.5 a	123.7 a	439.1 a	563 a	6.1 ab	31.6 ab	226.2 a	1.9 c	0.16 a	60.6 a	13.3 ab	56.5 a
	G16	5,382	13.0 b	8.9 bcde	138.1 a	295.0 bcd	433 abc	6.2 ab	33.0 ab	205.8 d	5.4 c	0.21 a	61.7 a	12.9 ab	63.1 a
	G210	5,382	17.5 ab	11.5 ab	118.8 a	441.0 a	560 a	7.9 a	51.3 a	212.2 bcd	7.7 bc	0.21 a	61.1 a	12.9 ab	62.1 a
	G30	5,382	26.7 a	10.5 abcd	86.7 a	420.2 a	507 ab	5.8 ab	29.5 ab	226.0 a	2.9 c	0.16 a	59.8 a	13.1 ab	58.9 a
	G41	5,382	17.3 ab	11.1 abc	101.3 a	434.8 a	536 a	6.2 ab	30.2 ab	225.1 ab	2.0 c	0.13 a	59.8 a	12.9 ab	62.9 a
	G935	5,382	23.3 ab	10.3 abcd	98.1 a	401.6 ab	500 ab	4.0 ab	32.7 ab	207.8 cd	0.3 c	0.21 a	60.9 a	12.7 b	63.2 a
	M26	5,382	17.2 ab	9.5 abcde	100.6 a	358.2 abc	459 ab	8.0 a	43.1 ab	212.6 abcd	1.0 c	0.21 a	60.8 a	12.8 ab	60.5 a
	M7	5,382	21.0 ab	6.2 e	59.6 a	240.0 d	300 c	2.7 b	14.2 b	217.4 abcd	34.1 a	0.23 a	61.1 a	13.2 ab	61.5 a
	M9	5,382	16.5 ab	7.5 de	92.7 a	261.9 cd	355 bc	4.5 ab	23.8 ab	211.9 bcd	20.0 b	0.15 a	59.5 a	13.3 ab	64.1 a
	$P \leq 0.05$	—	0.0047	<0.0001	0.0982	<0.0001	<0.0001	0.0325	0.0208	0.0352	<0.0001	0.4510	0.0595	0.0032	0.4531
TS	B118	3,262	47.3 a	13.7 a	65.2 a	320.2 a	385 a	2.6 b	13.4 c	213.9 c	1.2 b	0.23 a	61.7 a	13.2 a	61.5 a
	G11	3,262	22.9 b	15.5 a	65.1 a	330.5 a	396 a	5.9 a	27.6 ab	247.6 a	0.0 b	0.17 ab	58.7 ab	13.5 a	60.4 a
	G16	3,262	25.5 b	12.0 a	99.1 a	259.2 a	358 a	4.8 ab	24.5 abc	215.6 c	7.3 b	0.22 a	59.5 ab	13.2 a	64.5 a
	G210	3,262	20.0 b	13.6 a	81.0 a	307.2 a	388 a	5.9 a	30.3 a	215.1 c	4.1 b	0.13 b	60.7 ab	13.1 a	61.1 a
	G30	3,262	32.8 ab	15.8 a	81.7 a	370.9 a	453 a	4.2 ab	21.0 abc	219.5 bc	4.7 b	0.18 ab	60.9 ab	13.1 a	61.0 a
	G41	3,262	19.6 b	11.2 a	52.0 a	266.7 a	319 a	4.9 ab	23.7 abc	236.5 ab	0.1 b	0.24 a	58.0 b	13.5 a	60.5 a
	G935	3,262	30.1 ab	16.3 a	98.4 a	361.7 a	460 a	4.9 ab	23.9 abc	220.2 bc	4.7 b	0.12 b	59.8 ab	12.9 a	60.6 a
	M26	3,262	24.3 b	15.0 a	117.6 a	322.8 a	440 a	5.6 a	27.4 ab	225.5 bc	0.9b	0.12 b	60.9 ab	13.2 a	63.8 a
	M7	3,262	31.7 ab	12.4 a	63.4 a	284.8 a	348 a	3.7 ab	19.0 bc	216.8 c	34.9 a	0.23 a	61.8 a	13.0 a	65.3 a
	M9	3,262	15.8 b	8.6 a	58.3 a	194.6 a	253 a	5.1 a	24.6 abc	222.6 bc	17.7 ab	0.18 ab	60.1 ab	13.1 a	63.8 a
	$P \leq 0.05$	—	0.0018	0.0810	0.1566	0.0798	0.1072	0.0026	0.0025	<0.0001	0.0491	0.0298	0.0021	0.1011	0.6367
TAS	B118	2,243	52.4 a	18.9 ab	38.4 ab	328.6 ab	367 abc	3.2 b	16.9 b	223.7 ab	4.0 b	0.31 a	60.4 ab	13.5 ab	63.9 a
