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Performance of 'Fuji' Apple Trees on several size-controlling rootstocks in the 2014 NC-140 rootstock trial after eight years

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Additional index words: Abbreviations: TCA - trunk cross-sectional area, CRS – cumulative rootstock suckers, CY – cumulative yield; CYE – cumulative yield efficiency, FW – fruit weight. *Malus domestica* (Borkh.)

Abstract

This study evaluated the performance of 'Aztec Fuji®' grafted onto 14 rootstock genotypes and trained to a tall spindle orchard system. Herein we provide results of the 2014 NC 40 coordinated 'Fuji' trial, established at seven locations in the United States and Canada, eight years after initiation. 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 mortality, trunk cross-sectional area (TCA), tree canopy size, amount of rootstock suckering, yield, and number of fruits were recorded annually. All response variables were influenced by location and rootstock and the interaction of these two factors. By year eight, trees could be distinguished into three rather distinct rootstock vigor classes, as measured by TCA of the rootstock means pooled across all locations: those similar to M.9-T337 (G.935, B.10, G.214, G.11, G.41); those similar to M.26 EMLA (G.969, G.30, V.1); and those more vigorous than M.26 EMLA (V.7, V.5, V.6). Overall, G.935 was 6% smaller in TCA than M.9-T337, B.10, G.214, and G.41 were similar in size to M.9-T337, while G.11 was 3% larger than M.9-T337. G.969 and G.30 were 9% and 11% larger in TCA than M.26 EMLA, respectively, while V.1, V.7, V.5, and V.6 were 12%, 27%, 36%, and 39% larger, respectively than M.26 EMLA. Cumulative yield was not closely associated with tree vigor. All rootstocks out performed M.26 EMLA and M.9-T337 except B.10 and G.41. Averaged over all locations, cumulative yield efficiency (CYE) was greatest for G.935 and G.214. Tree mortality was highest on B.10 and M.9-T337, while suckering was high on M.9-T337, G.30, and G.935, as well as the Vineland rootstocks at some locations. As tree vigor, yield and yield efficiency are related to each scion and rootstock combination, it is necessary to evaluate these characteristics across multiple regions and management practices to identify which rootstocks perform consistently. These results will allow apple producers to make more informed decisions concerning rootstock selection for the tall spindle or similar orchard training systems based upon planting locations with similar growing conditions.

'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 2022, is ranked within the top five on the US Apple Association's list of most popular cultivars (Anonymous, 2023). '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

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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 because the roots are brittle, the rootstock is difficult to propagate in the stoolbed (Auvil et al., 2011), and the rootstock 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). Breeding improved apple rootstocks for resistance to disease remains a research priority.

With the continued adoption of intensive, higher-density supported orchard systems, rootstock selection is increasingly important for the economic viability of the orchard. However, selecting the most appropriate rootstock has become increasingly difficult with the array of choices and the introduction of several new rootstock genotypes which purport greater yields with a range of vigor control, and improved 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 per ha, the need for highly productive rootstocks that range in tree vigor and that can withstand a range of abiotic and biotic stresses has never been greater (Robinson, 2004; Marini and Fazio, 2018). The NC-140 Project is the primary vehicle for 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 at many sites and climates across North America.

The 2014 ‘Fuji’ rootstock trial was established to evaluate relatively new rootstocks from the University of Michurinsk (Russia) (1), Cornell-USDA (USA) (7), and Vineland (Canada) (4) breeding programs. The rootstocks evaluated range in vigor from dwarfing to semi-dwarfing. Budagovsky 10 (formerly Budagovsky 62-396) was developed from a cross of Budagovsky 9 and Budagovsky 13-14, and reportedly produces trees similar in size to M.9-T337 or larger depending on the growing region. B.10 is reportedly very cold hardy, resistant to fire blight and has been of increasing interest to growers. Several Cornell-Geneva rootstocks (G.11, G.202, G.214, G.30, G.41, G.935, and G.969) were tested and were reported to have 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 was: 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, and G.969 (M.7 size) (Fazio, 2018). All Geneva rootstocks are reported to be resistant to fire blight, tolerant to crown and root rot (*Phytophthora sp.*), winter hardy, and have low propensity to suckering and burrknots. In contrast, G.11 and G.935 are susceptible to woolly apple aphid, and G.11 is susceptible to apple replant disease (Fazio et al, 2015). 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 with ‘Gala’ (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 nursery in Simcoe, Ontario (J. Cline, unpublished data).

The objective of this study was to assess

Table 1. Cooperators, locations, and site details in the 2014 NC-140 'Fuji' apple planting

Location	NC-140 Cooperator	Affiliation	Longitude	Latitude	Elevation (m)	Soil type	Planting irrigated
(AL) Clanton, Alabam, USA	E. Coneva	Auburn University	86°40'13"W	32°55'12"N	184	Loam	yes
(ID) Parma, Idaho, USA	E. Fallahi	University of Idaho	116°56'40"W	43°48'5"N	703	Sandy loam	yes
(NJ) Pittstown, New Jersey, USA	W. Cowgill and M. Muehlbauer	Rutgers University	74°57'24"W	40°33'38"N	188	Silt Loam	yes
(ON) Simcoe, Ontario, Canada	J. Cline	University of Guelph	80°16'18"W	42°51'37"N	283	Sandy loam	yes
(PA) Rock Springs, Pennsylvania, USA	R. Crassweller	PennState University	77°57'22"W	40°42'44"N	373	Silt Loam	no
(SC) Seneca, South Carolina, USA	G. Reighard and D. Ouellette	Clemson University	82°52'41"W	34°36'16"N	222	Sandy loam	yes

and compare the performance of several new rootstocks from Cornell-Geneva, and Vineland rootstocks at multiple sites in North America, exposing the rootstocks to diverse climate, soil, and management conditions. Empowering growers to make informed science-based decisions concerning the performance of highly vigorous apple cultivars, such as 'Fuji', grafted on new commercially available rootstocks, will help provide best management practices establishing new orchards.

