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Early Performance of 'Fuji' Apple Trees on Several size-controlling rootstocks in the 2014 NC-140 Rootstock Trial

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Additional index words: trunk cross-sectional area, rootstock suckers, cumulative yield, cumulative yield efficiency, fruit weight, tree height, tree width, tree survival, tree mortality

Abstract

In 2014 a coordinated multi-year apple (*Malus domestica* (Borkh)) orchard experiment on 14 rootstock genotypes trained to a tall spindle orchard system was established at eight locations in Canada and the United States using 'Aztec Fuji®' as the scion cultivar. The rootstocks tested were: Budagovsky10 (B.10), the Cornell-Geneva rootstocks G.11, G.202, G.214, G.30, G.41, G.935, and G.969, and the Vineland rootstocks V.1, V.5, V.6, and V.7. The industry standard Malling rootstocks M.26 EMLA and M.9-T337 were included for comparison. Tree morality, trunk cross-sectional area, tree canopy size, amount of rootstock suckering, yield, and number of fruits were measured annually. All measured responses were influenced by location and rootstock and the interaction of these two factors. After five years and averaged over all locations, G.214 and B.10 were 10% and 5% smaller than M.9-T337, respectively. G.935, G.11, and G.41 were 1%, 2% and 3% larger than M.9- T337, respectively, while G.969 was 3% larger than M.26 EMLA, respectively. V.1 and G.30 were 25% and 32% larger than M.26 EMLA, respectively, while V.7, V.5, and V.6 were the largest in the trial, ranging from 49-66% larger than M.26 EMLA. Cumulative yield increased with tree vigor. Remarkably, all rootstocks out-yielded M.9-T337 and M.26 EMLA. Averaged over all locations, cumulative yield efficiency was greatest for G.935 and G.214. Overall, tree mortality and suckering were low, but were affected by planting location. These results will allow apple producers to make more informed decisions concerning rootstock selection for the tall spindle or similar orchard training systems and planting locations.

Fuji' is an increasingly popular apple cultivar throughout the world especially since the development and availability of a larger number of strains with improved red fruit color and earlier maturity dates. 'Fuji' is one of the top five cultivars in the United States (US) and as of 2019, 'Fuji' ranked third on the US Apple Association's list of most popular apples (Anonymous, 2019). 'Fuji' has a vigorous upright growth habit with strong biennial bearing tendencies. Matching the strong vigor of 'Fuji' with the appropriate rootstock is important for the desired orchard system and planting density, and to balance reproductive and vegetative growth to optimize production and fruit quality.

The East-Malling rootstocks M.9 and M.26 are the most widely planted rootstocks in North America. M.9 provides excellent size control, is precocious, yield-efficient, and resistant to crown and root rots (Marini and Fazio, 2018; Russo et al., 2007). However, trees on M.9 have poor anchorage due to brittle roots, the rootstock is difficult to propagate in the stool bed system (Auvil et al., 2011), and is very susceptible to fire blight (*Erwinia amylovora*) (Norelli et al., 2003), woolly apple aphid (*Eriosoma* lanigerum (Hausman)) (Beers et al., 2006), and winter injury in colder growing regions (Marini and Fazio, 2018). In addition, M.9 can produce moderate amounts of root suckers and burrknots and is susceptible to soil replant disease (Laurent et al., 2010). M.26 is prone to burrknots, is sensitive to fire blight, woolly apple aphid, and crown and root rots (Marini and Fazio, 2018). Identifying improved apple rootstocks remains a research priority.

With the continued adoption of modern higher density supported orchard production systems, selection of an appropriate rootstock is important for the economic viability of the orchard. Selecting the most appropriate rootstock, however, has become increasingly challenging with the introduction of many new rootstocks with potentially greater yields and yield efficiencies, a range of size controls, and pest and disease resistance (Autio et al., 2008). Evidence-based rootstock studies that measure performance characteristics over several years and locations help apple producers make informed decisions for rootstock selection to best match their cultivar, climate, site, and orchard planting system. Given the high investment costs for orchards ranging in density from 1000-6000 trees ha^{-1}, the need for highly productive rootstocks that range in tree vigor and can withstand a range of abiotic and biotic stresses has likely never been greater (Robinson, 2004). The NC-140 Project is the primary vehicle for North American importation and evaluation of rootstocks from around the world. With the assistance of commercial nurseries, trees on new rootstocks are propagated and evaluated for up to 10 years across many sites and climates across North America.

The 2014 'Fuji' rootstock trial was established to evaluate new rootstocks from the University of Michurinsk (Russia), Cornell-USDA (USA), and Vineland (Canada) breeding programs. The rootstocks evaluated range in vigor from dwarfing to semi-dwarfing. Several Cornell-Geneva rootstocks (G.11, G.202, G.214, G.30, G.41, G.935, and G.969) were tested with varying degrees of size control, productivity, yield efficiency, ease of nursery propagation, fire blight resistance, tolerance to extreme temperatures and resistance to soil pathogens. The reported order of increasing vigor of the Cornell-Geneva rootstocks tested in this trial is: G.11, G.41 (M.9-T337 size) G.214 (between M.9/M.26 size), G.935, G.202 (M.26 size), and G.30, G.969 (M.7 size) (Fazio, 2018). All the Geneva rootstocks are reported to be resistant to fire blight, tolerant to crown and root rots (*Phytophthora* sp.), winter hardy, and have low propensity to suckering and burrknots, while G.11 and G.935 are susceptible to woolly apple aphid, and G.11 is susceptible to apple replant disease. Budagovsky 10 (formerly Budagovsky 62-396) was developed from a cross of Budagovsky 9 x Budagovsky 13-14, and reportedly produces trees similar in size to M.9-T337 or larger depending on growing region. B.10 is reportedly very cold hardy and resistant to fire blight and has been of increasing interest to growers. V.1 from the Vineland program is a semi-dwarfing rootstock with cold hardiness and fire blight resistance (Cline et al., 2001). It was tested in a previous NC-140 trial (Marini et al., 2006a) but has not been tested in a NC-140 study with 'Fuji' as the scion. The other Vineland rootstocks in this trial, V.5, V.6, and V.7, have not been tested previously, but were assumed to be dwarfing to semi-dwarfing based on observations made on their stature in a research nursery in Simcoe, Ontario (J. Cline, personal communication).