	G11	2,243	17.4 cd	12.3 bc	27.5 ab	185.5 d	213 d	5.4 ab	25.1 sb	242.1 ab	1.3 b	0.21 a	57.0 b	13.4 ab	61.8 a
	G16	2,243	23.6 bcd	13.1 abc	58.4 ab	194.1 cd	253 cd	4.8 ab	23.8 ab	232.0 ab	9.2 b	0.18 a	61.8 a	13.5 ab	65.2 a
	G210	2,243	27.3 bcd	17.9 ab	62.9 a	299.5 abc	362 abc	6.0 a	30.1 a	224.2 ab	7.1 b	0.24 a	60.7 ab	12.9 b	60.9 a
	G30	2,243	33.2 bc	20.7 a	49.2 ab	368.4 a	418 a	5.9 a	30.2 a	214.2 ab	3.5 b	0.25 a	61.8 a	13.1 ab	64.2 a
	G41	2,243	20.0 bcd	11.2 bc	24.6 b	183.8 d	208 d	4.6 ab	21.9 ab	248.5 a	1.3 b	0.24 a	57.6 ab	13.6 a	64.0 a
	G935	2,243	33.5 bc	18.9 ab	57.6 ab	324.7 ab	382 ab	5.1 ab	26.4 ab	232.0 ab	6.1 b	0.26 a	59.1 ab	13.0 ab	65.2 a
	M26	2,243	23.4 bcd	13.9 abc	56.9 ab	223.5 bcd	280 bcd	5.5 ab	30.6 a	210.6 b	1.1 b	0.20 a	60.6 ab	13.0 ab	63.4 a
	M7	2,243	36.2 ab	14.1 abc	34.6 ab	228.2 bcd	263 bcd	3.2 b	16.8 b	224.3 ab	28.3 a	0.24 a	61.5 a	13.1 ab	65.4 a
	M9	2,243	14.0 d	8.9 c	33.2 ab	139.5 d	173 d	5.6 ab	27.5 a	223.5 ab	14.4 ab	0.20 a	59.1 ab	13.1 ab	58.8 a
	$P \leq 0.05$	—	<0.0001	0.0006	0.0086	<0.0001	<0.0001	0.0052	0.0006	0.0350	0.0004	0.3679	0.0019	0.0015	0.2858
VA	B118	1,656	48.9 a	20.4 a	35.9 a	267.8 a	304 a	3.8 c	17.4 b	248.5 a	0.6 c	0.23 ab	61.2 a	13.9 a	65.0 a
	G11	1,656	24.2 bc	20.6 a	59.4 a	247.8 a	307 a	7.7 abc	37.5 ab	224.4 ab	0.1 c	0.17 ab	59.4 abc	13.7 abc	64.8 a
	G16	1,656	19.3 c	14.7 a	50.2 a	160.3 a	211 a	11.1 ab	59.4 a	208.4 b	8.7 bc	0.18 ab	59.9 ab	13.2 c	64.6 a
	G210	1,656	23.6 bc	17.9 a	38.1 a	228.0 a	266 a	6.9 abc	35.0 ab	218.5 ab	3.8 bc	0.19 ab	58.7 abc	13.5 abc	64.3 a
	G30	1,656	38.4 ab	23.2 a	41.4 a	291.9 a	333 a	5.3 bc	27.6 b	221.3 ab	7.5 bc	0.24 ab	59.3 abc	13.8 ab	60.9 ab
	G41	1,656	25.6 bc	22.6 a	60.2 a	261.6 a	322 a	7.6 abc	36.9 ab	225.1 ab	0.7 c	0.16 ab	57.9 bc	13.2 c	61.6 ab
	G935	1,656	24.3 bc	20.3 a	38.0 a	247.2 a	285 a	6.5 abc	34.3 ab	206.7 b	4.6 bc	0.25 a	59.3 abc	13.1 c	64.1 a
	M26	1,656	23.2 bc	26.8 a	47.0 a	203.5 a	250 a	6.6 abc	33.6 ab	219.4 ab	1.7 c	0.19 ab	58.8 abc	13.4 abc	64.1 a
	M7	1,656	44.9 a	25.8 a	29.8 a	206.0 a	236 a	3.2 c	16.5 b	235.9 ab	49.2 a	0.22 ab	59.5 abc	13.9 a	55.0 b
	M9	1,656	15.6 c	13.0 a	36.2 a	151.2 a	187 a	12.1 a	60.3 a	217.6 ab	24.7 b	0.15 b	57.5 c	13.2 c	64.3 a
	$P \leq 0.05$	—	<0.0001	0.2829	0.1164	0.2090	0.2968	0.0013	0.0008	0.0151	<0.0001	0.0118	0.0015	<0.0001	0.0079