Material and Methods

'Aztec Fuji®' (DT2 cultivar) (hereon 'Fuji') trees on 14 size-controlling rootstocks were planted at seven locations (Table 1) in the spring of 2014. They were trained to a tall spindle 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). To use uniform trees and tree genetics, 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. Trees were planted in Alabama (AL), Idaho (ID), New Jersey (NJ), Pennsylvania (PA), South Carolina (SC), and Utah (UT), USA and Ontario (ON), Canada (Table 1). Due to a limited supply of some rootstocks, 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 was a completely randomized design with 10 single tree 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 and local management, were first fruited in 2015 or 2016. To prevent biennial bearing, crop load of each tree was hand-thinned to one fruit per cluster, leaving no more than 5-6 fruit per cm2 TCA. Once bearing, the date of full bloom was recorded annually, and in the autumn, root suckers were counted and removed, and tree mortality and harvest date, yield (total fruit weight; FW) and total fruit number per tree were recorded. Crop load per tree was calculated by dividing the total number of fruit by the TCA, and average FW was calculated by dividing total FW by total number of fruit per tree. Cumulative yield (CY) was calculated as the sum of yield from 2015 to 2021. Cumulative yield efficiency (CYE) was calculated using the sum of seven years of yield (2015-2021) divided by TCA in year eight (2021). Because of missing yield data for one or more years, CYE could not be calculated at ID and NJ. This method is used to normalize yields amongst rootstocks that range in tree vigor. Average FW for each rootstock was calculated using the mean FW for each year of cropping (2015 or 2016-2021). Following harvest and prior to pruning in 2021, the height and spread of the canopy was recorded. The biennial bearing index (BBI) was calculated for years three to eight (2016-2021) according to the method of Hoblyn et al. (1936) and Jonkers (1979) (Equation 1).

$$\text{biennial bearing index } (BBI) = \frac{\Sigma(\frac{a}{b})}{c} \text{ [Equation 1]},$$

where a is the difference in yield per tree between two consecutive years, b is the sum of the yield per tree in the two consecutive years, and c is the number of consecutive year pairs. BBI values were calculated from 2016 to 2021. BBI values can range from 0 to 1. A value of 0 indicates annual bearing and a value of 1 indicates that yields are completely biennial and trees are alternate bearing.

Each winter, data were sent to the first 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-Kramer test to separate means with treatments as fixed effects. Data were analyzed for each location separately because of significant rootstock and location interactions and also because only two rootstocks were common to all eight locations. 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, factors beyond the control of the researchers 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 was used to mitigate spring frost damage. In addition, the native soil has a pH of 7.6, which is more alkaline than most NC-140 locations, but similar to, or less alkaline than typical of commercial orchards in UT and elsewhere in the Intermountain West. In the early morning hours of 8 Sept 2020, a severe storm generated downslope winds with gusts measured at 87 km/h on the research farm and 159 km/h gusts measured near the farm. The storm resulted in orchard trellis failure and a loss of approximately half the planting. Trees that did not blow over had significant fruit drop due to the winds.

In AL, approximately 60% of trees were infected by *Botryosphaeria species* in the spring of 2015, making it necessary to cut back diseased branches to healthy tissue. This required severe pruning in some instances, heading the leader, and selecting and training a new one. This management reduced the number of flower buds and influenced CY and annual growth data. In SC, bee activity in 2017 was low, resulting in reduced fruit set. Consistently warm nights (low daily temperatures >20°C) during the ripening period reduced fruit color on Fuji. In PA, it was not possible to irrigate the trees. Prohexadione-calcium (Apogee™) was applied to trees in SC and in AL after year 5 (2018).

Tree Survival. Tree survival at year 8 was influenced by location and rootstock, and the interaction of the two factors was significant (P<0.016) (Table 2). Tree survival was significantly affected by rootstock at only 2 of 8 locations. In AL, tree survival on M.9-T337 was significantly lower than all the other rootstocks except M.26 EMLA, G.214, and B.10, which had intermediate tree survival (P=<0.0001). In SC, tree survival on M.9-T337 (60%) was lower than other rootstocks (ranging from 90-100%) at that location (P=0.0018). Overall, tree survival at year 8 ranged from 66-92% when pooled across all locations. Rootstock tree survival averaged across all locations was highest for V.7 (92%), V.1, G.30, G.11, V.6, V.5 (87-88%), G.214, G.41, G.935, M.26 EMLA, G.969 (80-83%), B.10 (76%) and M.9-T337(66%).

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

Rootstock	AL		ID	NJ	ON	PA	SC		UT	Mean
B.10	60	ab	100		100		100	a	20	76
G.11	100	a	90	90	100		100	a	50	88
G.214	70	ab	100	100	90	100	90	ab	30	83
G.30	100	a	100	100	100		100	a	30	88
G.41	80	a	100		100		100	a	30	82
G.935	90	a	90	100	100		100	a	10	82
G.969	100	a	90				100	a	30	80
M.26 EMLA	70	ab	70	100	100	100	90	ab	30	80
M.9 T337	30	b		89	100	100	60	b	20	66
V.1	100	a	100	100		100	100	a	30	88
V.5	100	a		90	100	100	100	a	30	87
V.6	90	a		100	100	100	90	ab	40	87
V.7	100	a		100	100	100	100	a	50	92
Mean	84		93	97	99	100	95		31	83
P-value	<0.0001		0.1140	0.6196	0.4489		0.0018		0.8734	

[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.

It is noteworthy that in UT, average tree survival was 31% and ranged from 10-50% across all rootstocks. This high tree mortality was not a direct result of rootstock genotype but was directly related to position in the orchard relative to the failed trellis structures in 2020, as discussed above. These data are consistent with another ‘Fuji’ NC-140 trial (Autio et al., 2020b) in that tree survival varied by rootstock and location.