Performance information for 'Fuji' on new commercially available rootstocks is important for producers' selection of the most suitable rootstock for their locations and orchard systems. The purpose of this study was to evaluate the performance of 'Fuji' on new dwarf apple rootstocks across a range of climates and soils.

Material and Methods

'Aztec Fuji ®' (DT2 cultivar) (hereon 'Fuji') trees on 14 size-controlling rootstocks were planted at eight locations (Table 1) in the spring of 2014. They were trained to a tall spindle training system (Robinson et al., 2006a) and spaced at distances of 1.5 m within rows and 4.0 m between rows (1661 trees per ha). Trees were propagated at Willow Drive Nursery (Ephrata, Washington). The rootstocks evaluated were B.10, G.11, G.202, G.214, G.30, G.41, G.935, G.969, M.26 EMLA, M.9-T337, V.1, V.5, V.6, and V.7. Due to a limited supply of some rootstocks for all locations, ID, NJ, ON and PA did not receive all 14 rootstocks. At each site, local guidelines were followed for irrigation and fertilization, the cultivar and frequency of pollinizer trees, as well as pest and disease management. The experimental design

Table 1. Cooperators in the 2014 NC-140 Fuji apple planting

Location	Name	Affilitation	Longitude	Latitude	Elevation (m)	Soil type	Planting irrigated ?
(AL) Clanton, AL	E. Coneva	Auburn University	86°40'13"W	32°55'12'"N	184	Loam	yes
(GA) Blairsville, GA	T. Konn	North Carolina State Univ.	83°55'23"W	34°50'21"N	645	Fine sandy loam	no
(ID) Parma, Idaho	E. Fallahi	University of Idaho	116°56'40"W	43°48'5"N	703	Sandy loam	yes
(NJ) Pittstown, New Jersey	W. Cowgill and M. Muehlbauer	Rutgers University	74°57'24"W	40°33'38"N	188	Silt Loam	yes
(ON) Simcoe, Ontario	J. Cline	University of Guelph	80°16'18"W	42°51'37"N	283	Sandy loam	yes
(PA) Rock Springs, PA	R. Crassweller	PennState University	77°57'22"W	40°42'44"N	373	Silt Loam	no
(SC) Seneca, SC	G. Reighard and D. Ouellette	Clemson University	82°52'41"W	34°36'70"N	285	Sandy loam	yes
(UT) Kaysville, UT	B. Black	Utah State University	111°55'50"W	41°01'20"N	1335	Fine sandy loam	yes

was a completely randomized design with 10 single trees replicates at each location. In addition, because G.202 did not grow well at most locations and was much more dwarfing than anticipated based on previous studies, it was excluded from analysis.

At planting and each fall, trunk circumference was measured 30 cm above the union and trunk-cross-sectional area (TCA) was calculated. Trees were defruited in 2014, and depending on tree size, were first allowed to fruit in 2015 or 2016. To prevent biennial bearing, crop load of each tree was hand thinned to one fruit per cluster and leaving no more than 5-6 fruit cm^{-2} TCA. Once bearing, the date of full bloom was recorded annually, and in the fall, root suckers were counted and removed, and tree mortality and harvest date, yield (total fruit weight) and total fruit number per tree were recorded. Crop load per tree was calculated by dividing the total number of fruits by the TCA, and average fruit weight (FW) was calculated by dividing total fruit weight by total number of fruits per tree. Cumulative yield was calculated as the sum of yield from 2015 to 2018. Cumulative yield efficiency (CYE) was calculated by dividing cumulative yield by TCA in 2018. Average fruit weight was calculated as the mean of FW for each year of cropping (2015-2018). Following harvest and prior to pruning in 2018, the height and spread of the canopy was recorded. Each winter, the data were sent to the senior author for summarization and statistical analysis.

Data were analyzed by the GLIMMIX procedure of SAS (version 9.4, SAS Institute, Inc., Cary, NC) and mean separation performed using Tukey's HSD test to separate means with treatments as fixed effects. The data were initially analyzed with all locations together. However, due to the unbalanced nature of the study and high frequency of rootstock and location interaction, each location was analyzed separately. Shapiro-Wilk test was used to test the assumption that the residuals were normally distributed. Scatterplots of studentized residuals were visually observed to test the assumption that the errors were not heterogeneous. In cases where there were large deviations from assumptions, data were corrected by log- or square root-transformation prior to analysis.