[z]Means followed by the same letter in each column are not significantly different at $P \leq 0.05$ according to Tukey’s honestly significant difference Test.

ABI = alternate bearing index; CCL = cumulative crop load; ECY = early cumulative yield (2009–12); CYE = cumulative yield efficiency; FF = flesh firmness; FW = fruit weight; MCY = mature cumulative yield (2013–17); SRC = skin red color; SSC = soluble solids content; TCSA = trunk cross-sectional area; TCY = total cumulative yield (2009–17); Y = average yield per tree (2009–17).

each main effect factor had a strong effect separately on yield. However, the interaction was significant for early, mature, and TCY per ha. Significant differences in cumulative yield per ha among rootstocks were found only within the SS and TAS systems. For TS system, 'G.11' trees had the highest yield and TCY and 'M.7EMLA' had the lowest values, whereas 'G.30' and 'M.9T337' on the TAS system had the highest and the lowest values, respectively. Other studies reported a significant interaction of system × rootstock on yield in the case of 'Gala', 'Fuji', and 'Honeycrisp' (Reig et al., 2019a). Therefore, it is important to test rootstocks in different systems and with different cultivars.

There was a significant interaction of system and rootstock on CYE and CCL (Table 5). In general, yield efficiency declined and CCL increased with increasing planting density (Figs. 5 and 6). According to Robinson et al. (2011b), generally the yield efficiency of a rootstock is inversely related to its vigor. However, among rootstocks in our study, their responses were a bit different, causing the significant interaction. With 'M.9T337' and 'G.16' there was a strong negative relationship between planting density and CYE, whereas with 'G.11', 'G.210', 'M.26EMLA', and 'G.30', planting density had little effect on CYE. 'G.935', 'M.7EMLA', and 'B.118' showed a negative relationship between planting density and CYE, but less steep than for 'M.9T337' and 'G.16'. The highest values for CYE were with 'G.210' for all training systems except for VA, where 'M.9T337' had the highest value. The lowest values were for all training systems with 'B.118' and 'M.7EMLA'.

In general, CCL increased with increasing planting density; however, with 'M.9T337' the relationship was negative and with 'G.41' and 'G.16' the relationship was quadratic with the lowest value at intermediate densities (Fig. 6), which resulted in the significant interaction of system and rootstock. The highest CCL was for SS, TS, and TAS with 'G.210, and for VA with 'G.16' and 'M.9T337', whereas the lowest CCL was for all systems with 'B.118' (Table 5).

The regression relationship of CCL (x-axis) and CYE (y-axis) showed, as expected, a positive and significant linear relationship (Fig. 7). Although the regression relationships were significant, there was significant variation that was not accounted for by this relationship. System × rootstock means that were outside the 95% confidence limits of the regression relationship showed some system × rootstock combinations gave greater yield than expected from a given crop load (mean above the upper 95% confidence limit) or less yield than expected from a given crop load (mean below the lower 95% confidence limit). Three systems (SS, TS, and TAS) with 'B.118' were below the regression line. Other system × rootstock combinations having less yield than expected were SS, TS, and TAS with 'M.7EMLA', and SS with 'G.210' and 'G.935'.