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; Figures 1 and 2). As such, caution must be made when generalizing rootstock vigor without considering location. Pooled over all locations, by year eight, TCA of the rootstock means separated into three rather distinct rootstock classes: those similar to M.9-T337 (G.935, B.10, G.214, G.11, G.41) those similar to M.26 EMLA (G.969, G.30, V.1), and those more vigorous than M.26 EMLA (V.7, V.5, V.6) (Fig. 2). Regardless of rootstock class, tree vigor

Table 3. Growth of 'Fuji' trees, as indicated by trunk cross-sectional area (cm2), after eight years as influenced by rootstock and location[z]

	AL		ID		NJ		ON		PA		SC		UT		Mean
B.10	27.1	d	41.9	cd			46.4	abc			20.5	e	48.6	c	36.9
G.11	42.1	cd	37.4	d	38.0	b	36.3	de			31.2	de	50.3	c	39.2
G.214	35.5	cd	33.6	d	35.7	b	34.2	de	36.3	cd	32.0	de	56.1	c	37.6
G.30	61.6	abc	65.0	a	50.1	ab	48.6	ab			52.8	abcd	63.4	bc	56.9
G.41	28.0	d	38.4	d			40.5	bcd			29.6	de	65.7	bc	40.4
G.935	32.8	d	34.8	d	35.7	b	29.0	e			31.4	de	48.5	bc	35.4
G.969	50.4	bcd	47.0	bcd							60.3	abc	66.8	bc	56.1
M.26 EMLA	60.6	abc	54.2	abc	50.0	ab	54.4	a	40.8	bcd	36.6	cde	63.5	bc	51.5
M.9 T337	28.6	cd			41.5	b	37.2	cde	32.1	d	29.2	de	53.8	c	37.1
V.1	62.5	abc	58.6	ab	51.3	ab			46.7	abcd	44.2	bcd	81.8	abc	57.5
V.5	78.3	a			59.9	a	46.4	abc	50.6	abc	62.2	ab	121.0	a	69.7
V.6	80.2	a			61.4	a	46.9	abc	56.1	a	71.2	a	113.9	a	71.6
V.7	72.7	ab			58.6	a	46.7	abc	54.3	ab	62.8	ab	97.1	ab	65.4
Mean	50.8		45.7		48.2		42.4		45.3		43.4		71.6		50.4
P-value	<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.

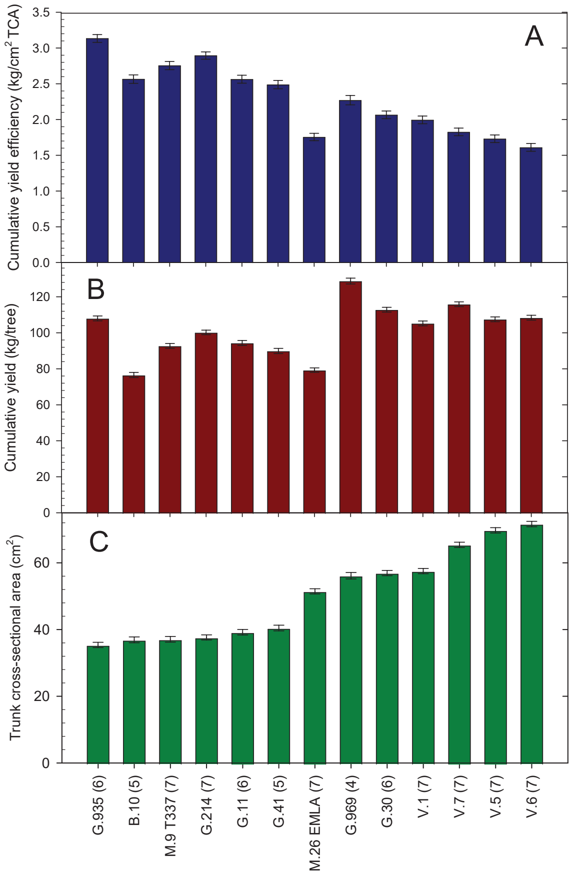

Figure 1. Cumulative yield efficiency (CYE, A), cumulative yield per tree (CY, B), and trunk cross-sectional area (TCA, C) of 'Fuji' trees on thirteen rootstocks. Data sorted by TCA, recorded in 2021 (8 years after planting), and CY and CYE represent yields from 2015-2021. Data represent the least square means (lsmeans) of rootstocks pooled across all planting locations. Numbers in parentheses beside the rootstocks indicate the number of locations at which the rootstock was tested. Error bars represent the standard error of the lsmeans taken from the GLMMIX model analyses.

(represented by TCA) increased linearly over the life of the orchard and did not slow appreciably as trees matured and began to yield more fruit (Fig. 2). In fact, since we last reported on the early performance of this trial (Cline et al, 2021a), annual yields peaked in year 5 and have fluctuated annually since then (data not shown). The lack of increased fruiting after year five and partitioning of photosynthates into reproductive rather than vegetative growth – perhaps because increased canopy shading reduced flowering – may explain why tree vigor has not begun to decrease over time as anticipated. It is also possible that once trees filled their space at year 5, annual yields became relatively stable due to the fact that the canopy volume was maintained by pruning.

Pooled over all locations, G.935 was 6% smaller in TCA than M.9-T337 (Fig. 1). B.10, G.214, and G.41 were similar in size to M.9-T337. G.11 was 3% larger than M.9-

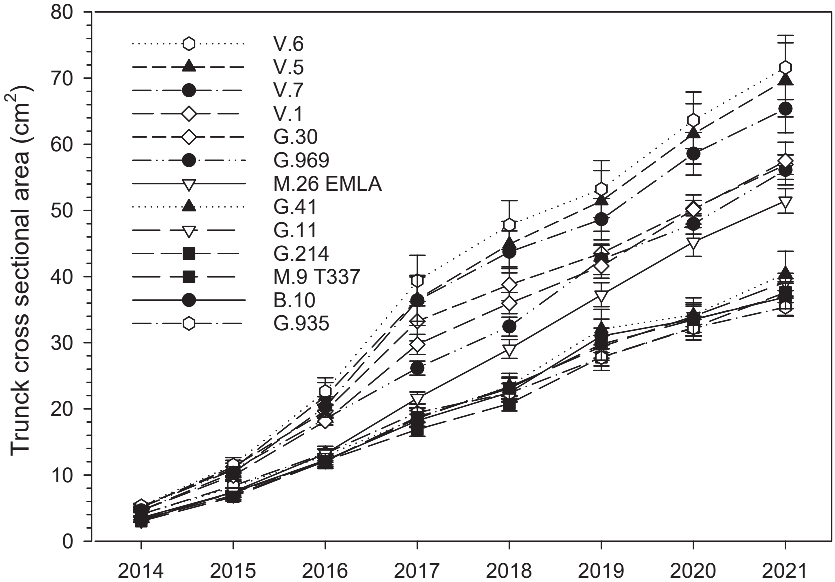

Figure 2. Annual trunk cross-sectional area of 'Fuji' trees on thirteen rootstocks between 2014 and 2021. Data represent the least square means (lsmeans) of rootstocks pooled across all planting locations. Error bars represent the standard error of the lsmeans taken from the GLMMIX model analyses.