Results and Discussion

Location specific information. In long-term multi-state experiments, there invariably exist factors beyond the control of the researchers that can influence study results. To properly interpret the results in these cases, we herein provide details of events that may affect the study outcomes to a lesser or greater degree. In UT, there were crop losses due to spring freezes at the planting site, particularly in the early years of the experiment. In 2018, a portable wind machine to mitigate spring frost damage was used. In addition, the soil has a native pH of 7.6, which is more alkaline than most NC-140, but only moderately alkaline compared to most of the commercial orchards in Utah. In AL, approximately 60% of the trees were infected by *Botryosphaeria* species in the spring of 2015. It was necessary to cut back diseased branches to healthy tissue. This required severe pruning in some instances, and the leader headed and a new was selected and trained. This management reduced the number of flower buds and influenced CY and annual growth data. In SC, bee activity in 2017 was poor, resulting in lower fruit set. Moreover, this location has a long growing season with high risk of fire blight as well as warm nights during harvest, making it difficult to achieve sufficient fruit color on Fuji. In GA and PA, it was not possible to irrigate the trees. A drought occurred late in the 2016 growing season in GA, resulting in reduced trunk growth rates. Finally, in the spring of 2016, a spring frost caused a partial crop loss, resulting in low yields.

Tree Survival. Tree survival at year 5 was influenced by location and rootstock, and the interaction of the two factors was significant (P<0.012) (Table 2). Tree survival was significantly affected by rootstock at only 2 of 8 locations. In ID, tree survival on M.26 EMLA was significantly lower than all the other rootstocks (P=0.0452). In South Carolina (SC), tree survival on M.9-T337 was lower than other rootstocks at that location (P=0.0002). Overall, tree survival was high at all locations; pooled across all rootstocks, survival ranged on average from 92% to 100%. Rootstock tree survival averaged across all locations was highest for V.1, V.5, and V.7 (all 100%), and lowest for M.9-T337 (87%) and M.26 EMLA (94%). Typically, more than five years is required to fully evaluate tree survival (Marini et al., 2006a); therefore, these data should be considered preliminary.

TCA. Tree vigor, as indicated by TCA, was influenced by location and rootstock, and the interaction of the two factors was significant (P<0.001) (Table 3; Figure 1). As such, caution must be made when generalizing rootstock vigor without considering location. Pooled over all locations, G.214 and B.10 were 10% and 5% smaller in TCA, respectively than M.9-T337 (Figure 1). G.935 and G.11 were similar in size to M.9-T337. G.969 was similar in TCA to M.26 EMLA, while V.1, G.30, V.7, V.5, and V.6 were 25%, 32%, 49%, 51% and 66% larger, respectively than M.26 EMLA. Pooled over all rootstocks, tree vigor was greatest in Utah (UT), New Jersey (NJ), and Alabama (AL) and lowest in Simcoe (ON). These data are confounded by the fact that not all sites had the same rootstocks, so the data may be skewed by locations with predominately vigorous rootstocks, such as Pennsylvania (PA). Factors that can affect

Table 2. Tree survival (%) of 'Fuji' trees after five years as influenced by rootstock and location[z]

Rootstock	AL	GA	ID		NJ	ON	PA	SC		UT	Mean
B.10	80	100	100	a		100		100	a	100	97
G.11	100	80	100	a	100	100		100	a	90	96
G.214	80	90	100	a	100	90	100	100	a	100	95
G.30	100	90	100	a	100	100		100	a	100	99
G.41	90	100	100	a		100		100	a	100	98
G.935	89	100	90	a	100	100		100	a	100	97
G.969	100	100	90	a				100	a	90	96
M.26 EMLA	89	100	70	b	100	100	100	90	a	100	94
M.9 T337	80	80			90	100	100	60	b	100	87
V.1	100	100	100	a	100		100	100	a	100	100
V.5	100	100			100	100	100	100	a	100	100
V.6	90	100			100	100	100	90	a	100	97
V.7	100	100			100	100	100	100	a	100	100
Mean	92	95	94		99	99	100	95		98	97
P-value	0.4746	0.1786	0.0452		0.4559	0.4489		0.0002		0.5328	

[z] Least square mean values within columns with the same letter are not significantly different according to the Tukey-Kramer test at P=0.05.

Table 3. Growth of 'Fuji' trees, as indicated by trunk cross-sectional area (cm^2), after five years as influenced by rootstock and location[z]

Rootstock	AL		GA		ID		NJ		ON		PA		SC		UT		Mean
B.10	19.6	e	14.0	e	23.8	cd			23.4	abc			14.4	e	31.2	d	21.1
G.11	27.9	cde	18.8	de	20.3	d	22.5	b	17.0	cde			18.4	de	33.9	d	22.7
G.214	17.8	e	15.3	e	21.6	cd	18.2	b	15.5	de	23.1	bc	16.9	de	32.3	d	20.1
G.30	35.9	a-d	36.0	bc	34.1	a	61.7	a	30.0	a			30.1	bc	39.9	cd	38.3
G.41	17.8	e	20.4	de	22.1	cd			23.4	abc			16.0	de	37.9	cd	22.9
G.935	22.6	de	22.8	de	21.5	cd	24.4	b	13.1	e			18.7	de	33.6	d	22.4
G.969	31.1	b-e	18.8	de	26.9	bc							31.3	abc	40.5	cd	29.7
M.26 EMLA	37.2	a-d	28.2	cd	28.3	abc	28.1	b	23.9	abc	23.1	bc	21.4	cde	41.4	cd	28.9
M.9 T337	28.0	cde	17.1	de			22.0	b	15.5	de	19.1	c	16.3	de	37.6	cd	22.2
V.1	41.1	abc	37.9	bc	32.6	ab	41.6	ab			28.3	abc	26.5	bcd	45.7	bc	36.3
V.5	44.6	ab	36.6	bc			59.9	a	22.2	bcd	32.8	ab	42.2	a	67.7	a	43.7
V.6	47.6	a	50.1	a			68.7	a	23.2	abc	36.5	a	42.5	a	68.4	a	48.1
V.7	47.5	a	39.2	b			66.3	a	24.5	ab	34.1	a	34.5	ab	55.5	b	43.1
Mean	32.2		27.3		25.7		41.3		21.1		28.1		25.3		43.5		30.7
P-value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		

[z] Least square mean values within columns with the same letter are not significantly different according to the Tukey-Kramer test at P=0.05.

