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Performance of 'Honeycrisp' Apple Trees on Several Size-Controlling Rootstocks in the 2014 NC-140 Rootstock Trial after Ten Years

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Abstract

In 2014, a multi-year orchard experiment of apple *Malus x domestica* (Borkh) was established at 13 locations in Canada, Mexico, and the United States using 'Honeycrisp' as the scion. Seventeen dwarf and semi-dwarf rootstock genotypes were tested, specifically: Budagovsky.10 (B.10), the Cornell-Geneva rootstocks G.11, G.202, G.214, G.30, G.41, G.890, G.935, G.969, the Malling rootstocks M.7, MM.106, 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 purposes. Tree mortality, trunk cross-sectional area, tree canopy size, amount of rootstock suckering, yield, and fruit number were measured annually. All measured parameters were influenced by location and rootstock, and the interaction of these two factors was significant. Overall, after 10 years and averaged over all locations, rootstock vigor separated into three distinct rootstock classes: those similar to M.9-T337 (G.11), those similar to M.26 EMLA (G.935, G.41, B.10, G.214, G.969), and those more vigorous than M.26 EMLA (V.1, G.30, M.7, V.7, MM.106, V.6, G.890, V.5). G.202 performance was unusual and therefore was omitted from data analysis. Cumulative yields were generally greater on trees with the highest vigor. Averaged over all locations, all Geneva, Vineland, and Budagovsky rootstocks had cumulative yields higher than the industry standards M.9-T337 and M.26 EMLA. The newer rootstocks B.10, V.5, V.6, V.7 and all the Geneva rootstocks, had good to excellent cumulative yields. G.890 stood out as having exceptional cumulative yield among all the rootstock genotypes evaluated. Averaged over all locations, cumulative yield efficiency was greatest for M.9-T337 and all the Geneva rootstocks, as well as B.10. Overall, the strong rootstock by location interaction on cumulative yield observed in this trial illustrates the importance of testing rootstocks at a regional level. These results are reflective of orchard vigor and yields after 10 years and provide apple producers with performance indicators to make more informed decisions concerning rootstock selection for their orchard training systems and planting locations using a weak scion cultivar.

Introduction

'Honeycrisp' is a high-value popular apple cultivar that has seen a substantial increase in planting acreage across North America over the past three decades. Currently, 'Honeycrisp' is within the top five most produced apple varieties in the USA with 9.8% of total production (USApple 2025). 'Honeycrisp' is characterized by low vigor, weak growth and biennial bearing (Cline and Gardner 2009; Greene and Weis 2001), a high propensity to bitter pit (Griffith and Einhorn 2022; Valverdi and Kalcsits 2021) and is subject to rootstock effects on fruit maturity and quality (Baldassi et al. 2025). 'Honeycrisp', perhaps more so than most cultivars, requires matching with an appropriate rootstock to optimize fruit quality and long-term orchard productivity. It is also very precocious and if cropped too early, tree growth may be stunted, resulting in incomplete canopy infilling and low orchard productivity (Robinson and Lopez 2010). Furthermore, rootstocks can influence other physiological disorders including leaf zonal chlorosis (Howard et al. 2019) and fruit storage (Greene and Weis 2001).

Over the past two decades clones of M.9 and M.26, the most widely planted apple rootstocks in North America, have been slowly displaced with newer rootstocks that provide size control with enhanced disease resistance. Although M.9 performs well under many conditions and is considered the standard for dwarf rootstocks globally, it is not without production issues. Although this rootstock confers precocity combined with high yield efficiency and is resistant to crown and root rots (Marini and Fazio 2018), it has poor anchorage due to brittle roots, is difficult to propagate in the stoolbed, and is very susceptible to fire blight (*Erwinia amylovora*) and woolly apple aphid (*Eriosoma lanigerum* (Hausman)). In addition, M.9 can produce moderate amounts of root suckers and burrknots and is susceptible to soil replant disease. M.26 is prone to burrknots, is sensitive to fire blight, woolly apple aphid, and crown and root rots, and can form weak graft unions with 'Honeycrisp' as well as other cultivars, resulting in tree breakage if not adequately supported (Cline and Gardner 2009).

There remains a need for highly productive rootstocks that confer a range of levels of tree vigor and that can withstand a range of abiotic and biotic stresses. The NC-140 Regional Research Project (www.nc140.org) is the primary coordinated North American effort to evaluate temperate tree fruit rootstocks from around the world. With the assistance of commercial nurseries, trees on new rootstocks are acquired and propagated for new trials, and scientific project cooperators evaluate these trees for up to a decade, covering many sites and climatic regions across North America.

Several Cornell-Geneva rootstocks (G.11, G.202, G.214, G.30, G.41, G.890, G.935, and G.969) 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 have not been extensively tested with 'Honeycrisp'. The reported order of increasing vigor of the Cornell-Geneva rootstocks as reported by the breeding program, is G.11, G.41 (M.9-T337; 30-40% of standard tree height), G.214 (M.9/M.26 size), G.935, G.202 (M.26 size; 40-50% of standard tree height), G.969, G.30, and G.890 (M.7 size; 50-65% of standard tree height; Fazio et al. 2018; Ferree and Warrington 2003). 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 burrknot development, while G.11 and G.935 are only partially tolerant to woolly apple aphid, and G.11 is susceptible to apple replant disease. Budagovsky 10 (B.10) was developed at the University of Michurinsk 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 growing region. B.10 is cold hardy and resistant to fire blight and has been of increasing interest to North American 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 'Honeycrisp' as the scion. The other Vineland rootstocks in this trial, V.5, V.6, and V.7, have not been tested previously, but were considered dwarfing to semi-dwarfing based on observations made in a nursery at the Simcoe Research Station (J. Cline, pers comm).

An area of increasing scientific interest is the influence of rootstock on scion resistance to abiotic and biotic stresses. With the aid of new metabolomic and molecular tools, there is growing evidence that rootstocks can impart vary degrees of tolerance to drought, heat, and fireblight (Ferree et al. 2002; Zhou et al. 2016) to the scion. Empirically rootstock do not confer complete scion resistance, yet this is a common objective of modern breeding programs (Marini and Fazio 2018).

Performance information for ‘Honeycrisp’ on new commercially available rootstocks is important for producers’ selection of the most suitable rootstock for their locations and orchard systems. Early performance of these rootstocks after five years was reported previously (Cline et al. 2021a). The purpose of this study was to evaluate the performance of ‘Honeycrisp’ grafted on new rootstocks from the University of Michurinsk (Russia), joint Cornell-USDA (USA) and Vineland (Canada) breeding programs over 10 years across a range of environments.

Material and Methods

In spring 2014, ‘Honeycrisp’ trees on 17 size-controlling rootstocks (B.10, G.11, G.202, G.214, G.30, G.41, G.890, G.935, G.969, M.26 EMLA, M.7, M.9-T337, MM.106, V.1, V.5, V.6, and V.7) were planted at 13 locations (Table 1). To evaluate ‘Honeycrisp’ on a sandy, northern site, the larger semi-dwarf Malling rootstocks M.7 and MM.106 were included at Simcoe, ON despite their reputed problems with lower precocity, yield efficiency, higher suckering and burrknot development, among others. Trees were trained to a tall spindle training system (Robinson et al. 2006) and spaced at 1.22 m within row and 3.66 m between rows (2240 trees·ha^{-1}). All trees were propagated at Willow Drive Nursery (Ephrata, WA, USA) and shipped to cooperators in the spring of 2014. At each site, irrigation, fertilization, pest, and disease management protocols followed local guidelines. The experimental design was a completely randomized design with 10 single tree replicates at each location. Not all sites received a full complement of rootstocks because of shortages from the nursery, and V.1 was not certified virus-free, preventing importation by two Ontario (ON) sites. In addition, because G.202 did not grow well at most locations and was atypically more dwarfing than anticipated based on previous studies, it was excluded from analysis.