The regression relationships between CCL and CYE showed that most of the training system × rootstock combinations had yield efficiency levels that could be predicted from CCL. The training system × rootstock combinations that gave either greater yield efficiency or less yield efficiency than expected can be explained by larger or smaller than average fruit size. In general 'M.7EMLA' and 'B.118' seemed to produce smaller fruit size at a given crop load than other rootstocks. There also seemed to be a trend that the TS gave less yield than expected from its crop load, whereas SS had

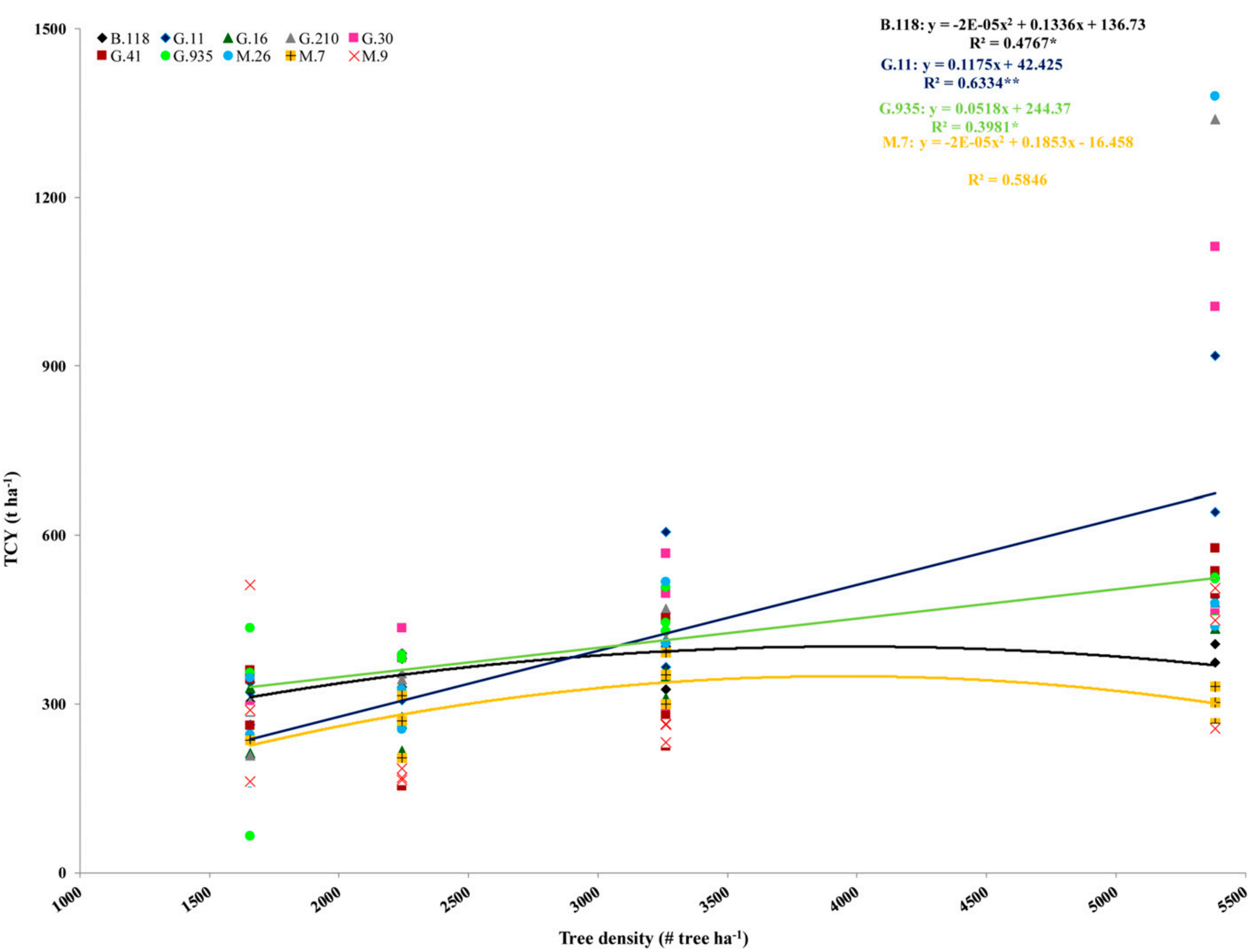

Fig. 4. Regression of tree planting density with total cumulative yield (TCY) of 'Delicious' apple trees after 11 years in Hudson, NY. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