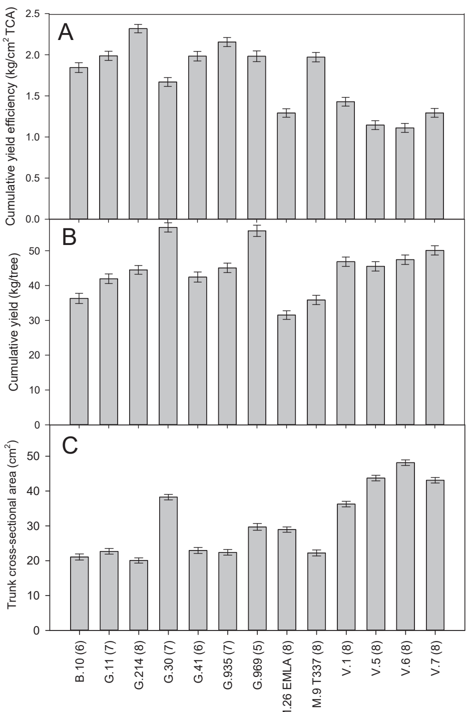

Figure 1. Cumulative yield efficiency (CYE, A), and cumulative yield per tree (CY, B) and trunk cross-sectional area (TCA, C) of 'Fuji' trees on thirteen rootstocks. TCA was measured in 2018, 5 years after planting, and CY and CYE represent yields from 2015-2018. Data represent the least square means (lsmeans) of rootstocks pooled across all planting locations. Error bars represent the standard error of the lsmean taken from the GLMMIX model analyses.

site vigor include soil properties, early cropping, environmental conditions, tree nutrition, annual crop load, and pre-plant treatments such as fumigation.

For all locations that had trees on G.11, G.41, and G.935, vigor of trees on these rootstocks was consistently similar to M.9-T337. These data agree with Fazio (2018) and Autio et al. (2020), who classified these rootstocks in the 'dwarfing' category. Additionally, in a companion study on 'Honeycrisp', G.11, G.41, and G.935 were similar in vigor to M.9-T337 (Cline et al., 2021). In a New York (NY) study comparing the performance of 'Fuji' on several Geneva rootstocks with two orchard systems (Slender Axis, Tall Spindle), Reig et al. (2019) found that G.11 and G.41 were similar in TCA to M.9-T337 after 10 years. In all locations where B.10 was included (AL, GA, ID, ON, SC, UT), it was approximately 7% smaller than M.9-T337, except in ON where it was 50% larger than M.9-T337. In another NC-140 companion study with 'Honeycrisp', B.10 was closer to M.26 EMLA in vigor rather than M.9-T337 (Cline et al., 2021). In a 'Golden Delicious' trial in PA, B.10 trees were similar in size to G.935 and M.9-T337 after 10 years (Marini et al., 2014). In a multi-location 'Honeycrisp' trial, B.10 was 4% larger than M.9-T337 by year 5 (Autio et al., 2017a), while in a similar trial on 'Fuji', B.10 was slightly larger than M.9-T337 (Autio et al., 2017b). In a 'Fuji' rootstock experiment in NY, G.935 conferred vigor similar to M.26 (Robinson et al., 2008); in the present trial G.935 tended to be less vigorous than M.26 at all locations except in ON. The semi-dwarfing rootstock, G.969, which has been previously classified in the M.7 size range (Cummins et al., 2013), was similar to M.26 EMLA at all locations. Robinson et al. (2014) categorized G.969 between the sizes of M.26 and M.7. A previous study in MA classified V.1 rootstock in the semi-dwarfing size range, similar to Mark rootstock (Autio and Krupa, 2001). In another study in the same region using McIntosh as the scion, V.1 was slightly smaller than M.26 EMLA (Autio et al., 2005). G.30 has shown high vigor in other studies including one in NY where it was 48-68% more vigorous than M.26 EMLA (Reig et al., 2020; Robinson et al., 2006b) and a NC-140 'Gala' rootstock trial where its size was either similar to or greater than M.26 EMLA (Marini et al., 2006b). This is the first study evaluating the V.5, V.6, and V.7 genotypes next to a companion study (Cline et al., 2021). They both had TCA values 51-66% larger than M.26 EMLA, and consequently are likely too vigorous for use in single-leader modern high-density orchard systems, especially for a high-vigor cultivar such as 'Fuji'. However, such rootstocks may be beneficial in weaker sites, lower density planting systems, or multi-leader training systems.