T337. G.969 and G.30 were 9% and 11% larger in TCA than M.26 EMLA, respectively, while V.1, V.7, V.5, and V.6 were 12%, 27%, 36%, and 39% larger, respectively than M.26 EMLA. Pooled over all rootstocks, tree vigor was greatest in UT, AL, and NJ, and lowest in 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 PA. Factors that can affect 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 G.11, G.41, and G.935 rootstocks, tree vigor was consistently similar to M.9-T337 (Table 3). These data agree with Fazio (2018), Autio et al. (2020a) and Sherif 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 based on initial five-year data (Cline et al., 2021b). In a 'Fuji' trial after eight years at seven locations, Autio et al. (2020b) found that B.10 and G.214 had TCA values similar to M.9-T337, while G.41 and G.935 were intermediate between M.9-T337 and M.26 EMLA. In a New York study comparing the performance of 'Fuji' on several Geneva rootstocks using two orchard systems (slender axis, tall spindle), Reig et al. (2019, 2020) found that G.11 and G.41 were similar in TCA to M.9-T337 after 10 years. In a study of 'Fuji cv. Rising Sun' in Virginia, G.41 and G.30 had similar tree vigor as M.9-NIC 29 after year 7, whereas G.30 had vigor at a level between that of M.9-Nic 20 and M.26 (Sherif et al, 2020). G.30 has shown high vigor in other studies. These include one in New York (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).

In AL, SC, and UT, where B.10 was included, B.10 was approximately 5-30% smaller than M.9-T337, except in ON where it was 25% 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., 2021b). 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), whereas in a similar trial on 'Fuji', B.10 was slightly larger than M.9-T337 (Autio et al., 2017b). In a multi-location rootstock trial with 'Gala', B.9 was less vigorous in the warmer growing regions compared to cooler locations, and overall B.9 vigor was extremely variable across the 25 study locations (Marini et al., 2006a); this could explain, in part, the wide location variability in B.10, a rootstocks from the same breeding program. In a 'Fuji' rootstock experiment in NY, G.935 conferred vigor similar to M.26 (Robinson et al., 2008). The semi-dwarfing rootstock, G.969, which was previously classified in the M.7 size range (Cummins et al., 2013), was similar to M.26 EMLA at all locations where it was included. Robinson et al. (2014) categorized G.969 as being between M.26 and M.7 in size. A previous study with 'Ginger Gold' in Massachusetts (MA) classified V.1 rootstock in the semi-dwarfing size range, similar to Mark rootstock (Autio and Krupa, 2001). In another study in MA using 'McIntosh' as the scion, V.1 was slightly smaller than M.26 EMLA (Autio et al., 2005). This is the first study evaluating the V.5, V.6, and V.7 genotypes with 'Fuji' apart from a companion study with 'Honeycrisp' (Cline et al., 2021b). In both studies, TCA values of the Vineland rootstocks were 27-40% larger than M.26 EMLA, and consequently are likely too vigorous for use in single-leader modern high-density orchard systems such as the Tall Spindle, especially for a high-vigor cultivar such as 'Fuji'. However, V.5, V.6, and V.7 rootstocks may be beneficial in weaker sites, lower-density planting systems, weaker growing cultivars, or multi-leader training systems where the additional benefits of fire blight and cold hardiness resistance may be realized.

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 except NJ. Pooled across rootstocks,

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

Rootstock	AL		ID		NJ	ON		PA		SC		UT		Mean
B.10	3.5	c	3.5	ab		3.0	b			3.3	d	3.9	a	3.4
G.11	4.0	abc	3.4	ab	2.8	3.4	a			4.2	abc	3.9	a	3.6
G.214	4.1	abc	3.5	ab	2.7	3.2	ab	3.8	ab	4.4	abc	4.0	a	3.6
G.30	4.1	abc	3.9	a	2.7	3.0	b			4.6	a	4.3	a	3.8
G.41	3.8	bc	3.4	ab		3.1	ab			3.6	d	4.3	a	3.6
G.935	3.6	c	3.2	b	2.8	3.2	ab			3.8	cd	3.5	a	3.3
G.969	4.1	abc	3.8	a						4.5	ab	4.3	a	4.2
M.26 EMLA	4.3	ab	3.6	ab	2.6	3.2	ab	3.5	ab	3.8	bcd	3.9	a	3.6
M.9 T337	4.0	abc			2.7	3.2	ab	3.3	b	3.8	bcd	3.7	a	3.5
V.1	4.2	ab	3.8	ab	2.8			3.5	ab	3.9	bcd	4.4	a	3.8
V.5	4.4	a			2.9	3.2	ab	3.8	ab	4.4	ab	4.9	a	3.9
V.6	4.5	a			2.9	3.1	ab	3.9	a	4.5	ab	4.8	a	3.9
V.7	4.5	a			2.6	3.1	ab	3.8	a	4.6	a	4.6	a	3.9
Mean	4.1		3.6		2.7	3.2		3.7		4.1		4.2		3.7
P-value	<0.0001		0.0065		0.5861	0.0267		0.0030		<0.0001		0.0110		

[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 eight years as influenced by rootstock and location[z]

Rootstock	AL		ID		NJ	ON	PA	SC		UT	Mean
B.10	1.7	c	1.8	ab		1.8		1.3	e	2.5	1.8
G.11	2.0	abc	1.6	b	1.5	1.9		1.8	abcd	2.6	1.9
G.214	2.0	abc	1.8	ab	1.5	1.9	2.1	1.8	abcd	2.5	1.9
G.30	2.2	ab	2.1	a	1.6	1.7		2.0	a	2.7	2.1
G.41	1.9	bc	1.7	b		2.0		1.6	cd	2.7	2.0
G.935	1.7	c	1.6	b	1.5	1.9		1.6	cd	2.5	1.8
G.969	2.0	abc	1.6	b				1.9	abc	2.5	2.0
M.26 EMLA	2.1	abc	1.8	ab	1.4	1.9	2.0	1.5	de	2.5	1.9
M.9 T337	1.9	abc			1.5	1.9	2.0	1.7	bcd	2.2	1.9
V.1	2.2	ab	1.9	ab	1.4		2.1	1.7	bcd	2.6	2.0
V.5	2.2	ab			1.6	1.9	2.3	1.9	abc	2.9	2.1
V.6	2.3	a			1.7	1.9	2.3	2.0	ab	3.0	2.2
V.7	2.2	a			1.7	1.9	2.2	2.0	ab	2.9	2.2
Mean	2.0		1.8		1.5	1.9	2.1	1.8		2.6	2.0
P-value	<0.0001		0.0033		0.3259	0.3785	0.0077	<0.0001		0.1808	