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, cooperators were asked to adjust the crop load of each tree by hand thinning to one fruit per cluster, leaving no more than 5-6 fruit/cm^2 TCA. Once bearing, the date of full bloom was recorded annually. In the autumn, root suckers were counted and removed; tree mortality, harvest date, yield (total fruit weight; FW), and total fruit number per tree were recorded. Crop density 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 2023. Cumulative yield efficiency (CYE) was calculated by dividing CY by TCA in 2023. If any annual data used to calculate cumulative rootstock suckers (CRS), CY, or CYE were missing, data for the entire tree were excluded from analyses when presenting these metrics. Overall average FW was calculated as the mean of FW for each year of cropping (2015-2023). Following harvest and prior to pruning in 2018 and 2023, the height and spread of the canopy was recorded in both the east-west and north-south direction. Each winter, the data were sent to the senior author for summarization and statistical analysis. 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):

$$biennial\ bearing\ index\ (BBI) = \frac{\Sigma(\frac{a}{b})}{c}$$

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.

Data were analyzed by the GLIMMIX procedure of SAS (version 9.4, SAS Institute, Inc., Cary, NC, USA) 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 high frequency of rootstock and location interaction, each location was analyzed separately. The 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 adjusted by log- or square root-transformation prior to analysis.

Results and Discussion

Tree Survival. Tree survival was influenced by location and rootstock, and the interaction of the two factors was significant (P<0.0001; Table 2). Tree survival was significantly affected by rootstock at only four of the 13 locations. Tree survival was lowest in Mexico (MEX), followed by MI (Michigan), Maine (ME), Minnesota (MN), and New Jersey (NJ). Pooled over all locations, tree survival was highest for B.10 and lowest for G.41 and G.30. However, rootstocks had a significant effect on tree survival only in MI, NJ, and Ontario – Ridgetown (ON-R). In MI, G.935 had the lowest survival (P<0.001) while in NJ, V.5 and V.6 also had the lowest survival (P=0.04). In ON-R, G.11, V.7, G.41, and G.30 had the lowest survival (P<0.0001). In MN, 3% of tree mortality was attributed to breakage at the graft union in the year of planting. In NJ, by the second year, breakage at the graft union accounted for 2.4% of tree mortality (data not shown). In ME, the primary cause of mortality was breakage at the graft union following high winds. Rootstocks did not significantly affect survival at the remaining locations.

TCA. Tree vigor, as indicated by TCA, was influenced by location and rootstock, and the interaction of the two factors was significant (P<0.0001; Table 3; Fig.1). Therefore, generalizations of rootstocks' effects on vigor were difficult to make. Pooled over all locations by year 10, TCA of the rootstock means fell into three somewhat distinct rootstock classes: those similar to M.9-T337 (G.11), those similar to M.26 EMLA (G.935, G.41, B.10, G.214, G.969), and those more vigorous than M.26 EMLA (V.1, G.30, M.7, V.7, MM.106, V.6, G.890, V.5; Figs. 1 and 2). More specifically, G.11 was 5% smaller than M.9-T337 and was the only rootstock in the trial with less vigor than M.9-T337. G.935, G.41, B.10, and G.214 had an intermediate level of vigor between M.9-T337 and M.26 EMLA, which was 12%, 10%, 6%, and 5% smaller, than M.26 EMLA, respectively. G.969, V.1, and G.30 were 6%, 42% and 53% larger than M.26 EMLA, respectively, while V.7, V.6, G.890, and V.5 were the largest of all, ranging from 67-89% larger than M.26 EMLA.

Regardless of rootstock class, tree vigor (based on TCA) increased linearly over the life of the orchard and did not slow appreciably as trees matured and produced more fruit annually (Fig. 2). The one exception was that V.1 showed reduced vigor starting in 2019 (year 5). After 2018, the growth of MM.106 and M.7 increased at a higher rate compared to the other rootstocks (Fig. 2).

Tree vigor of G.11 was consistently low and similar to M.9-T337 at all 12 locations. These data agree with Fazio et al. (2018), Autio et al. (2020), and Cline et al. (2021a 2021b), who classified these rootstocks in the 'dwarfing'

Table 1. Cooperators, locations, soil type and irrigation status of the 2014 NC-140 'Honeycrisp' rootstock trial.

Location	Name	Affiliation	Longitude	Latitude	Elevation (m)	Soil type	Planting irrigated
(CH) Cuauhtémoc, Chihuahua, Mexico	R. Parra-Quezada.	Universidad Autónoma de Chihuahua	106º58’58”W	28º28’32”N	2143	Clay loam	yes
(MA) Blecherton, Massachusetts	J. Clements and W. Autio	University of Massachusetts	72°24'3"W	42°16'37"N	166	Sandy loam	yes
(ME) Monmouth, Maine	R. Moran	University of Maine	70°04'17"W	44°13'57"N	125	Sandy loam	yes
(MI) Traverse City, Michigan	T. Einhorn and G. Lang	Michigan State University	85°40'42"W	44°52'55"N	248	Sandy loam	yes
(MN) Chanhassen, Minnesota	E. Hoover	University of Minnesota	93°36'55"W	44°51'43"N	297	Loam	yes
(NJ) Pittstown, New Jersey	M. Muehlbauer and W. Cowgill	Rutgers University	74°57'24"W	40°33'38"N	188	Silt loam	yes
(NY) Geneva, New York	T. Robinson, J. Lordan, P. Francescatto, L. Gonzalez Nieto	Cornell University	77°01'48"W	42°51'45"N	224	Silt loam	yes
(ON-R) Ridgetown, Ontario	J. Zandstra	University of Guelph	82°05'28"W	42°14’45”N	199	Gravelly loam	yes
(ON-S) Simcoe, Ontario	J. Cline	University of Guelph	80°16'18"W	42°51'37"N	237	Sandy loam	yes
(PA) Rock Springs, Pennsylvania	R. Crassweller, J. Schupp	PennState University	77°57'22"W	40°42'44"N	368	Silt loam	(2014 only)
(VA) Piney River, Virginia	S. Sherif	Virginia Tech	79°1'33"W	37°44'37"N	239	Loam	yes
(WA) Wenatchee, Washington	S. Musacchi and S. Serra	Washington State University	120°03'59.6"W	47°18'35"N	266	Silt loam	yes
(WI) Sturgeon Bay, Wisconsin	M. Stasiak and R. Wiepz	University of Wisconsin	87°20'4"W	44°52'53"N	223	Silt loam	yes

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

Rootstock	MA	ME	MEX	MI		MN	NJ		NY	ON-R		ON-S	PA	VA	WA	WI	Mean
B.10				100	a		100	a	100			100		100		100	100
G.11	100	100	70	90	a	100	100	a	100	50	abc	100		100	100	100	93
G.214	100	89		100	a	80	100	a	100			90		100	100	100	96
G.30	90	90	50	100	a	100	100	a	100	0	c	100		100	100	100	86
G.41	90		70	100	a	100	100	a	90	40	bc	80		100	100	80	86
G.890	100					89			100				100		100	100	98
G.935	100	89		40	b	100	100	a	100	90	ab	90		100	100	100	92
G.969	90	70	80	100	a	100	100	a	100	80	ab	100	100	100	100	100	94
M.26 EMLA	100	100	70	100	a	90	100	a	100	90	ab	100	100	100	100	100	96
M.7												100					100
M.9-T337	100		40	90	a	100	100	a	100	80	ab	100	100	89	100	100	92
MM.106												90					90
V.1	100	100		90	a	100	100	a	90				100	100	100	100	98
V.5	100	100		89	a	89	100	a	100	90	ab	100	100	100	100	100	97
V.6	100		25	89	a	67	78	a	100	100	a	100	100	100	100	100	88
V.7	100	83		100	a	78	88	a	100	50	abc	88	100	100	100	88	89
Mean	98	91	58	91		92	97		99	67		96	100	99	100	98	93
P-value	0.662	0.387	0.180	<0.0001		0.088	0.040		0.584	<0.0001		0.440	NA	0.445	NA	0.058	

[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 'Honeycrisp' trees, as indicated by trunk cross-sectional area (cm^2), after ten years as influenced by rootstock and location[z].