Canopy Size. Tree height and width were influenced by location and rootstock, and the interaction of the two factors was significant ($P<0.0001$) (Tables 4 and 5). Tree height was significantly affected by rootstock in all locations. Pooled across rootstocks, tree height ranged from 3.3 m to 4.2 m and was greatest in SC and UT. Cooperators were requested to restrict tree height to 3.5 m by pruning, based on the protocol for the Tall Spindle training system. In all locations, tree height exceeded 3.5 m for at least one rootstock by the fifth leaf. Pooled across locations, tree height was lowest for B.10, G.935, and M.9-T337 and tallest for G.30, V.7, V.5, and V.6. Early development of the tree canopy and maximization of tree height are key to maximizing precocity and yield. Clearly, with 'Fuji' as the scion, rootstocks such as G.30, V.5, V.6, and V.7 would be too vigorous for the Tall Spindle system at most locations, and would require excessive pruning of the tree canopy to maintain the canopy within the allotted space (1.52 x 3.96 m). Tree width was significantly affected by rootstock in 4 of 8 locations (Table 5) and there was a significant rootstock by location interaction ($P<0.001$). Pooled across rootstocks, tree width was lowest in ID, NJ, ON and SC (< 2 m) and greatest in UT, PA and GA. Rootstock effect on tree width is confounded by the require-

Table 4. Tree height (m) of 'Fuji' trees after five years as influenced by rootstock and location[z]

Rootstock	AL		GA		ID		NJ		ON		PA		SC		UT		Mean
B.10	2.5	e	3.1	e	3.2	c			3.7	a			3.4	e	4.1	cd	3.3
G.11	3.3	a-e	3.8	abc	3.4	abc	3.5	ab	3.4	ab			4.3	abc	4.2	bcd	3.7
G.214	2.7	de	3.6	bcd	3.5	abc	3.5	ab	3.4	ab	3.5	ab	4.1	a-d	3.9	d	3.5
G.30	3.4	a-d	4.1	a	3.8	a	3.6	ab	3.8	a			4.7	a	4.1	cd	3.9
G.41	3.0	b-e	3.5	cde	3.3	bc			3.6	a			3.6	de	4.1	cd	3.5
G.935	2.8	cde	3.5	cde	3.2	c	3.3	b	3.0	b			3.9	b-e	4.0	cd	3.4
G.969	3.6	abc	3.3	de	3.7	ab							4.4	abc	4.1	cd	3.8
M.26 EMLA	3.4	a-e	3.5	cde	3.4	abc	3.3	b	3.6	a	3.3	ab	3.7	cde	4.3	bcd	3.6
M.9 T337	3.1	b-e	3.3	de			3.3	ab	3.3	ab	3.2	b	3.8	b-e	4.0	cd	3.4
V.1	3.5	a-d	3.9	abc	3.5	abc	3.6	ab			3.3	ab	4.0	a-e	4.2	bcd	3.7
V.5	4.0	a	3.9	abc			3.7	a	3.5	ab	3.5	ab	4.3	abc	4.8	a	3.9
V.6	3.7	abc	4.1	a			3.6	ab	3.6	a	3.7	a	4.5	ab	4.6	ab	4.0
V.7	3.7	ab	4.0	ab			3.7	ab	3.6	a	3.5	ab	4.6	ab	4.5	abc	3.9
Mean	3.3		3.7		3.4		3.5		3.5		3.4		4.1		4.2		3.7
P-value	<0.0001		<0.0001		0.0003		0.0039		0.0003		0.0225		<0.0001		<0.0001		

[z] Least square mean values within columns with the same letter are not significantly different according to the Tukey-Kramer test at P=0.05.

Table 5. Canopy spread (m) of 'Fuji' trees after five years as influenced by rootstock and location[z]

Rootstock	AL		GA		ID	NJ	ON		PA	SC		UT		Mean
B.10	1.7	e	2.0	f	1.3		2.0	a		1.5	c	2.4	c	1.8
G.11	2.2	abc	2.4	b-f	1.3	1.5	1.9	a		1.8	abc	2.6	bc	1.9
G.214	1.7	e	2.0	f	1.2	1.5	1.9	a	2.5	1.6	bc	2.5	c	1.9
G.30	2.3	abc	2.9	ab	1.5	1.6	2.0	a		1.9	ab	2.6	bc	2.1
G.41	1.7	de	2.3	def	1.2		2.0	a		1.6	c	2.8	abc	1.9
G.935	2.0	cde	2.4	c-f	1.3	1.5	1.7	a		1.7	abc	2.4	c	1.9
G.969	2.1	bcd	2.2	ef	1.4					1.8	abc	2.7	abc	2.0
M.26 EMLA	2.2	abc	2.6	a-e	1.4	1.4	1.8	a	2.3	1.5	c	2.5	c	2.0
M.9 T337	2.1	a-d	2.2	ef		1.5	1.9	a	2.3	1.5	c	2.4	c	2.0
V.1	2.1	bcd	2.7	a-d	1.4	1.4			2.3	1.7	abc	2.8	abc	2.1
V.5	2.3	abc	2.6	a-e		1.6	2.0	a	2.2	1.9	ab	3.0	ab	2.2
V.6	2.5	a	2.9	a		1.7	2.0	a	2.4	1.9	ab	3.2	a	2.3
V.7	2.4	ab	2.7	abc		1.7	2.0	a	2.5	1.9	a	3.0	ab	2.3
Mean	2.1		2.4		1.3	1.5	1.9		2.4	1.7		2.7		2.0
P-value	<0.0001		<0.0001		0.1320	0.0599	0.0352		0.1287	<0.0001		<0.0001		

[z] Least square mean values within columns with the same letter are not significantly different according to the Tukey-Kramer test at P=0.05.

ment of cooperators to prune trees when they reach their allotted space of 2 m (to prevent encroachment on adjacent trees). Therefore, both tree height and width data must be interpreted cautiously, as it is clear some cooperators restricted canopy spread more than others. Due to high tree vigor, in several locations, tree width exceeded 1.52 m on several rootstocks by the fifth leaf. This was most apparent, but not exclusive to G.30, V.5, and V6 rootstocks; however, it depended on location, early cropping and pruning practices. Excessive pruning of the canopy will lead to losses in productivity because of an imbalance in reproductive growth. Renewal pruning is an important practice to reduce excessive vigor and promote sustainable long-term yields.