[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.

tree height ranged from 3.3 m to 4.2 m and was greatest in UT, AL and SC and lowest in NJ and ON. 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, and on average, trees were 3.7 m by year eight. Pooled across locations, tree height was shortest for G.935, B.10, and M.9-T337 and tallest for G.969, V.6, V.5, and V.7. Early development of the tree canopy and maximization of tree height are important to maximize precocity and yield. With ‘Fuji’ as the scion, rootstocks such as G.30 and the Vineland rootstocks were 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 (1.5 x 4 m) recommended for this system.

Tree width was significantly affected by rootstock in 4 of 7 locations (Table 5) and there was a significant rootstock by location interaction ($P<0.001$). Pooled across rootstocks, tree width was lowest in NJ, ID, SC, and ON (< 2 m) and greatest in AL, PA and UT. Pooled across locations, tree width was smallest on G.935 and B.10 rootstocks and greatest on G.30 and the Vineland rootstocks. B.10 and the Vineland rootstocks had the greatest variability in tree width across locations while M.9 T337, G.935 and G.969 and the least variability in tree width across locations. Rootstock effect on tree width is confounded by the requirement of cooperators to prune trees when they reach their allotted space of 1.5 m to prevent encroachment on adjacent trees. Therefore, both tree height and width data must be interpreted cautiously, as it is clear that some cooperators restricted canopy spread more than others. Because of the high tree vigor of ‘Fuji’, in several locations, tree width exceeded 1.52 m on most rootstocks by the eighth leaf. This was most apparent, but not exclusive to G.41, G.30, V.7, V.5, and V6 rootstocks; however, it depended on location, cropping and pruning practices. Where trees did not set adequately, keeping the canopy width more pendant proved to be particularly difficult. Excessive pruning of the canopy will lead to losses in productivity because of the imbalance in reproductive growth. Renewal pruning is an important practice to reduce excessive vigor and promote sustainable long-term yields.

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

Rootstock	AL		ID		NJ		ON		PA	SC		UT	Mean
B.10	2	bc	2	b			2	b		3	c	3	2
G.11	0	c	0	b	1	b	0	b		1	c	4	1
G.214	6	abc	10	a	1	b	3	b	15	15	bc	16	10
G.30	21	a	5	ab	3	ab	13	ab		33	ab	5	13
G.41	1	bc	4	ab			8	ab		8	bc	3	5
G.935	6	abc	5	ab	1	b	2	b		33	ab	8	9
G.969	4	bc	6	ab						10	bc	4	6
M.26 EMLA	1	bc	1	b	4	ab	1	b	7	2	c	9	4
M.9 T337	9	abc			12	a	12	ab	5	26	abc	25	15
V.1	13	abc	7	ab	9	ab			23	48	a	1	17
V.5	18	ab			3	ab	10	ab	23	34	ab	19	18
V.6	16	ab			7	ab	23	a	19	25	abc	7	16
V.7	21	a			5	ab	14	ab	29	33	ab	22	21
Mean	9		4		5		8		17	21		10	10
P-value	<0.0001		0.0081		0.0037		0.0002		0.2097	<0.0001		0.0616	

[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.

Rootstock Suckers. The number of cumulative root suckers (CRS) (2015-21) 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 two locations. Pooled across rootstocks, GA and ON had the fewest CRS and PA, SC, and UT had the most CRS (> 9 cumulative suckers per tree). Pooled over all locations, the most CRS were observed for all the Vineland rootstocks (> 15 cumulative suckers per tree) and the least for G.11, B.10, M.26, and G.41. Rootstock had a significant effect on CRS in AL, ID, NJ, ON, and SC. CRS for some rootstocks ranged widely depending on location. For example, for V.1 rootstock, there was one CRS in UT, while in SC there were 48. Although there were significant rootstock effects on CRS, the average quantity of CRS was relatively low for G.11, B.10, M.26 EMLA, G.41, and G.969 across all locations. 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., 2020a 2020b; 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 unable to be calculated from ID and NJ because one or more years of yield data were missing. CY for the remaining five locations was influenced by location and rootstock, and the interaction of the two factors was significant (P<0.001) (Table 7; Fig. 1 and 3). The lowest CYs were observed on B.10 and M.26 EMLA, and the highest on G.969, G.30, and V.7 (Fig. 3). Locations with high CY (where data were available) included SC and UT (exceeding 114 kg per tree on average) while the lowest CY was observed in ON. At some locations, CY exceeded 160 kg per tree on G.30, G.935, G.969, V.5, and V.6 rootstocks, even though at other locations CYs were

Table 7. Cumulative yield (2015-2021; kg/tree) of 'Fuji' trees after eight years as influenced by rootstock and location[z]

Rootstock	AL		ID[y]	NJ[y]	ON	PA		SC		UT		Mean
B.10	64.1	b			62.8			93.8	d	85.5	ab	76.5
G.11	89.2	ab			66.9			108.5	d	112.8	ab	94.3
G.214	86.5	ab			61.8	102.0	a	131.5	bcd	119.2	ab	100.2
G.30	104.4	ab			60.0			174.5	a	112.3	ab	112.8
G.41	78.7	ab			69.8			103.4	d	107.8	ab	89.9
G.935	91.4	ab			59.9			119.1	cd	161.6	a	108.0
G.969	111.6	a						166.6	ab	108.0	ab	128.8
M.26 EMLA	87.4	ab			51.9	73.0	b	102.8	d	81.3	b	79.3
M.9 T337	93.4	ab			70.9	92.7	ab	106.3	d	100.5	ab	92.7
V.1	87.3	ab				84.6	ab	123.4	cd	125.5	ab	105.2
V.5	99.9	ab			57.9	98.8	ab	164.5	ab	116.5	ab	107.5
V.6	95.8	ab			61.5	102.5	a	170.6	ab	111.6	ab	108.4
V.7	109.6	a			70.9	96.0	ab	156.9	abc	146.0	a	115.9
Mean	92.3				63.1	92.8		132.4		114.5		101.5
P-value	0.0125				0.1169	0.0146		<0.0001		0.0389		

[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.