Rootstock	MA		ME		MEX		MI		MN		NJ		NY		ON-R		ON-S		PA		VA		WA		WI		Mean
B.10							11.8	ef			22.5	fg	26.2	ef			31.3	bc			16.0	e			29.4	de	22.9
G.11	15.8	fg	13.2	d	25.9	b	10.6	ef	18.5	ef	19.5	g	17.9	f	18.2	b	22.3	d			17.4	e	14.7	e	20.8	e	17.9
G.214	22.9	def	17.8	cd			16.3	de	18.1	ef	25.9	efg	29.3	ef			29.2	cd			29.1	cd	19.5	e	23.3	e	23.1
G.30	31.4	bc	38.0	a	40.2	a	27.8	ab	26.3	cde	42.2	bc	45.9	cd			39.9	a			36.7	abc	34.8	abcd	45.6	bc	37.2
G.41	20.4	def			25.9	b	13.8	ef	23.9	def	25.4	efg	25.9	ef	18.4	b	23.8	cd			18.9	e	18.3	e	26.9	de	22.0
G.890	39.8	a							41.8	a			60.2	ab					40.4	a			35.0	abcd	53.1	ab	45.1
G.935	18.8	efg	16.8	cd			13.2	ef	18.3	ef	28.7	def	23.9	ef	23.4	b	23.6	cd			21.9	de	19.9	e	27.2	de	21.4
G.969	25.5	cde	22.8	c	22.5	bc	12.6	ef	22.8	ef	37.1	cd	28.9	ef	21.9	b	30.4	c	27.5	bc	33.9	bc	21.0	cde	27.5	de	25.7
M.26 EMLA	20.0	def	17.6	cd	15.2	c	13.9	ef	20.3	ef	33.3	de	32.5	e	29.5	b	38.1	ab	24.0	c	23.6	de	21.4	de	26.8	de	24.3
M.7																	40.1	a									40.1
M.9-T337	11.8	g			18.2	bc	9.5	f	17.4	f	26.0	efg	25.0	ef	17.4	b	25.7	cd	21.2	c	19.9	e	14.6	e	18.5	e	18.8
MM.106																	41.1	a									41.1
V.1	26.6	cd	30.2	b			21.3	cd	31.6	bcd	45.1	bc	37.0	de					43.9	a	39.3	ab	34.3	bcd	36.3	cd	34.6
V.5	35.1	ab	40.7	a			33.0	a	42.2	a	48.4	ab	61.4	a	45.0	a	45.3	a	49.0	a	42.1	ab	48.1	a	60.8	a	45.9
V.6	39.5	a			44.9	a	23.0	bc	37.8	ab	57.7	a	47.4	bcd	45.7	a	44.5	a	52.8	a	42.3	a	38.6	abc	56.2	ab	44.2
V.7	32.6	abc	32.0	ab			27.3	abc	34.9	abc	47.1	b	54.8	abc	46.3	a	43.1	a	39.7	ab	38.8	ab	41.5	ab	48.9	abc	40.6
Mean	26.2		25.5		27.6		18.0		27.2		35.3		36.9		29.5		34.2		37.3		29.2		27.8		35.8		31.5
P-value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<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.

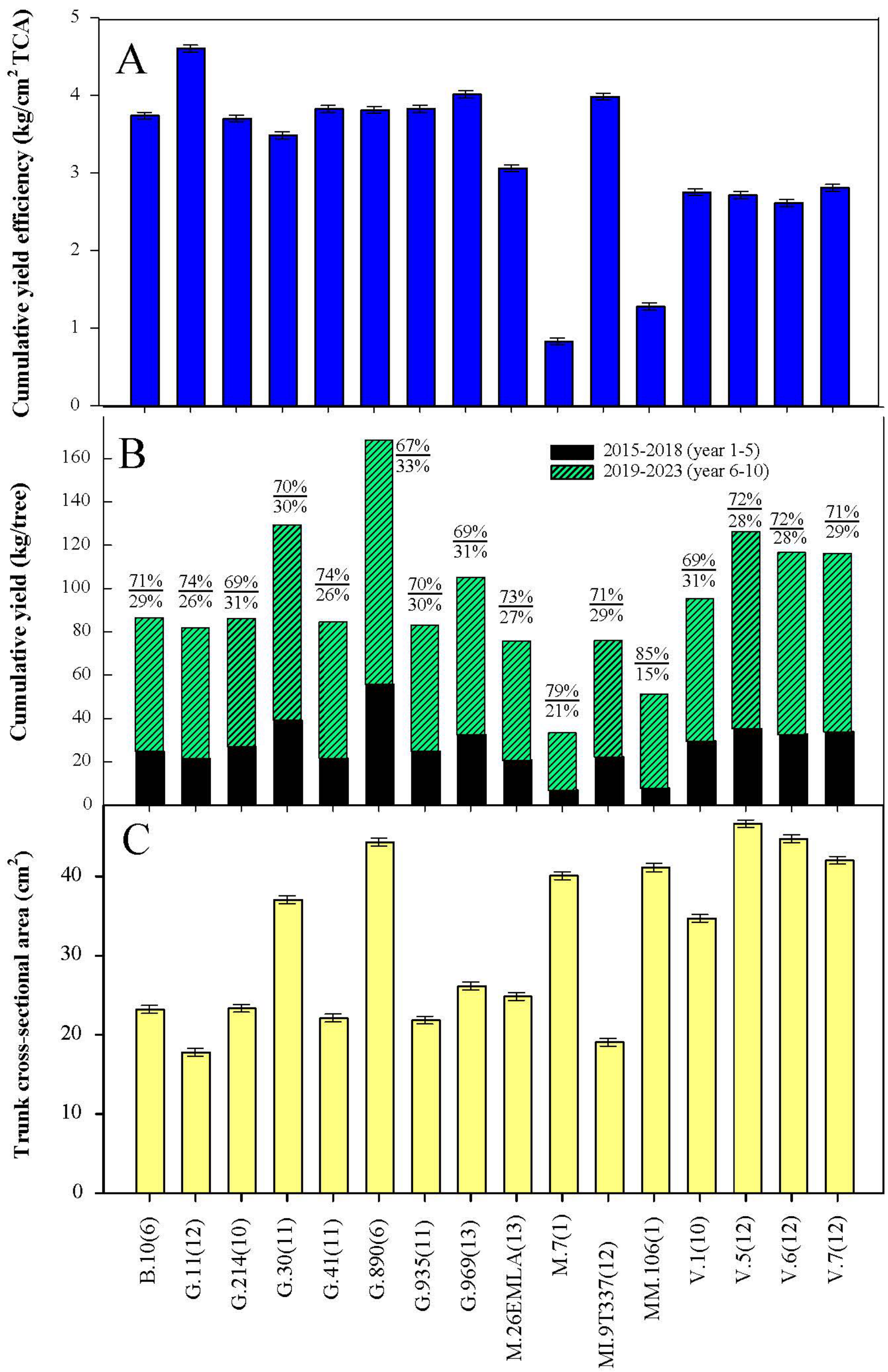

Figure 1. Trunk cross sectional area (TCA, A), cumulative yield per tree (CY, B), and cumulative yield efficiency (CYE, C) of 'Honeycrisp' trees on sixteen rootstocks. TCA was recorded in 2023, 10 years after planting, and CY represents yields from 2015-2018 and 2023, and CYE represent yields from 2015-2023. Data represent the lsmeans of rootstocks pooled across all planting locations. The numbers above the bars in panel B indicate the percent yield in years 6-10 (numerator) and 1-5 (denominator). The number within the brackets beside the rootstock indicates the number of locations at which the rootstock was tested. Error bars represent the standard error of the lsmean taken from the GLMIX mixed model analyses.