Rootstock Suckers. Quantity of cumulative root suckers (CRS) (2015-18) was influenced by location and rootstock, and the interaction of the two factors was significant ($P<0.0001$) (Table 6). CRS were significantly affected by rootstock in all but one location. Pooled across rootstocks, there were fewest CRS in GA and ON and the most CRS (> 3 cumulative suckers per tree) in AL, SC, and UT. Pooled over all locations, the most CRS were observed for all the Vineland rootstocks (> 4 cumulative suckers per tree) and the least for G.11, B.10, and M.26 EMLA. Rootstock had a significant effect on CRS in AL, GA, ID, NJ, ON, SC, and UT. CRS for some rootstocks ranged widely depending on location. For example, for V.1 rootstock, there was 1 CRS in GA, while in SC there were 14 CRS for V.1. Although there were significant rootstock effects on CRS, the average quantity of CRS in this study was relatively low. The strong rootstock by location interaction on suckers observed in this trial also has been observed in previous NC-140 trials (Marini et al., 2006a). The amount of variation in rootstock suckers is related to tree vigor and was observed in other NC-140 studies (Autio et al., 2020; Marini and Fazio, 2018). Other factors such as graft compatibility, soil type, environmental conditions, and orchard management likely explain some of this variation, but further research is needed to explain these factors specifically. Rootstock suckers are undesirable in the orchard as they can act as an infection site for fire blight (Marini and Fazio, 2018), and harbor pests like woolly apple aphid (Johnson et al., 2020). If suckers are profuse, they can also interfere with in-row weed management and can absorb systemic herbicides such as glyphosate, potentially injuring the tree (Johnson et al., 2020).

Cumulative Yield. CY was influenced by location and rootstock, and the interaction of

Table 6. Cumulative rootstock suckers (number) from 'Fuji' trees after five years, as influenced by rootstock and location[z]

Rootstock	AL		GA		ID		NJ		ON		PA	SC		UT		Mean
B.10	1	cd	0	a	1	a			1	ab		1	b	1	bcd	1
G.11	0	d	1	a	0	a	1	a	0	b		0	b	0	d	0
G.214	3	bcd	0	a	4	a	0	a	1	ab	1	5	b	4	a-d	2
G.30	9	ab	1	a	2	a	1	a	2	ab		7	ab	2	bcd	4
G.41	1	cd	0	a	3	a			2	ab		3	b	2	bcd	2
G.935	2	bcd	0	a	1	a	0	a	0	b		7	ab	0	d	2
G.969	2	cd	0	a	5	a						1	b	4	a-d	3
M.26 EMLA	1	cd	1	a	1	a	1	a	0	b	2	1	b	2	bcd	1
M.9 T337	5	a-d	1	a			4	a	1	ab	0	7	ab	9	abc	4
V.1	8	abc	1	a	5	a	5	a			4	14	a	1	cd	5
V.5	12	a	3	a			2	a	1	ab	3	6	ab	11	a	6
V.6	8	abc	3	a			3	a	4	a	5	4	b	6	a-d	5
V.7	11	a	2	a			2	a	3	ab	9	7	ab	9	ab	6
Mean	5		1		3		2		1		3	5		4		3
P-value	<0.0001		0.0263		0.0193		0.0168		0.0120		0.1473	<0.0001		<0.0001		

[z] Least square mean values within columns with the same letter are not significantly different according to the Tukey-Kramer test at P=0.05.

the two factors was significant (P<0.001) (Table 7; Figure 1). The lowest CYs were observed on M.9-T337, M.26 EMLA, and B.10 and the highest on G.969 and G.30. Locations with high CY included ID, SC, and UT (all exceeding 60 kg tree^{-1} on average) while the lowest CY was observed in ON. At some locations, CY exceeded 80 kg tree^{-1} on G.214, V.5, V.6, V.7, and G.30 rootstocks – even though at other locations CYs were considerably lower for the same rootstock. CY did not increase with tree vigor. On average, M.9-T337 and M.26 EMLA had similar yields (32 and 36 kg tree^{-1}, respectively), and all other rootstocks out-yielded these two standard rootstocks by almost 2-fold. The newer rootstock B.10 offered a slight improvement on CY over M.9-T337, while the Vineland and Geneva rootstocks had CY that exceeded M.9-T337 by 17-58%.

Overall, the strong rootstock by location interaction on CY observed in this trial indicates the importance of testing rootstocks at a regional level. Whether these rootstock differences will continue as the trees mature and continue to grow is unclear. However, it is likely that several rootstocks with high vigor will become less productive as more pruning is required to restrict them to their orchard space. On average, trees on G.969

Table 7. Cumulative yield (2015-2018; kg/tree) of 'Fuji' trees after five years as influenced by rootstock and location[z]