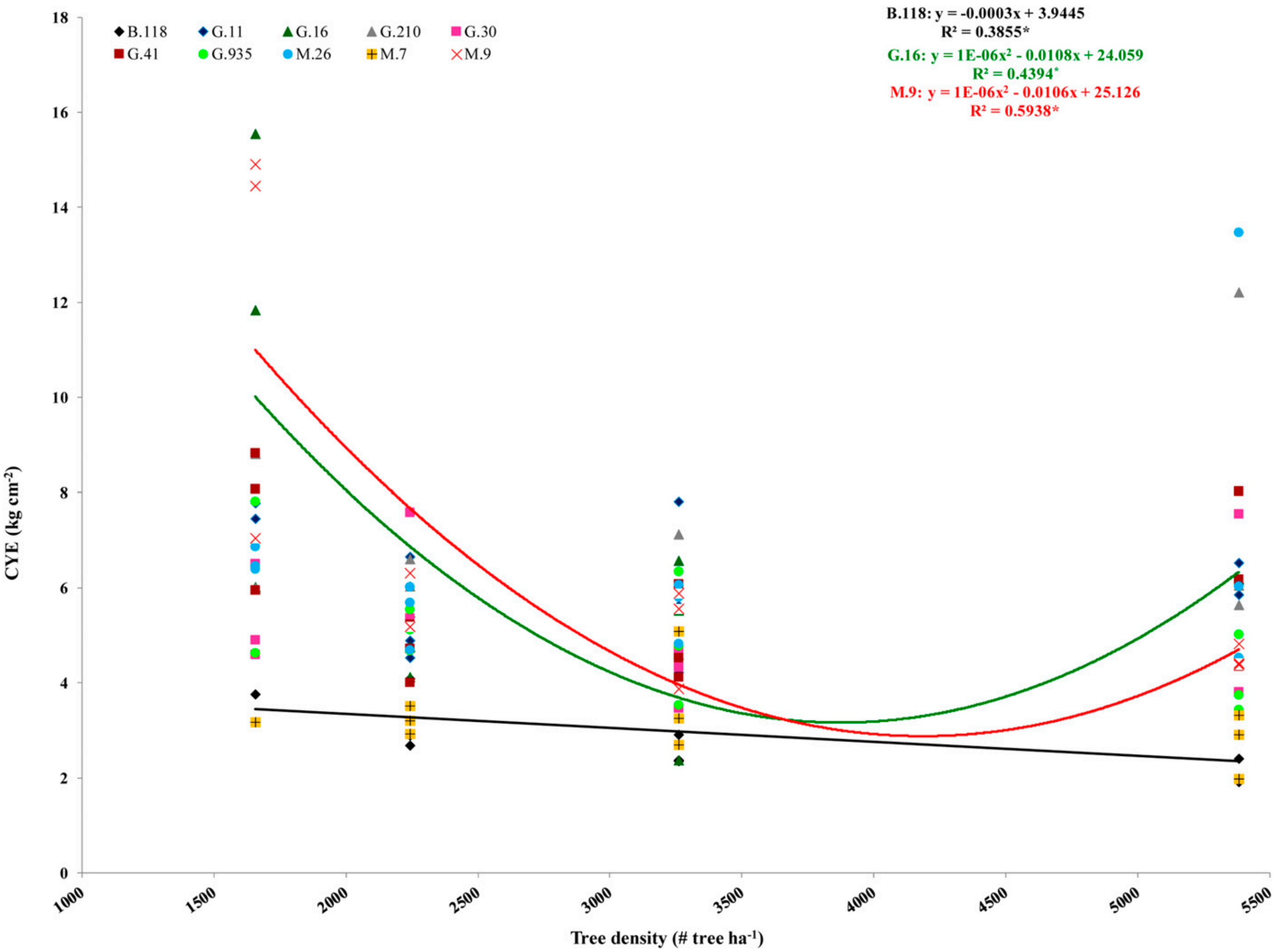

Fig. 5. Regression of tree planting density with cumulative yield efficiency (CYE) of 'Delicious' apple trees after 11 years in Hudson, NY. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ns, not significant.

greater yield than expected. This indicates that fruit size was smaller than expected at a given crop load for TS, which could be due to the style of pruning of the TS, which requires the removal of all large limbs to contain the trees in the small allotted space. This somehow reduces fruit size at a given crop load (Reig et al., 2019a).

Slightly significant differences were observed among system and rootstock combinations on ABI. The highest values were for TS with 'B.118', followed by TAS with 'G.30' and 'G.935', and VA with 'G.935' (Table 5). The lowest ones were for TS with 'G.935', 'M.26EMLA', and 'G.210', and SS with 'G.41'.

Although root sucker number was primarily related to rootstock with 'M.7EMLA' followed by 'M.9T337' having the highest number of suckers for all training systems, it is noteworthy to mention that both rootstocks produced higher number of suckers on VA system, followed by SS, TS, and TAS.

Finally, there were no significant interactions of system and rootstock on fruit quality, FF, and SRC, except for SSC. For SS and VA systems, Delicious fruits from 'B.118' were the sweetest ones, whereas those from 'G.935' had the least sweet fruits.

Effect of tree density. Each planting system we evaluated is a combination of a unique tree density and a specific training recipe; however, tree density is the dominant factor of the two variables (Lordan et al., 2019a; Robinson, 2007b; Robinson et al., 1991). Thus, to further understand our results, we conducted regression analysis of the data with tree planting density. Regression analysis of the effect of tree density using four training systems and 10 rootstocks