[y] Cumulative was unable to be calculated because yield data for one or more years was missing from these locations.

considerably lower for the same rootstock. CY did not increase with tree vigor (data not shown). On average, M.26 EMLA had lower CY than M.9-T337 (79 and 93 kg per tree, respectively) but both were similar to B.10 (77 kg per tree) and G.41 (90 kg per tree). All other rootstocks out performed M.9-T337 by as much as 40%. Comparing early cropping (2015-2018) and 'mature' yields (2019-2021), 44% of fruit were produced

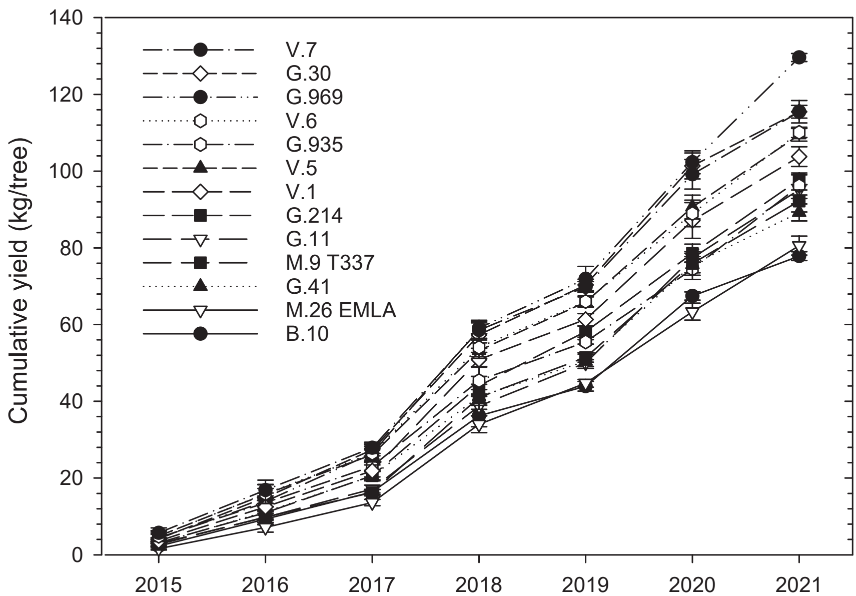

Figure 3. Cumulative yield of 'Fuji' trees on thirteen rootstocks between 2015 and 2021. Data represent the least square means (lsmeans) of rootstocks pooled across all planting locations. Error bars represent the standard error of the lsmean taken from the GLMMIX model analyses.

early while 56% were produced later, with little difference among rootstocks (data not shown). To summarize, the newer rootstock, B.10, had lower CY compared to M.9-T337. Although significant at only SC, the Vineland and Geneva rootstocks (except G.41) had CY that exceeded M.9-T337 by as much as 39%. Overall, the strong rootstock by location interaction on CY observed in this trial indicates the importance of testing rootstocks at a regional level. Since the early performance of these rootstocks reported previously (Cline et al., 2021a), continued differences in CY have been observed as the trees matured. Even the high-vigor rootstocks have remained productive, despite the greater amount of pruning required to restrict them to their orchard space.

On average, trees on G.969 were 39% and 62% more productive, respectively, than on M.9-T337 and M26 EMLA. These data are consistent with other studies where several of the Geneva rootstocks outperformed M.9 clones. 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 studies. In northern Italy where 'Gala', 'Golden Delicious', and 'Fuji' were compared on semi-dwarfing rootstocks trained to a multi-leader tree system, three cultivars on G.935 and G.969 out-yielded M.9-T337 (Dallabetta et al., 2021). However, in a Washington study of "WA38" (Cosmic Crisp®), Anthony et al. (2020) found that G.41 produced similar yields to M.9-Nic29 when grown in a 'V' or 'Spindle' orchard configuration. A Virginia study evaluated 'Fuji cv. Rising Sun' on 10 rootstocks (G.30, G.41, G.935, M.26 common to the present trial). M.26 and G.935 had the highest CY values (after five cropping years) but were statistically similar to those on M.9-Nic 29, G.41, and G.30, despite the wide variation in CY (Sherif et al., 2020). The CY data are more indicative of the yield potential of 'Fuji' on the rootstocks tested in this study than are the absolute yields that could be obtained at a particular location. This is because tree productivity is influenced by a multitude of factors including light intensity and interception, tree nutrition, and orchard environment and management factors. When these factors are optimized collectively, the full potential of the rootstock will be realized.

Cumulative Yield Efficiency. CYE was influenced by location and rootstock, and the interaction of the two factors was significant (P=0.05) (Tables 8; Fig. 1). CYE was significantly affected by rootstock at all locations. Pooled across rootstocks, CYE was lowest in ON and UT, intermediate in AL and PA, and greatest (3.5 kg per tree TCA) in SC. Pooled over all locations, CYE was highest for G.935, G.214, and M.9-T337, and lowest for all Vineland rootstocks and M.26 EMLA. Averaged over locations, M.26 EMLA had the third lowest CYE, while M.9-T337 had the third highest CYE. Across locations, CYE was highest on B.10 in SC, G.214 in SC, and G.935 in SC. Irrespective of rootstock CYE values ranged widely across locations.

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; see Fig. 1 for comparison purposes). In a Virginia study using 'Fuji cv Rising Sun', CYE was similar among G.30, G.41, G.935, and M.26 (Sherif et al., 2020). Past NC-140 trials measured total yields. Future experiments therefore are required to investigate fruit packout, and consequently overall crop value, which incorporate fruit size and color that likely differ among the rootstocks evaluated in this study.