Rootstock	AL		GA		ID		NJ		ON		PA		SC		UT		Mean
B.10	24.3	c	21.2	c	58.8	ab			19.7	ab			44.1	e	52.6	b	36.8
G.11	33.1	abc	36.5	abc	75.4	ab	32.7	abc	17.8	ab			45.0	e	56.3	b	42.4
G.214	30.1	bc	24.1	c	87.0	a	32.0	abc	15.1	ab	52.7	a	60.9	bcd	59.2	b	45.1
G.30	42.7	a	48.5	a	86.7	a	45.5	a	24.6	a			86.8	a	66.0	ab	57.3
G.41	25.0	c	34.5	abc	60.7	ab			24.1	a			48.4	e	64.3	ab	42.8
G.935	33.0	abc	36.1	abc	78.2	ab	44.5	ab	14.5	ab			69.0	abc	59.3	b	47.8
G.969	45.9	a	29.8	bc	74.8	ab							73.4	ab	57.8	b	56.3
M.26 EMLA	23.5	c	28.4	bc	43.3	b	28.7	bc	11.5	b	30.5	b	48.3	e	52.8	b	33.4
M.9 T337	34.1	abc	43.3	ab			27.6	c	20.1	ab	43.6	ab	52.0	de	55.8	b	39.5
V.1	33.0	abc	28.9	bc	71.2	ab	35.1	abc			45.1	ab	60.9	cde	61.9	ab	48.0
V.5	40.6	ab	32.7	bc			27.7	bc	19.6	ab	51.7	a	83.8	ab	62.6	ab	45.5
V.6	42.4	a	36.1	abc			37.5	abc	18.5	ab	53.7	a	88.0	a	59.7	b	48.0
V.7	45.3	a	34.2	abc			34.2	abc	23.6	ab	52.9	a	80.8	ab	79.8	a	50.1
Mean	34.8		33.4		70.7		34.5		19.0		47.2		64.7		60.6		45.6
P-value	0.0025		<0.0001		0.0016		0.0030		0.0122		0.0004		<0.0001		0.0020		

[z] Least square mean values within columns with the same letter are not significantly different according to the Tukey-Kramer test at P=0.05.

were 55% and 79% more productive, respectively, than on M.9 and M26. These data are consistent with other studies where several of the Geneva rootstocks outperformed M.9. These include a study in WA, where Auvil et al. (2011) reported that G.11, G.41, G.935, and G.214 outperformed M.9 in several trials. In a study in northern Italy that compared 'Gala', 'Golden Delicious', and 'Fuji' on semi-dwarfing rootstocks trained to a multi-leader tree system, it was observed that the three cultivars on G.935 and G.969 outyielded M.9-T337 (Dallabetta et al., 2021). The CY data are more indicative of the early yield potential of 'Fuji' on the rootstocks tested in this study rather than the absolute yields that could be obtained at a particular location. This is because tree productivity is influenced by tree nutrient status and environmental and orchard management factors; when these factors are optimized, the full potential of the rootstock will be realized.

Cumulative Yield Efficiency. CYE was calculated using the sum of four years of yield (2015-2018) and TCA in year 4 (2018). This method is used to normalize yields amongst rootstocks that range in tree vigor. In this study, CYE was influenced by location and rootstock, and the interaction of the two factors was significant (P<0.0001) (Tables 8; Figure 1). CYE was significantly affected by rootstock at all locations. Pooled across rootstocks, CYE were lowest in AL, NJ, and ON, and greatest (> 2.5 kg tree^{-1} TCA^{-1}) in ID and SC. Pooled over all locations, CYE was highest for G.214, G.935, and lowest for V.5 and V.6. Averaged over locations, M.26 EMLA had the third lowest CYE, while M.9-T337 had among the highest CYE. Across locations, CYE was highest on G.214 in ID and G.935 in SC. Among other locations, the highest CYE was for M.9 T337 in SC. Rootstocks with the highest CYE had values that ranged widely across locations. For example, the CYE for G.214 was 1.0 kg tree^{-1} TCA^{-1} in ON but 4.1 kg tree^{-1} TCA^{-1} in ID. A five-year study (Dallabetta et al., 2021) reported that 'Fuji' and 'Gala' on G.935 had higher CYE than M.9-T337, whereas, depending on the cultivar, G.969 had CYE that was similar to and sometimes lower than M.9-T337. In the same study, 'Golden Delicious' on M.9-T337 had higher CYE than both G.935 and G.969. In another study, Robinson et al. (2011) observed that yield efficiency of a rootstock was generally inversely related to its vigor. This is consistent with the results in this experiment where CYE decreased in a linear fashion with increasing TCA (data not shown). Overall, our CYE data may not adequately predict relative CYs of mature orchards. This is because once tree canopies fill their allotted space, rootstock effects on yield efficiency are modified differentially by pruning severity (Autio et al., 2017a).

Fruit weight. FW (2015-18) was influ-

Table 8. Cumulative yield efficiency (2015-2018; kg tree^{-1} cm^{-2} TCA 2018) of 'Fuji' trees after five years as influenced by rootstock and location[z]

Rootstock	AL		GA		ID		NJ		ON		PA		SC		UT		Mean
B.10	1.3	ab	1.5	b-e	2.6	bcd			0.8	ab			3.1	abc	1.7	a	1.8
G.11	1.4	ab	2.0	ab	3.7	ab	1.5	abc	1.1	ab			2.5	bc	1.7	a	2.0
G.214	1.7	a	1.6	bcd	4.1	a	2.1	a	1.0	ab	2.3	a	3.8	a	1.9	a	2.3
G.30	1.2	ab	1.4	b-e	2.6	bcd	1.1	bcd	0.9	ab			2.9	abc	1.7	a	1.7
G.41	1.4	ab	1.7	bc	2.8	abcd			1.1	ab			3.2	ab	1.7	a	2.0
G.935	1.7	ab	1.6	bcd	3.6	abc	1.9	a	1.1	a			3.9	a	1.8	a	2.2
G.969	1.5	ab	1.7	bc	2.8	abcd							2.4	bc	1.4	abc	2.0
M.26 EMLA	0.8	b	1.1	cde	1.6	d	1.2	bcd	0.5	b	1.3	b	2.5	bc	1.3	abc	1.3
M.9 T337	1.2	ab	2.6	a			1.7	ab	1.3	a	2.3	a	3.2	abc	1.6	a	2.0
V.1	0.9	b	0.8	e	2.2	cd	0.9	cd			1.7	b	2.5	bc	1.4	abc	1.5
V.5	0.9	ab	1.0	cde			0.6	d	0.9	ab	1.6	b	2.1	c	0.9	bc	1.1
V.6	1.0	ab	0.7	e			0.6	d	0.8	ab	1.5	b	2.2	bc	0.9	c	1.1
V.7	1.0	ab	0.9	de			0.7	d	1.0	ab	1.6	b	2.4	bc	1.5	ab	1.3
Mean	1.2		1.4		2.9		1.2		0.9		1.7		2.8		1.5		1.7
P-value	0.0008		<0.0001		<0.0001		<0.0001		0.0139		<0.0001		<0.0001		<0.0001		

[z] Least square mean values within columns with the same letter are not significantly different according to the Tukey-Kramer test at P=0.05.