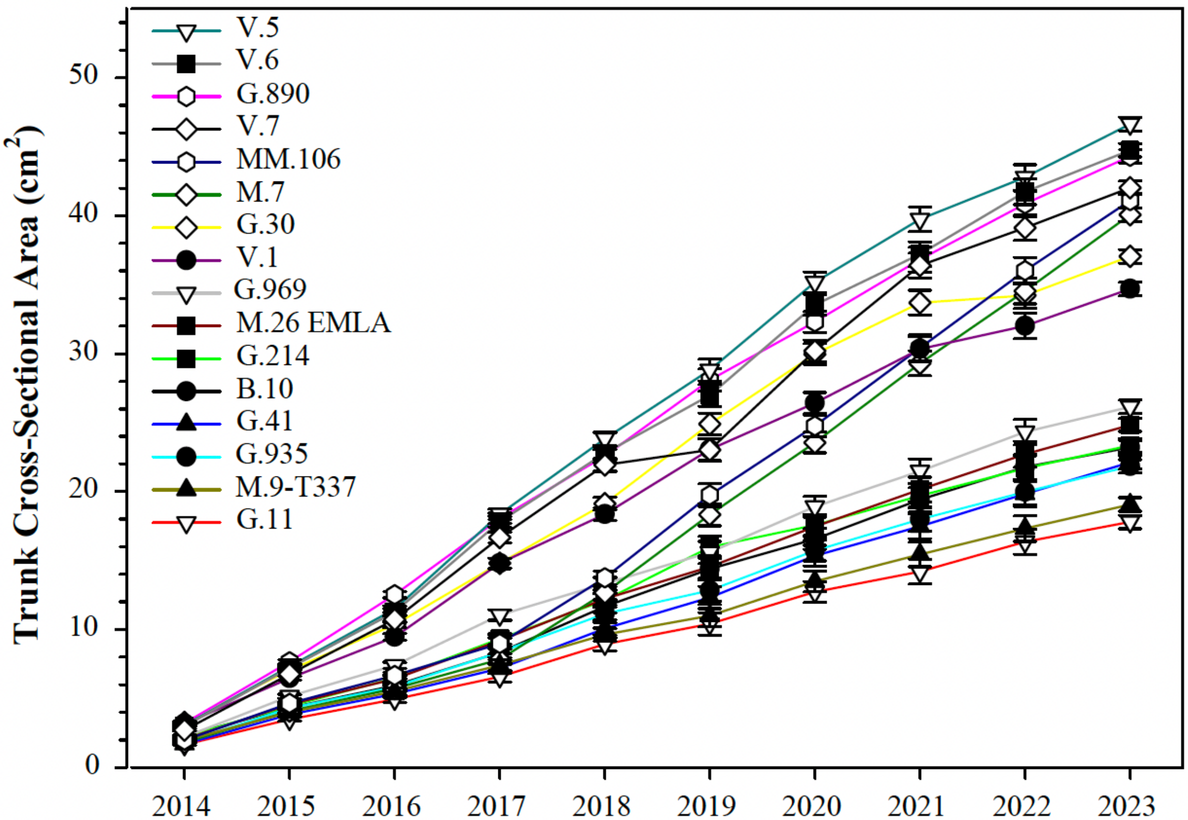

Figure 2. Annual trunk cross-sectional area of 'Honeycrisp' trees on 16 rootstocks between 2014 and 2023. Data represent the least square means (lsmeans) of rootstocks pooled across all planting locations. Error bars represent the standard error of the lsmeans taken from the GLIMMIX model analyses.

category. In a NY study comparing the performance of 'Honeycrisp' on several Geneva rootstocks, Reig et al. (2019) found that G.11 and G.41 were similar in TCA to M.9-T337 after 10 years. Numerous studies (Autio et al. 2011a; Dallabetta et al. 2018b; Lordan et al. 2018; Marini et al. 2014; Robinson et al. 2011) reported that trees on G.41 were similar in size and yield efficiency to comparable trees on M.9. In all locations that tested B.10, it was statistically similar in TCA to M.9-T337 and had intermediate vigor between M.9-T337 and M.26 EMLA. In a 'Honeycrisp' trial, Autio et al. (2020) classified B.10 as a 'moderate dwarf' and the study trees were similar to M.9-T337 and G.11. In a related study using 'Fuji' as the scion, B.10 was also classified as a 'moderate dwarf' with tree vigor similar to M.9-T337, G.11, G. 214, and G.41 (Autio et al. 2020b). In a 'Honeycrisp' rootstock experiment in NY, G.935 conferred vigor similar to M.26 (Robinson et al. 2008), which is consistent with a majority all locations except MI, NY, ON-R, Ontario-Simcoe (ON-S), where G.935 was notably smaller than M.26 EMLA. However, in a study on 'Golden Delicious' (Marini et al. 2014) and Fuji (Cline et al. 2023), G.935 was more similar to M.9. However, it is important to exercise caution when comparing rootstock TCA with industry standards in some circumstances. Indeed, in the present study, M.9-T337 and M.26 EMLA had similar TCA values at most locations, which was unexpected based on other studies.

The similar vigor of G.214 and M.26 EMLA in the present study is consistent with two studies in NY on 'Honeycrisp' (Lordan et al. 2019) and 'Golden Delicious' (Robinson et al. 2011) but differs from another study in the same region that categorized G.214 as a dwarfing rootstock most similar to M.9 (Robinson et al. 2012). Cline et al. (2023) also observed that G.214 was more similar with M.9-T337 with 'Fuji' as the scion.

The semi-dwarfing rootstock G.969 has previously been classified in the M.7 size range (Cummins et al. 2013a). In MA, ME, MEX, MN, NJ, PA, Virginia (VA), and WI, G.969 was consistently larger than M.26 EMLA. However, in MI, NY, ON-R, ON-S, and Washington (WA), G.969 was smaller than M.26 EMLA. Robinson et al. (2014) categorized G.969 between M.26 and M.7 size, while Cline et al. (2023) found G.969 to be more similar to M.26.

Across several studies (Dallabetta et al. 2018a; Lordan et al. 2018; Marini et al. 2014; Robinson et al. 2011), trees on G.11 were similar in size to trees on M.9. Rootstock genotype differences in vigor can be attributed to differences in scion (Lawrence et al. 2025), soil texture and other soil physio-chemical properties, as well as nutrients, canopy management, diseases, and insects (Fazio et al. 2014).

A previous study in MA classified V.1 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). Hampson (2012) found V.1 markedly larger than M.9 and similar in vigor to V.2, but smaller than V.4 with 'Aurora Golden Gala' as the scion. Cline et al. (2023) observed that V.1 was 12% larger than M.26 with 'Fuji' as the scion. 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. 2019; Robinson et al. 2006) and in a NC-140 'Gala' rootstock trial where its size was either similar to or greater than M.26 EMLA (Marini et al. 2006b).

In previous studies, G.890 has been classified in the same size class as M.7 (Cummins et al. 2013b) as well as M.111 (Robinson et al. 2014). In the present study, G.890 was among the largest rootstocks, except in PA. Bradshaw et al. (2023) classified G.890 as a large semi-dwarf rootstock with 'Modi' as the scion cultivar. The present and a companion study (Cline et al. 2021b; 2023) are the first to evaluate V.5 and V.6 genotypes. With 'Fuji' as the scion, after eight years, V.5 and V.6 were 36% and 39% more vigorous than M.26 (Cline et al. 2023) and in the present study, were 89% and 82% more vigorous than M.26 EMLA, respectively. For this reason, in most instances, V.5 and V.6 are likely unsuitable for use in single-leader modern high-density supported orchard systems. However, they may be beneficial in weaker sites for a free-standing or multi-leader training system.

Pooled over all rootstocks, tree vigor was greatest in Pennsylvania (PA), New York (NY), Wisconsin (WI), and NJ, and lowest in MI. The MI site consisted of very sandy soils (Emmet-Leelanau complex) which explains its low vigor in contrast to most other sites that have more vigorous clay loam soils. These data are confounded by the fact that not all sites had the same rootstock, so the data may be skewed by sites with predominately vigorous rootstocks, such as PA. The site characteristics that can affect tree vigor include soil chemical and physical properties, environmental conditions, tree fertility, and whether the site was fumigated prior to planting. However, examining the interaction of these factors with rootstock is beyond the scope of this study.