Fruit weight. FW (2015-21) was influenced by location and rootstock, and the interaction

Table 8. Cumulative yield efficiency (2015-2021; kg cm^{-2} TCA 2021) of 'Fuji' trees after eight years as influenced by rootstock and location[z]

Rootstock	AL		ON		PA		SC		UT		Mean
B.10	2.4	abc	1.4	bcd			4.6	a	1.9	abc	2.6
G.11	2.3	abc	1.9	abc			3.8	abcd	2.3	ab	2.6
G.214	2.8	ab	1.9	ab	2.8	a	4.5	ab	2.4	ab	2.9
G.30	1.8	bc	1.3	bcd			3.4	abcd	1.8	abc	2.1
G.41	2.7	ab	1.8	abc			3.8	abcd	1.7	abc	2.5
G.935	2.9	a	2.1	a			4.2	abc	3.3	a	3.1
G.969	2.3	abc					2.9	bcd	1.6	abc	2.3
M.26 EMLA	1.4	c	1.0	d	1.9	b	3.1	abcd	1.4	bc	1.8
M.9 T337	3.3	a	1.9	ab	2.9	a	3.7	abcd	1.9	abc	2.8
V.1	1.5	c			1.9	b	3.1	abcd	1.5	abc	2.0
V.5	1.5	c	1.2	cd	2.0	b	3.0	bcd	1.0	c	1.7
V.6	1.3	c	1.3	bcd	1.9	b	2.6	d	1.0	c	1.6
V.7	1.6	c	1.5	abcd	1.8	b	2.7	cd	1.5	bc	1.8
Mean	2.1		1.6		2.2		3.5		1.8		2.3
P-value	<0.0001		<0.0001		<0.0001		<0.0001		0.0009		

[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.

of the two factors was significant (P<0.0001) (Table 9). There was a significant rootstock effect on FW in AL, ID, SC, and UT. Pooled across rootstocks, average FW ranged from 174 g in AL to 219 g in ID. In general, FW was lowest in AL, ON, and PA, and highest in ID, NJ, SC, and UT. Pooled across locations, trees on G.30, G.11, V.5, V.7, and V.1 had the highest FW, whereas trees on G.935, M.9-T337, G.214, and B.10 had the lowest FW. However, FW ranged widely within several locations, and rootstock effect on FW was inconsistent. To minimize biennial bearing and improve fruit quality, cooperators were requested to reduce crop load each year to 5-6 fruits per cm^2 TCA. Due to circumstances

Table 9. Fruit weight (g), averaged over all cropping years (2015-2021) of 'Fuji' trees after eight years as influenced by rootstock and location[z]

Rootstock	AL		ID		NJ	ON		PA	SC		UT		Mean
B.10	164	b	215	a		200	ab		193	c	200	bc	194
G.11	187	a	223	a	181	203	ab		221	a	206	bc	204
G.214	167	ab	212	a	177	192	ab	168	209	abc	201	bc	190
G.30	175	ab	236	a	191	195	ab		217	ab	207	bc	204
G.41	166	b	219	a		200	ab		199	bc	189	bc	195
G.935	170	ab	203	a	171	177	b		207	abc	187	c	186
G.969	172	ab	204	a					212	abc	208	bc	199
M.26 EMLA	172	ab	220	a	199	200	ab	182	203	abc	210	bc	198
M.9 T337	177	ab			175	206	a	175	201	abc	200	bc	189
V.1	172	ab	237	a	203			176	198	bc	215	bc	200
V.5	175	ab			194	196	ab	179	208	abc	259	a	202
V.6	180	ab			196	196	ab	181	212	abc	228	ab	199
V.7	179	ab			207	189	ab	188	219	a	226	abc	201
Mean	174		219		189	196		178	208		210		197
P-value	0.0211		0.0188		0.1113	0.0651		0.0986	<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.

that were beyond the control of the researchers, 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 within and between locations, resulting in differential impact on FW. It is well recognized that crop load has a major effect on fruit size, and vice versa. In previous studies, FW was influenced by crop load, rootstock, and location (Marini and Barden, 2004). Analyses of covariance is required to properly adjust FW for crop density (Marini et al., 2012a, 2012b), but this analysis was beyond the scope of the current study.

Biennial Bearing Index. BBI (2015-21) was influenced by location and rootstock, and the interaction of the two factors was significant ($P<0.0001$) (Table 10). There was a significant rootstock effect on BBI in ID, NJ, and SC. Pooled across rootstocks, average BBI ranged from 0.35 in SC to 0.72 in UT. Trees in ON and SC had the lowest biennial bearing, as indicated by BBI values <0.5. Trees in UT were very biennial (with the exception of G.935), as indicated by BBI values >0.5 and <=0.94 (M.9-T337). Pooled across locations, trees on G.41, M.26 EMLA, M.9-T337, V.1, and V.7 were the most biennial; however, data must be interpreted with caution since rootstocks performed differently across locations. Furthermore, in addition to rootstock genotype, biennial bearing may be related to differences in annual crop load management practices (fruit thinning) or environmental factors that reduce flowering, such as spring frost injury or the effects of water stress on flower bud initiation.

Summary

In this study, the vigorous scion 'Fuji' was evaluated on several relatively new Geneva and Vineland series rootstocks across eight locations in North America. After eight years, there was significant interaction between rootstocks and locations in the metrics used to measure rootstock performance (survival, vigor, suckering, cumulative yield, CYE, and fruit size). As a result of the interaction, rootstocks did not perform the same at all locations, similar to the results of previous studies. While pooled rootstock means have been presented for comparative pur-

Table 10. Biennial bearing index (BBI), averaged over all cropping years (2015-2021) of 'Fuji' trees after eight years as influenced by rootstock and location[z]

Rootstock	AL	ID		NJ		ON	PA	SC		UT	Mean
B.10	0.51	0.57	ab			0.35		0.25	b	0.82	0.50
G.11	0.52	0.57	ab	0.45	abc	0.38		0.35	ab	0.69	0.49
G.214	0.52	0.44	b	0.43	abc	0.36	0.55	0.28	b	0.59	0.45
G.30	0.50	0.61	ab	0.30	c	0.31		0.34	ab	0.67	0.46
G.41	0.49	0.62	ab			0.33		0.32	ab	0.82	0.52
G.935	0.45	0.51	ab	0.45	abc	0.37		0.50	a	0.44	0.45
G.969	0.49	0.44	ab					0.27	b	0.57	0.44
M.26 EMLA	0.57	0.47	ab	0.59	ab	0.39	0.51	0.30	ab	0.72	0.51
M.9 T337	0.52			0.66	a	0.36	0.53	0.45	ab	0.94	0.58
V.1	0.47	0.68	a	0.31	c		0.52	0.32	ab	0.88	0.53
V.5	0.51			0.40	bc	0.50	0.48	0.37	ab	0.67	0.49
V.6	0.50			0.30	c	0.29	0.55	0.35	ab	0.73	0.46
V.7	0.51			0.39	bc	0.43	0.53	0.40	ab	0.86	0.52
Mean	0.50	0.54		0.43		0.37	0.52	0.35		0.72	0.49
P-value	0.7247	0.0174		<0.0001		0.2034	0.5016	0.0111		0.2586	

[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.