showed, in general, a negative effect of increasing tree density on TCSA (Fig. 3), but a positive effect of increasing tree density on cumulative yield per ha, except for 'B.118' and 'M.7EMLA' (Fig. 4). For these two rootstocks, the shape of the curve had implications for profitability, as adding mores trees per ha did not give a constant incremental increase in yield (Robinson et al., 2007). The relationships were not significant for some rootstocks, but they had a similar trend. The slope of the significant relationships of tree density to cumulative yield varied between ≈118 kg of additional yield for each additional tree planted per ha to ≈143 kg of additional yield per additional tree. There was a significant negative interaction of rootstock and planting density for yield efficiency (Fig. 5) and a positive relationship with CCL (Fig. 6).

Conclusions

Our results confirm the results reported by other studies (Robinson, 2007b), that increasing tree density results in smaller tree size (TCSA), which allows successful long-term management of high-density plantings without excessive vigor and excessive pruning. This study strongly supports the results of previous studies of the significant benefit of high-density orchards on the cumulative yield of apple trees (Balkhoven-Baart et al., 2000; Hampson et al., 2002; Lordan et al., 2018a, 2018b; Reig et al., 2019a, 2019b; Robinson 2007b; Robinson et al., 1991, 2003). Our results also show that the shape of the relationship is curvilinear over a wide density range on rootstocks with a wide range of vigor, such as 'B.118' and 'M.7EMLA' in agreement with previous studies (Reig et al., 2019a); however, we saw a linear relationship with the other rootstocks we evaluated ('G.11' and 'G.935'). The magnitude of the difference in cumulative yield between the lowest and the highest densities was 2.5 to 4.0 times. These large differences in yield with