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 12 locations (data missing for VA). Pooled across rootstocks, tree height was lowest in ME, MEX, MN, and ON-R (all below 3 m) and

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

Rootstock	MA		ME		MEX		MI		MN		NJ		NY		ON-R		ON-S		PA		WA		WI		Mean
B.10							2.6	c			2.7	b	2.8	e			3.3	ab					3.0	de	2.9
G.11	3.5	cd	2.6	c	3.0	ab	3.0	abc	2.5	cd	2.9	ab	3.1	de	2.6	abc	3.3	ab			2.9	cd	3.1	de	3.0
G.214	3.8	abc	2.7	bc			3.1	abc	2.6	bcd	2.9	ab	3.4	abcd			3.4	ab			2.9	cd	3.3	bcde	3.1
G.30	4.0	abc	3.4	a	3.2	a	3.1	a	3.0	ab	3.4	a	3.8	abc			3.6	a			3.4	a	4.0	a	3.5
G.41	3.7	cd			2.7	bc	2.9	abc	2.6	bcd	3.0	ab	3.3	bcde	2.2	c	3.3	ab			3.0	abcd	3.5	abcd	3.0
G.890	4.0	abc							3.1	a			3.9	ab					3.4	ab	3.2	abcd	3.8	ab	3.6
G.935	3.6	cd	2.4	c			3.2	abc	2.5	cd	3.1	ab	3.1	de	2.7	abc	3.2	b			2.9	bcd	3.0	de	3.0
G.969	3.8	bcd	2.7	bc	2.6	c	3.2	a	2.7	abcd	3.0	ab	2.9	de	2.5	bc	3.3	ab	3.3	ab	3.1	abcd	3.3	bcd	3.0
M.26 EMLA	3.2	de	2.4	c	2.3	d	2.8	abc	2.4	d	2.9	ab	3.2	de	2.9	abc	3.2	b	3.0	b	2.9	cd	3.2	cde	2.9
M.7																	3.3	ab							3.3
M.9-T337	2.8	e			2.6	bcd	2.6	bc	2.4	d	2.8	ab	3.0	de	2.3	c	3.2	b	3.3	ab	2.8	d	2.7	e	2.8
MM.106																	3.3	ab							3.3
V.1	3.7	cd	2.7	bc			3.1	ab	2.8	abc	3.3	ab	3.2	cde					3.6	a	3.1	abcd	3.5	abcd	3.2
V.5	4.3	ab	3.1	ab			3.1	a	2.8	abc	3.0	ab	3.9	a	3.2	ab	3.2	b	3.7	a	3.3	ab	3.9	a	3.4
V.6	4.4	a			3.2	ab	3.1	abc	2.9	abc	3.2	ab	3.8	abc	3.3	a	3.3	ab	3.6	a	3.2	abcd	3.8	ab	3.4
V.7	4.0	abc	2.8	bc			3.1	ab	2.8	abcd	3.1	ab	3.8	ab	3.1	abc	3.4	ab	3.7	a	3.3	abc	3.8	abc	3.4
Mean	3.8		2.7		2.8		3.0		2.7		3.0		3.4		2.8		3.3		3.4		3.1		3.4		3.2
P-value	<0.0001		<0.0001		<0.0001		0.0002		<0.0001		0.0164		<0.0001		<0.0001		0.0011		0.0029		<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. Some Lsmeans share the same letter with different letters due to rounding to 1 decimal.

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

Rootstock	MA		ME		MEX		MI		MN		NJ		NY		ON-R		ON-S		PA		WA		WI		Mean
B.10							1.2	de			1.5	b	1.5	bcde			1.5	bc					2.1	bcd	1.55
G.11	1.7	abc	1.4	c	1.2	ab	1.2	cde	2.1	cdef	1.6	ab	1.5	e	1.5	abcd	1.5	bc			1.2	e	1.8	d	1.52
G.214	1.9	abc	1.7	bc			1.4	abcd	2.1	cdef	1.7	ab	1.6	abcde			1.5	c			1.3	de	1.9	d	1.66
G.30	1.9	abc	2.2	a	1.4	a	1.6	ab	2.4	ab	1.8	a	1.8	abc			1.7	ab			1.9	abc	2.3	abc	1.89
G.41	1.6	cd			1.2	bc	1.2	cde	2.2	bcde	1.7	ab	1.6	abcde	1.3	bcd	1.5	c			1.5	cde	2.0	bcd	1.58
G.890	1.8	abc							2.6	a			1.8	a					1.9	bcd	1.5	bcd	2.3	ab	1.99
G.935	1.6	cd	1.4	c			1.3	bcde	1.9	ef	1.7	ab	1.5	cde	1.3	cd	1.5	c			1.2	de	1.9	cd	1.54
G.969	1.8	abc	1.6	bc	1.1	bc	1.3	cde	2.0	def	1.7	ab	1.6	abcde	1.3	cd	1.6	abc	1.7	cde	1.4	cde	2.0	bcd	1.60
M.26 EMLA	1.7	bcd	1.3	c	1.0	c	1.2	cde	1.8	f	1.7	ab	1.5	bcde	1.4	bcd	1.6	abc	1.5	e	1.3	de	1.9	d	1.49
M.7																	1.8	a							1.76
M.9-T337	1.3	d			1.1	bc	1.0	e	1.8	f	1.7	ab	1.5	de	1.1	d	1.5	c	1.7	de	1.1	e	1.8	d	1.42
MM.106																	1.6	abc							1.64
V.1	1.8	abc	1.9	ab			1.4	abcd	2.4	abc	1.7	ab	1.6	abcde					2.0	abc	1.6	bcd	2.2	abcd	1.85
V.5	2.0	ab	1.9	ab			1.6	a	2.5	ab	1.8	a	1.8	a	1.7	ab	1.7	abc	2.2	ab	1.9	a	2.3	ab	1.95
V.6	2.0	a			1.3	ab	1.5	abc	2.6	a	1.8	a	1.8	abcd	1.8	a	1.7	abc	2.3	a	1.9	ab	2.5	a	1.92
V.7	2.0	abc	1.6	bc			1.6	ab	2.3	abcd	1.8	a	1.8	ab	1.6	abc	1.7	abc	1.9	bcd	1.8	abc	2.3	abc	1.85
Mean	1.8		1.6		1.2		1.3		2.2		1.7		1.6		1.4		1.6		1.9		1.5		2.1		1.7
P-value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		0.0087		<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. Some Lsmeans share the same letter with different letters due to rounding to 1 decimal.

greatest in MA, NY, PA, and WI. Cooperators were requested to restrict tree height to 3.5 m by pruning, based on the protocol for the tall spindle training system. In several locations, tree height exceeded 3.5 m on several rootstocks by the tenth leaf: these included all rootstocks except M.9-T337, M.26 EMLA, B.10, M.7, and MM.106 (Table 4; n=12). Early development of the tree canopy and maximizing tree height are important to maximize precocity and yield. At select locations with 'Honeycrisp' as the scion, by year five, G.890, V.5, V.7, and G.30 exceeded the maximum height of the tall spindle system and by year 10, this also included G.11, G.935, G.41, G.969, G.214, V.1, and V.6. Tree width was significantly affected by rootstock in all 12 locations (Table 5; n=12). Pooled across rootstocks, tree width was lowest in MEX, MI, and ON-R (≤ 1.4 m) and greatest in MA, NJ, PA, and WI. Rootstock effect on tree width is confounded by the requirement of cooperators to prune trees when they reach their allotted space of 1.2 m (to prevent encroachment on adjacent trees); thus, both tree height and width data must be interpreted cautiously. Moreover, tree width and height were measured in the fall, so the trees had the whole season to grow and exceeded the target width. Because of high tree vigor, in several locations tree width exceeded 1.2 m on several rootstocks by the fifth leaf (G.969, V.6, V.7, and V.5) and tenth leaf (G.11, G.30, G.935, G.969, M.26 EMLA, V.1, V.5, V.6, and V.7); however, it was dependent on location, pruning practices at each location and seasonal growth. When the tree canopy exceeds its allotted space of 1.2 x 3.6 m for the tall spindle, excessive pruning can lead to losses in productivity because of an imbalance in reproductive growth.

Rootstock Suckers. Quantity of cumulative root suckers (CRS; 2015-23) was influenced by location and rootstock, and the interaction of the two factors was significant (P<0.0001; Table 6; n=8). CRS were significantly affected by all eight locations where data were available (five locations either did not record these data or data was missing for one or more years). Pooled across rootstocks, there were the fewest CRS in MEX, MN, NY, ON-S, and the greatest number (>15 suckers per tree on average) in MA, PA, VA, and WI. Although there were significant rootstock effects on CRS in MEX, MN, NY, and ON-S, the overall average amount of rootstock suckering was relatively low (<11 CRS per tree) compared to the other locations.

Pooled over all locations, the most CRS were observed for M.7, G.890, G.214, G.935, and G.30, and the least for MM.106, B.10, G.11, G.41, and M.26 EMLA. For some rootstocks, CRS ranged widely depending on location. For example, for G.30, there were 2.8 cumulative suckers in ON-S, while in MA, there were 82.1 cumulative suckers per tree; both sites are sandy loam soils. In MA, CRS were highest on G.30, G.890, and G.214 (>65 suckers per tree). CRS was highest on G.890 in PA, MA and WI.