[y] BBI values can range from 0 to 1 where 0 indicates annual bearing and 1 indicates biennial bearing.

Table 11. Summary of the main effects of rootstock characteristics averaged over all trial locations, and location effects averaged over all rootstocks after eight years with 'Fuji' as the scion cultivar.[z] Rootstocks listed in order of tree vigor.

Rootstock/ Location	Tree survival	Vigor (cm^2 TCSA)	Tree height (m)	Tree spread (m)	Cumulative suckers (no/tree)	Cumulative yield (year 2-8) (kg/tree)	Cumulative yield efficiency (year 2-8) (kg/tree/cm2 TCSA)	Average fruit weight (g) (year 2-8)	Biennial bearing index (year 2-8) (0=annual; 1=biennial)	Notable characteristics
Rootstock										
B.10	76	37	3.4	1.8	2.1	77	2.6	194	0.50	Poor tree survival, low vigor (M.9 class), low suckering, and low cumulative yields
G.11	88	39	3.6	1.9	1.0	94	2.6	204	0.49	Low vigor (M.9 class), low suckering, moderate cumulative yields
G.214	83	38	3.6	1.9	9.5	100	2.9	190	0.45	Low vigor (M.9 class), moderate suckering, moderate cumulative yields
G.30	88	57	3.8	2.1	13.3	113	2.1	204	0.46	Moderate vigor (M.26 class), moderate suckering, good cumulative yields, lower cumulative yield efficiency
G.41	82	40	3.6	2.0	4.9	90	2.5	195	0.52	Low vigor (M.9 class), low suckering, low cumulative yields
G.935	82	35	3.3	1.8	9.0	108	3.1	186	0.45	Low vigor (M.9 class), moderate suckering, good cumulative yields, very high cumulative yield efficiency, more annual bearing
G.969	80	56	4.2	2.0	6.0	129	2.3	199	0.44	Moderate vigor (M.26 class), low suckering, very high cumulative yields, moderate cumulative yield efficiency
M.26 EMLA	80	51	3.6	1.9	3.6	79	1.8	198	0.51	Moderate vigor, low suckering, low cumulative yields and very low cumulative yield efficiency
M.9 T337	66	37	3.5	1.9	14.6	93	2.8	189	0.58	Poor tree survival, low vigor, low suckering, moderate cumulative yield, high cumulative yield efficiency, tendency of biennial bearing
V.1	88	58	3.8	2.0	17.1	105	2.0	200	0.53	High vigor, moderate-high sucker, moderate cumulative yield, low cumulative yield efficiency
V.5	87	70	3.9	2.1	17.6	108	1.7	202	0.49	High vigor, moderate-high sucker, moderate cumulative yield, low cumulative yield efficiency.
V.6	87	72	3.9	2.2	16.2	108	1.6	199	0.46	High vigor, moderate-high sucker, moderate cumulative yield, very low cumulative yield efficiency
V.7	92	65	3.9	2.2	20.5	116	1.8	201	0.52	High vigor, moderate-high sucker, moderate cumulative yield, low cumulative yield efficiency
Location										
AL	84	51	4.1	2.0	9.0	92	2.1	174	0.50	Early infection of Botryosphaeria species in the spring of 2015 required severe pruning on some instances, resulting in reduced early yield. Prohexadione-caclium (Apogee™ was not used prior to 2018 for tree vigor control
ID	93	46	3.6	1.8	4.5	–[y]	–	219	0.54	
NJ	97	48	2.7	1.5	4.7	–	–	189	0.43	
ON	99	42	3.2	1.9	7.9	63	1.6	196	0.37	
PA	100	45	3.7	2.1	17.1	93	2.2	178	0.52	Trees not irrigated
SC	95	43	4.1	1.8	20.8	132	3.5	208	0.35	Reduced fruit set in 2017. Difficult to achieve fruit color at harvest in this location because of warm nighttime temperatures. Prohexadone-calcium (Apogee™ was used to help control tree vigor)
UT	31	72	4.2	2.6	9.7	115	1.8	210	0.72	Early crop losses from spring freezes. Alkaline soil. In 2020, trellis failure from high winds.

[z] These summary characteristics need to be interpreted with caution because of the Signiant influence of location on rootstock performance. Orchard location effects can be caused by both environmental factors (soil and climatic factors, and difference in local management that fall outside the experimental protocols.

[y] Cumulative yield and cumulative yield efficiency was unable to be calculated because yield data for one or more years was missing from these locations.

poses, data must be interpreted with caution. Notwithstanding, the study provides insight on the performance of these rootstocks after eight years of production. These rootstock effects have been presented collectively in Table 11 to help illustrate the complexity of this dataset. Taken together with site-specific information, the data will help inform apple producers about the characteristics of these rootstocks grafted on vigorous scion cultivars such as 'Fuji' and their performance using a Tall Spindle orchard system. There are multiple factors to consider when selecting a rootstock; these include: scion, orchard system, tree spacing, tree vigor, and desired resistance to biotic and abiotic stress such as cold hardiness, replant disease, and fire blight. Rootstock selection can have a profound effect on orchard profitability and return on investment (Dallabetta et al., 2021; Gonzalez Nieto et al., 2023). Due to their reported resistance to fire blight and other abiotic and biotic stressors (Fazio, 2018), the Geneva series demonstrates potential as an alternative to the Malling series in North American apple-producing regions. The aim of the NC-140 trials was to provide performance data on new and novel rootstocks and will help growers make evidence-based decisions when establishing new orchards.

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