Table 9. Fruit weight (g), averaged over all cropping years (2015-2018) for 'Fuji' trees after five years as influenced by rootstock and location[z]

Rootstock	AL	GA		ID	NJ	ON		PA		SC	UT		Mean
B.10	160	149	c	210		183	a			199	196	cd	183
G.11	178	165	abc	227	180	198	a			216	211	bcd	196
G.214	156	153	bc	220	200	171	ab	188	ab	206	209	bcd	188
G.30	158	166	abc	231	208	190	a			211	204	bcd	195
G.41	157	172	ab	219		198	a			205	191	cd	190
G.935	161	158	abc	214	185	144	b			211	189	d	180
G.969	171	149	c	212						210	213	bcd	191
M.26 EMLA	168	170	abc	239	182	206	a	205	a	205	212	bcd	198
M.9 T337	173	165	abc		180	197	a	191	ab	202	200	cd	187
V.1	170	171	ab	233	217			181	b	205	213	bcd	199
V.5	165	174	a		198	181	a	186	ab	203	263	a	196
V.6	171	176	a		209	185	a	182	b	207	240	ab	196
V.7	176	175	a		202	185	a	189	ab	216	230	abc	196
Mean	166	165		223	196	185		189		207	213		192
P-value	0.1664	<0.0001		0.0603	0.0717	<0.0001		0.0276		0.0851	<0.0001		

[z] Least square mean values within columns with the same letter are not significantly different according to the Tukey-Kramer test at P=0.05.

enced by location and rootstock, and the interaction of the two factors was significant ($P<0.0001$) (Table 9). There was a signification rootstock effect on FW in GA, ON, PA, and UT. Pooled across rootstocks, FW ranged from 144 g in ON to 263 g in UT. In general, FW was lowest in AL, GA, ON, and PA, and highest in ID, NJ, SC, and UT. Pooled across locations, trees on V.1 and M.26 EMLA had the highest FW, while trees on G.935, B.10, M.9-T337, and G.214 had the lowest. However, FW ranged widely within several locations, and rootstock effect on FW was quite inconsistent. To minimize biennial bearing and improve fruit quality, co-operators were requested to reduce crop load each year to 5-6 fruits per TCA. Due to circumstances that were beyond the control of the co-operator, in some cases fruit set was light and well below this threshold. This would have led to crop load differences between trees on different rootstocks in the same location and across locations, resulting in differential impact on FW. It is well recognized that crop load has a major effect on fruit size, and return. In previous studies, FW was influenced by crop load, rootstock, and location (Marini and Barden, 2004), therefore, covariance analysis is likely required to properly adjust FW for crop density (Marini et al., 2012a; 2012b). Conducting covariance analysis to adjust and test for rootstock differences in fruit weight based on crop load for each year of the study and the large number of rootstocks and locations is a sizeable undertaking and beyond the scope of this study. These analyses, however, may be investigated in future years of this study.

The ‘Fuji’ data in this study were compared with ‘Honeycrisp’ from a companion study with similar rootstocks and locations and the same planting year (Cline et al., 2021). Findings indicated that ‘Fuji’ tree vigor was 2-fold greater than ‘Honeycrisp’. However, that ranking of rootstock vigor differed for some but not all rootstocks. For example, in the ‘Honeycrisp’ trial, tree size of G.214 was similar to M.26 EMLA, whereas, when ‘Fuji’ was the scion, it was the weakest rootstock in the study – even compared to M.9-T337. This points to the importance of testing different scions when investigation rootstock vigor. In addition, CYs averaged for all locations and rootstocks were ~23 kg $tree^{-1}$ for ‘Honeycrisp’ and ~47 kg $tree^{-1}$ for ‘Fuji’, representing a 2-fold increase for ‘Fuji’. G.30 and G.969 were common amongst these trials and were consistently the highest yielding. Rootstock effect on CY was largely similar amongst these two trials.

In this study, the vigorous scion ‘Fuji’ was evaluated on several newer Geneva and Vineland series rootstocks across eight locations in North America. After five years, there was significant interaction between rootstocks and locations in the metrics used to measure rootstock performance (survival, vigor, suckering, cumulative yield, cumulative yield efficiency, and fruit size). The interaction indicates rootstocks did not perform the same at all locations, which is common. While the pooled rootstock means have been presented for comparative purposes, overgeneralized interpretations must be made with caution. This caveat notwithstanding, the study provides insight on the performance of these rootstocks in the first five years of production. This information will help inform apple producers of the characteristics of these rootstocks. As the mature trees are managed to maintain their orchard space, additional data from the trial will enable better selection for various orchard training systems and planting locations. Rootstock selection can have a profound effect on orchard profitability and return on investment (Dallabetta et al., 2021). Therefore, apple producers should be aware of new and novel rootstock opportunities when establishing a new orchard.

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