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 has been observed in other NC-140 studies (Autio et al. 2020; Marini and Fazio 2018). Marini (2020) concluded that although root sucker production is ultimately controlled by genetics, factors related to the site, such as soil conditions, environmental factors, planting depth or orchard practices also influence the development of root suckers; further research is needed to explain these factors specifically. Rootstock suckers are undesirable in the orchard as they can act as infection sites for fire blight (Marini and Fazio 2018; Racsko 2019), and harbor pests like woolly apple aphid (Johnson et al. 2020). If suckers are profuse, they also can interfere with in-row weed management and can absorb systemic herbicides such as glyphosate, potentially injuring the tree (Johnson et al. 2020).

Table 6. Cumulative number of rootstock suckers (number) of 'Honeycrisp' trees between 2015-2023 as influenced by rootstock and location[z].

Rootstock	MA		MEX		MN		NY		ON-S		PA		VA		WI		Mean
B.10							0.3	bc	1.2	b			4.6	cd	1.7	b	2.0
G.11	8.2	c	0.0	a	2.0	a	0.2	c	0.6	b			0.8	d	6.9	b	2.7
G.214	65.6	a			13.0	a	5.2	bc	9.1	b			42.5	ab	47.3	a	30.5
G.30	82.1	a	4.4	a	3.9	a	5.6	ab	2.8	b			28.1	bcd	16.9	b	20.5
G.41	16.0	c	0.0	a	1.1	a	0.3	bc	5.4	b			9.3	cd	7.4	b	5.6
G.890	80.1	a			16.5	a	10.7	a			169.4	a			55.8	a	66.5
G.935	41.9	b			4.5	a	3.3	bc	1.1	b			63.2	a	22.9	b	22.8
G.969	28.3	bc	3.1	a	3.3	a	0.9	bc	1.5	b	34.2	b	12.5	cd	3.9	b	11.0
M.26 EMLA	23.9	bc	1.0	a	1.4	a	0.6	bc	0.1	b	20.8	b	3.3	cd	9.3	b	7.5
M.7									102.6	a							102.6
M.9-T337	26.2	bc	0.0	a	9.9	a	0.6	bc	1.7	b	61.7	b	32.8	bc	14.3	b	18.4
MM.106									0.0	b							0.0
V.1	14.1	c			2.6	a	1.8	bc			48.2	b	14.4	cd	11.0	b	15.3
V.5	12.6	c			2.1	a	0.2	c	12.3	b	55.0	b	11.3	cd	6.8	b	14.3
V.6	15.1	c	5.0	a	2.2	a	0.8	bc	3.5	b	26.8	b	13.9	cd	5.0	b	9.0
V.7	20.7	bc			3.1	a	2.4	bc	4.1	b	51.4	b	15.1	bcd	4.1	b	14.4
Mean	33.5		1.9		5.1		2.3		10.4		58.4		19.4		15.2		21.5
P-value	<0.0001		0.0248		0.0179		<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. Cumulative number of rootstocks is not reported for ME, MI, NJ, ON-R, and WI because yield data was missing for one or more years between 2015 and 2023.

Table 7. Cumulative yield (2015-2023; kg/tree) of 'Honeycrisp' trees as influenced by rootstock and location[z].

Rootstock	MA	ME	MEX	MI	MN	NY	ON-S	PA	VA	WA	WI	Mean
B.10				51.0 de		122.5 de	85.2 a		58.8 c		111.2 ef	85.8
G.11	79.1 def	64.3 de	113.4 bc	58.4 cde	63.1 cdef	118.3 de	70.4 ab		68.1 c	70.4 d	117.0 ef	82.2
G.214	85.4 cde	74.9 cd		73.8 bcd	53.4 efg	115.2 de	68.7 ab		103.9 a	87.7 d	94.4 f	84.2
G.30	120.2 ab	148.5 a	179.9 a	91.7 ab	83.4 bcd	182.9 ab	55.2 b		101.3 a	144.1 ab	173.3 bc	128.0
G.41	77.6 def		100.6 cd	53.9 cde	64.1 cdef	135.7 cd	72.9 ab		65.6 c	71.1 d	133.0 cdef	86.0
G.890	137.2 a				121.0 a	220.9 a		184.7 a		131.3 abc	226.0 a	170.2
G.935	79.4 def	70.1 cd		49.2 cde	55.8 efg	105.2 de	63.5 b		76.8 bc	84.0 d	126.9 def	79.0
G.969	105.6 bc	89.9 bc	106.8 bc	64.1 bcde	62.3 def	133.4 cd	70.4 ab	147.9 bc	106.2 a	85.2 cd	145.6 bcde	101.6
M.26 EMLA	70.1 ef	45.8 e	73.0 d	48.3 de	38.0 g	117.4 de	55.4 b	84.9 e	72.4 bc	73.1 d	91.0 f	69.9
M.7							33.3 c					33.3
M.9-T337	59.5 f		84.7 cd	37.8 e	43.8 fg	94.5 e	67.9 ab	109.0 de	72.3 bc	73.0 d	91.1 f	73.4
MM.106							51.7 bc					51.7
V.1	77.9 def	71.8 cd		62.4 bcde	64.2 cdef	105.0 de		125.6 cd	93.4 ab	108.8 bcd	118.3 ef	91.9
V.5	98.0 bcd	108.6 b		110.4 a	96.9 ab	193.1 ab	64.1 ab	139.5 bcd	101.2 a	155.9 a	180.2 b	124.8
V.6	108.7 bc		151.8 ab	76.0 bcd	88.7 bc	163.1 bc	61.4 b	163.8 ab	98.1 a	132.2 abc	162.8 bcd	120.7
V.7	99.7 bcd	97.4 b		85.1 abc	73.7 bcde	185.5 ab	72.4 ab	149.0 bc	92.0 ab	145.3 ab	184.4 ab	118.4
Mean	92.2	85.7	115.7	66.3	69.9	142.3	63.8	138.0	85.4	104.8	139.7	93.8
P-value	<0.0001	<0.0001	<0.0001	<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. Cumulative yield is not reported for NJ and ON-R, because yield data was missing for one or more years between 2015 and 2023.

Cumulative Yield. CY was influenced by location and rootstock, and the interaction of the two factors was significant (P<0.001; Table 7; Figs. 1 and 3). The lowest CYs were observed on M.7, MM.106, M.26 EMLA, and M.9-T337, and the highest, by a wide margin on G.890 (Fig. 3). Except for M.7 and MM.106 (which were planted at only one location – ON-S), the lowest yields (pooled across all locations) were observed on M.26 EMLA, M.9-T337, and G.935, and the highest on G.890.

Locations with high yields included MEX, NY, PA, WA, and WI (all exceeding 100 kg/tree). At some locations, CYs exceeded 150 kg tree-1 on V.7, V.6, V.5, G.30, and G.890 rootstocks – even though at other locations, yields were considerably lower for the same rootstock. It is unclear why CYs in WI were the second highest of all locations next to NY. WI is situated more northerly, but this may be offset by the reported high vigor of this site. Generally, CYs were greater on trees with the highest vigor. On average, M.26 EMLA and M.9-T337 had similar yields (69.9 and 73.4 kg/tree, respectively), and 12 of the 14 other rootstocks outperformed these two standard rootstocks - B.10, V.5, V.6, V.7, and all the Geneva rootstocks had CYs that exceeded M.9-T337 and M.26 EMLA.