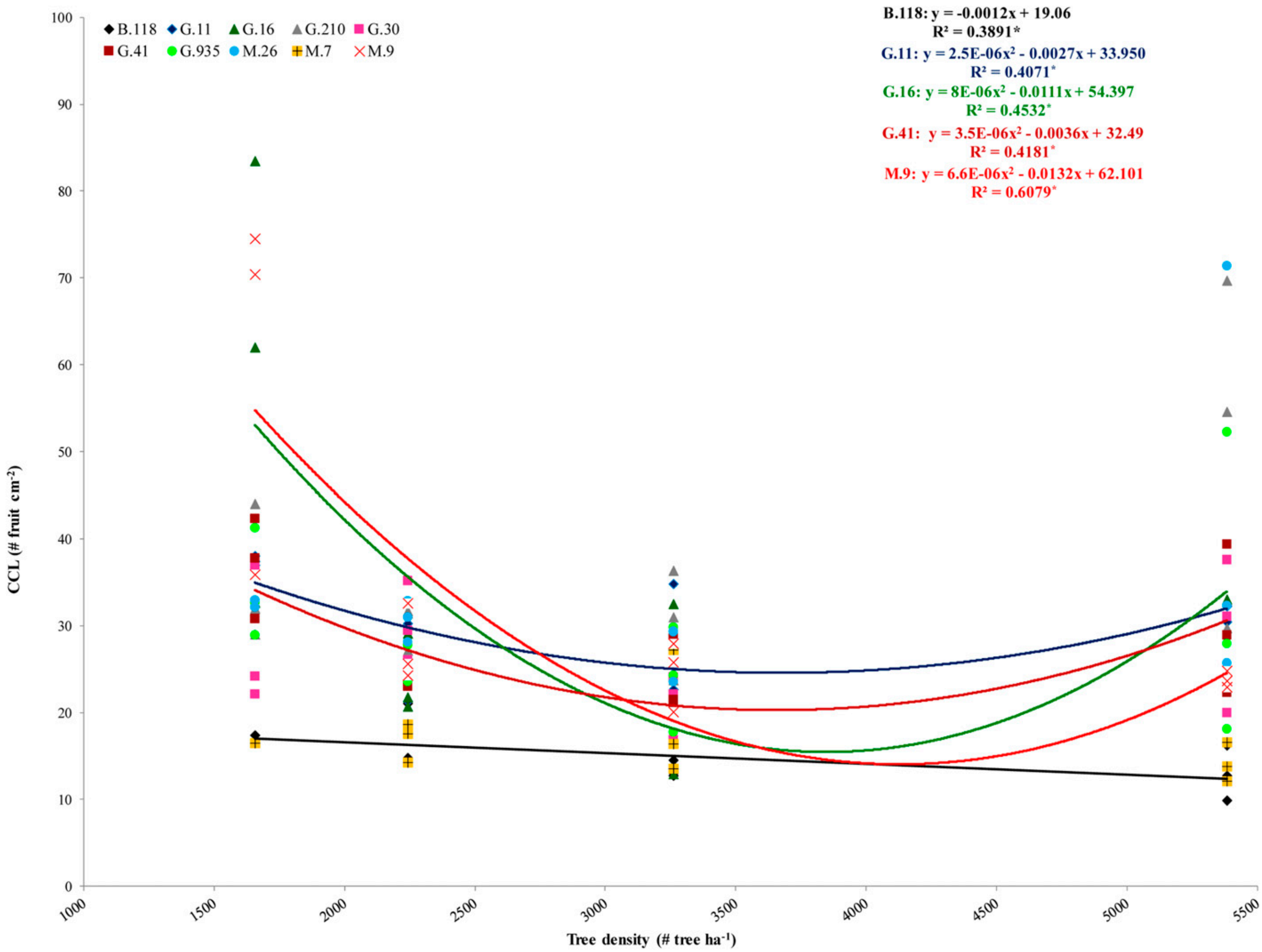

Fig. 6. Regression of tree planting density with cumulative crop load (CCL) of 'Delicious' apple trees after 11 years in Hudson, NY. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ns, not significant.