On average across all locations, trees on G.890, G.30, and V.5 were 132%, 75%, and 70% more productive, respectively, than on M.9-T.337, whereas V.1, G.969, V.7, and V.6 were 25%, 38%, 61%, and 64% more productive, respectively, than M.9-T.337. In addition, G.935, G.11, G.214, B.10, and G.41 were 8%, 12%, 15%, 17% and 17% more productive, respectively, than M.9-T.337. The yields on the latter rootstocks were more consistent across locations than the aforementioned rootstocks, but some, such as B.10, were tested at fewer locations which likely resulted in less variation. These data are

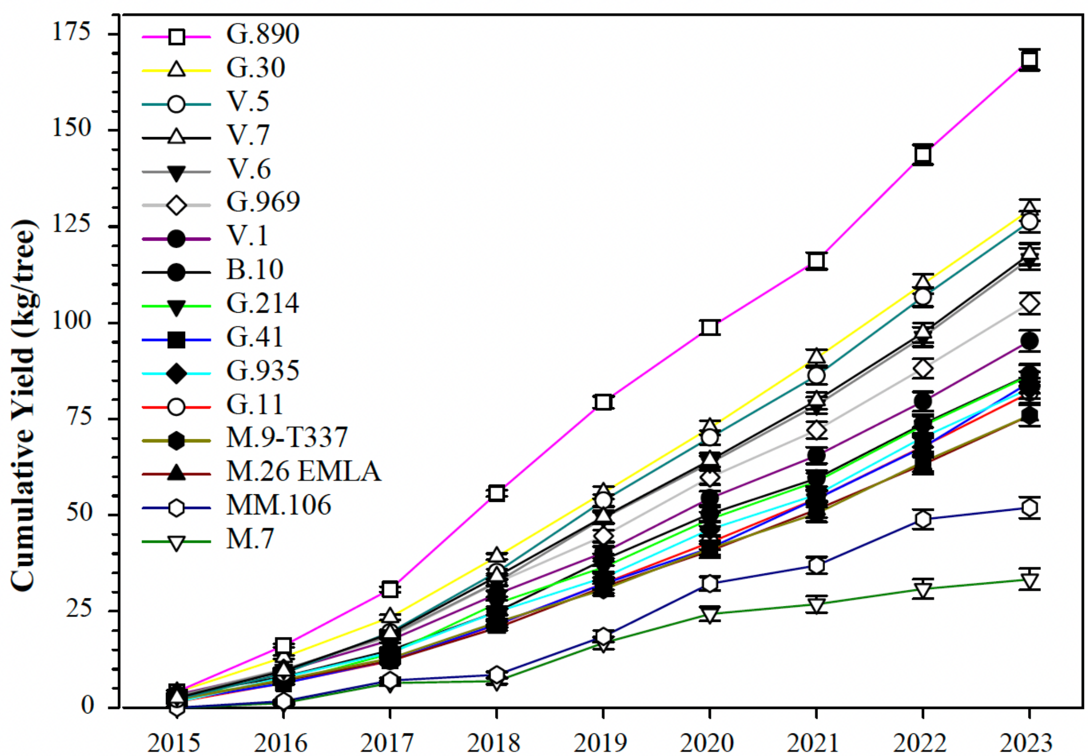

Figure 3. Cumulative yield of 'Honeycrisp' trees on sixteen rootstocks between 2015 and 2023. Data represent the least square means (lsmeans) of rootstocks pooled across all planting locations. Error bars represent the standard error of the lsmean taken from the GLIMMIX model analyses.

consistent with other studies where several of the Geneva rootstocks outperformed M.9 – such as 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 out-yielded M.9-T337 (Dallabetta et al. 2021). In a multi-state trial on 'Fuji' after eight years, all Geneva rootstocks had higher CYs than M.9-T337, M.26 EMLA, and B.10 (Cline et al. 2021b). The CY data are more indicative of yield potential of 'Honeycrisp' 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 achieved.

Overall, the strong rootstock by location interaction on CY indicates the importance of testing rootstocks at a regional level. The same rootstock ranking in CY were observed after five years (Cline et al. 2021a) and have continued consistently year to year as the trees matured. It is interesting that rootstocks with high vigor in their establishment years (years 1-5) continued to be as productive years 5-10 as indicated by their cumulative mature yields (2019-2025; Fig. 4). This was true even though more pruning was required to restrict trees to their allotted orchard space. In fact, across all rootstocks, except M.7 and MM.106, 67-74% of the total CY was obtained in years 2019-2023 (Fig. 1b; data shown as kg/tree and percentage); for the less precocious M.7 and MM.106 rootstocks, 79% and 93% of the total CY was produced after year five (2019-2023).

Cumulative Yield Efficiency. CYE was calculated using the sum of nine years of yield (2015-2023) and the TCA in year 10 (2023). This method is used to normalize yields amongst rootstocks that range in tree vigor. CYE was influenced by location and rootstock, and the interaction of the two factors was significant ($P<0.0001$; Table 8; Fig. 1A). Pooled across rootstocks, CYE was lowest in MN and ON-S and greatest (>3.5 kg/TCA) in MA, ME, MEX, MI, NY, PA, WA, and WI.

CYE was significantly affected by rootstock at all 11 locations where it could be calculated. Pooled over all locations, CYE was highest (≥4.0 kg/cm^2 TCA) for G.935, B.10, G.969, M.9-T337 and G.11 and lowest (<3.0 kg/cm^2 TCA) for M.7, MM.106, V.5, V.1, and V.6. Across locations, CYE was highest on G.11 in NY, on G.41 in WI and NY, and on G.969 in PA and WI. Some rootstocks varied widely in CYE across locations. For example, the CYE for G.969 was 2.3 kg/cm^2 TCA in ON-S but 5.4 kg/cm^2 TCA in PA and WI. 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, Reig et al. (2018) observed that yield efficiency of a rootstock was generally inversely related to its vigor. In contrast to a companion study on 'Fuji' after eight years, many of the same rootstocks were two-fold less yield efficient than the present study, but the rankings were similar (Cline et al. 2021b). Data from the current study after five years indicated that G.935, G.214, M.9-T337, G.11, G.890, and G.969 were the most yield efficient while M.7, MM.106, V.5 and V.6 were least yield efficient (Cline et al. 2021a). After ten years, the CYE of G.890 was lower due to its high vigor, while M.7, MM.106, and all the Vineland rootstocks had the least CYE. When tree canopies fill their allotted space, rootstock effects on yield efficiency are modified differentially by pruning severity (Autio et al. 2017).

Table 8. Cumulative yield efficiency (2015-2023; kg/cm^2 TCA) of 'Honeycrisp' trees as influenced by rootstock and location[z].

Rootstock	MA		ME		MEX	MI		MN		NY		ON-S		PA		VA		WA		WI		Mean
B.10						4.4	abc			5.3	abc	2.8	ab			3.7	ab			3.8	cdefg	4.0
G.11	5.0	a	4.9	a	4.4	5.4	a	3.4	a	6.7	a	3.3	a			4.0	a	4.7	ab	5.6	a	4.7
G.214	3.7	bcd	4.2	b		4.6	ab	3.0	abc	4.0	bcde	2.4	abc			3.6	ab	4.5	abc	4.5	abcdef	3.8
G.30	3.9	bc	3.9	b	4.6	3.4	bc	3.2	ab	4.0	bcde	1.4	d			2.8	bc	4.2	abcde	3.8	cdefg	3.5
G.41	3.8	bcd			3.9	4.0	abc	2.8	abcde	5.4	ab	3.1	ab			3.5	ab	3.9	abcde	5.0	abcd	3.9
G.890	3.5	bcd						3.0	abcd	3.7	bcde			4.9	ab			3.8	bcde	4.3	abcdefg	3.8
G.935	4.2	ab	4.2	b		3.9	abc	3.1	abc	4.6	bcde	2.9	ab			3.7	ab	4.3	abcd	4.7	abcde	4.0
G.969	4.2	ab	4.0	b	4.8	5.1	a	2.8	abcde	4.7	bcd	2.3	bc	5.4	a	3.2	abc	4.2	abcde	5.4	ab	4.2
M.26 EMLA	3.5	bcd	2.6	c	4.8	3.4	bc	1.9	e	3.9	bcde	1.5	cd	3.6	c	3.1	abc	3.6	cde	3.5	defg	3.2
M.7												0.8	d									0.8
M.9-T337	5.0	a			4.8	4.0	abc	2.7	abcde	3.9	bcde	2.8	ab	5.1	ab	3.7	ab	4.9	a	5.0	abc	4.2
MM.106												1.3	d									1.3
V.1	3.0	cd	2.4	c		3.0	c	2.1	de	2.9	e			3.0	c	2.4	c	3.2	e	3.3	efg	2.8
V.5	2.8	d	2.7	c		3.4	bc	2.3	bcde	3.2	de	1.4	cd	3.0	c	2.4	c	3.4	de	3.0	fg	2.8
V.6	2.8	d			3.4	3.3	bc	2.4	bcde	3.6	cde	1.4	d	3.3	c	2.3	c	3.6	cde	3.0	g	2.9
V.7	3.3	bcd	3.1	c		3.1	bc	2.1	cde	3.5	de	1.7	cd	3.9	bc	2.4	c	3.6	cde	3.9	bcdefg	3.1
Mean	3.8		3.6		4.4	3.9		2.7		4.2		2.1		4.0		3.2		4.0		4.2		3.3
P-value	<0.0001		<0.0001		0.0672	<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. Cumulative yield efficiency is not reported for NJ and ON-R, because yield data was missing for one or more years between 2015 and 2023. Some Lsmeans share the same letter with different letters due to rounding to 1 decimal.