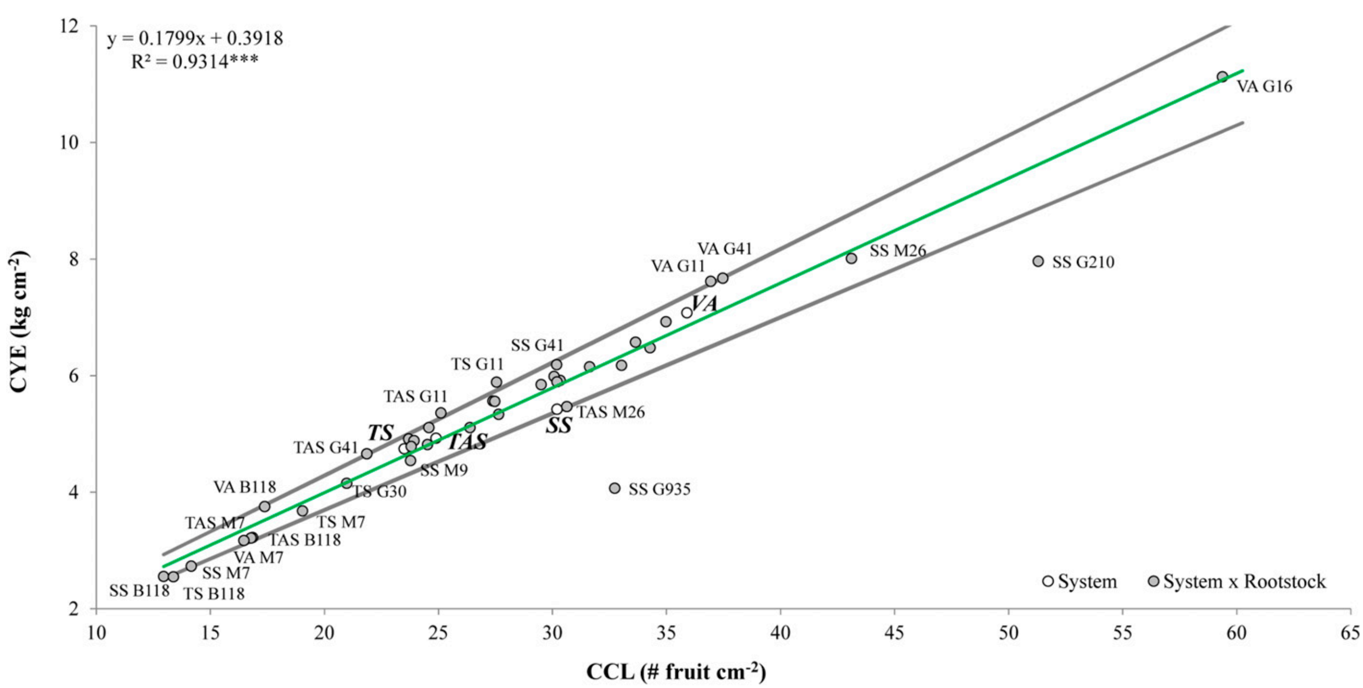

Fig. 7. Regression relationship of cumulative crop load (CCL) with cumulative yield efficiency (CYE) for four orchard systems and 40 treatments. The linear regression is represented by the green line, whereas the 95% confidence interval is represented by the gray lines. Regressions were analyzed by a Student *t*-test (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ns, not significant). SS = Super Spindle; TAS = Triple Axis Spindle; TS = Tall Spindle; VA = Vertical Axis.

the slow-growing, spur-type cultivar Delicious should have large consequences on the economics of planting this cultivar.

However, the significant interaction of system × rootstock on yield indicates it is important to test rootstocks in different systems and with different cultivars. This study is the first to use a weak and compact growing cultivar to assess the suitability of both dwarfing and vigorous rootstocks in a range of densities and systems. Although in general, the highest density SS system was more productive and efficient than the moderate-density TS system, or lower density TAS or VA systems, the economic feasibility of such a high-density system must be evaluated. SS is a planting system that maximizes profitability through early yield, improved fruit quality, and reduced spraying, pruning, and training costs; however, a relative high capital investment is required to establish the system, mostly associated with the large number of trees planted per ha. To overcome this reality, early bearing, in the second through sixth years, is very important for this system. The lower tree density from the TAS and the VA systems makes them less expensive systems to establish, but annual pruning is more complex. This, together with the delayed onset of production when compared with SS, along with lower yield, will likely make these systems less profitable. We are currently conducting a full economic analysis of these data and will present the results in a later companion paper.

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