Fruit weight. FW (2015-23) was influenced by location and rootstock, and the interaction of the two factors was significant (P<0.0001; Table 9). There was a significant rootstock effect on FW at all locations except MN. Pooled across rootstocks, FW ranged from 119 g in MN to 304 g in MA. Pooled across locations, trees on G.30, V.5, and V.6 had the highest FW, while trees on G.969, G.214, M.9-T337 and G.935, and had the lowest. However, FW ranged widely across several locations, and rootstock effect on FW was very inconsistent. To minimize biennial bearing and improve fruit quality, co-operators were requested to reduce crop load each year to 5-6 fruits cm^2 TCA. Due to circumstances beyond the control of the cooperator, 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. In previous studies, FW was influenced by crop load, rootstock, and location (Marini and Barden 2004; Marini et al. 2014), therefore, covariance analysis is required to properly adjust FW for crop load (Marini et al. 2012a; 2012b). Conducting covariance analysis to adjust and assess for rootstock differences in FW based on crop load for each year of the study and the considerable number of rootstocks and locations is a sizeable undertaking that is beyond the scope of this study.

Biennial Bearing Index (BBI). BBI (2015-23) 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 averaged over 9 years in MA, ME, MEX, NY, VA, and WA. Pooled across rootstocks, average BBI ranged from 0.37 in PA and 0.39 in ME to 0.67 in WA and 0.71 in MN. Trees in ME, PA, NY, ON-S, VA, and WI had the lowest biennial bearing, as indicated by BBI values ≤0.5. Trees in MN and WA were very biennial, as indicated by BBI values >0.60 for several rootstocks.

Pooled across locations, trees on V.1 and V.6 exhibited the strongest biennial habit; 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. ‘Honeycrisp’ is known to be prone to set excessive crop loads in some years leading to alternate bearing the following year (cycle year “on” and year “off”; Campbell and Kalcsits 2024; Embree and Nichols 2005; Hoblyn et al. 1937). For this reason, the chemical thinning targeting the optimized crop load (5-6 fruit/cm^2 TCA) for this variety - and its timing- is crucial to minimize its biennial nature (Dennis 2000; Link 2000; Robinson et al. 2009; Serra et al. 2016).

Summary and Conclusions

This study provides insight on the performance of ‘Honeycrisp’ on several Geneva and Vineland rootstocks after 10 years of production. These rootstock effects have been presented collectively in Table 11 to help illustrate the complexity of this dataset. With site-specific information, the aim of the study was to provide performance data on new and novel rootstocks that will assist growers to make evidence-based decisions when establishing new orchards. There are multiple factors to consider when selecting a rootstock; these include: scion, orchard system, tree spacing, soil properties, 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

Table 9. Fruit weight (g), averaged over all cropping years (2015-2023) for 'Honeycrisp' trees as influenced by rootstock and location[z].

Rootstock	MA		ME		MEX		MI		MN	NY		ON-S		PA		VA		WA		WI		Mean
B.10							182	d		229	abcde	291	abc			166	e			238	abcd	221
G.11	325	a	203	bcd	229	a	207	bcd	120	213	de	303	ab			175	de	192	e	220	bcd	219
G.214	291	abc	185	d			228	abc	110	218	cde	280	abcd			195	abcd	211	bcde	206	d	214
G.30	310	abc	237	a	233	a	251	a	126	244	abc	310	a			193	abcd	236	abc	250	ab	239
G.41	322	ab			215	a	238	ab	120	220	cde	293	abc			182	bcde	202	de	245	abc	226
G.890	327	a							123	252	a			216	ab			234	abc	233	abcd	231
G.935	282	bc	193	cd			220	abcd	117	206	e	252	d			185	abcde	199	e	205	d	207
G.969	281	bc	193	cd	206	a	189	cd	113	203	e	266	cd	188	c	193	abcd	187	e	209	cd	203
M.26 EMLA	296	abc	190	cd	205	a	198	bcd	112	218	cde	300	abc	186	c	181	cde	193	e	256	a	212
M.7												292	abc									292
M.9-T337	275	c			205	a	187	cd	114	221	bcde	272	bcd	184	c	182	cde	196	e	213	cd	205
MM.106												285	abcd									285
V.1	291	abc	209	bc			225	abcd	121	219	cde			201	bc	189	abcd	207	cde	235	abcd	211
V.5	312	abc	227	ab			241	ab	127	249	ab	295	abc	229	a	200	abc	245	a	255	a	238
V.6	326	a			253	a	229	abc	125	231	abcde	294	abc	233	a	204	a	237	ab	244	abc	238
V.7	312	abc	216	abc			237	ab	121	241	abcd	300	abc	224	ab	205	ab	230	abcd	234	abcd	232
Mean	304		206		221		218		119	226		288		208		188		213		232		229
P-value	<0.0001		<0.0001		0.0148		<0.0001		0.1579	<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.

Table 10. Biennial bearing index (BBI), averaged over all cropping years (2016-2023) for 'Honeycrisp' trees after ten years as influenced by rootstock and location[z].

Rootstock	MA		ME		MEX		MI	MN	NJ	NY		ON-S	PA	VA		WA		WI	Mean
B.10							0.62		0.50	0.44	a	0.49		0.48	a			0.44	0.49
G.11	0.51	ab	0.34	bc	0.57	ab	0.56	0.73	0.63	0.52	a	0.49		0.50	a	0.75	ab	0.42	0.52
G.214	0.61	ab	0.42	abc			0.49	0.68	0.47	0.56	a	0.48		0.47	a	0.59	b	0.56	0.52
G.30	0.50	ab	0.32	bc	0.57	ab	0.53	0.60	0.43	0.43	a	0.48		0.50	a	0.61	b	0.50	0.49
G.41	0.51	ab			0.76	a	0.54	0.72	0.52	0.50	a	0.50		0.37	a	0.65	ab	0.53	0.54
G.890	0.46	b						0.73		0.45	a		0.35			0.66	ab	0.49	0.52
G.935	0.57	ab	0.39	abc			0.46	0.67	0.48	0.56	a	0.53		0.49	a	0.67	ab	0.52	0.52
G.969	0.54	ab	0.27	c	0.52	b	0.55	0.64	0.56	0.51	a	0.49	0.31	0.44	a	0.68	ab	0.47	0.48
M.26 EMLA	0.61	ab	0.53	ab	0.43	b	0.60	0.71	0.51	0.44	a	0.51	0.34	0.39	a	0.74	ab	0.49	0.52
M.7												0.62							0.62
M.9-T337	0.67	a			0.50	b	0.44	0.74	0.47	0.55	a	0.46	0.40	0.41	a	0.62	ab	0.59	0.53
MM.106												0.57							0.57
V.1	0.68	a	0.54	a			0.42	0.66	0.56	0.59	a		0.39	0.39	a	0.85	a	0.56	0.56
V.5	0.62	ab	0.34	abc			0.52	0.74	0.52	0.49	a	0.49	0.37	0.46	a	0.57	b	0.48	0.50
V.6	0.63	ab			0.52	ab	0.64	0.81	0.55	0.48	a	0.42	0.39	0.47	a	0.66	ab	0.55	0.55
V.7	0.68	a	0.36	abc			0.63	0.76	0.58	0.51	a	0.41	0.38	0.43	a	0.66	ab	0.45	0.52
Mean	0.58		0.39		0.55		0.54	0.71	0.52	0.50		0.50	0.37	0.45		0.67		0.50	0.53
P-value	0.0003		0.0008		0.0029		0.3252	0.6335	0.5845	0.0226		0.1283	0.233	0.0192		0.0061		0.0573	

[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 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 'Honeycrisp' as the scion cultivar[z].

Rootstock/ Location	Tree survival	Vigor (cm^2 TCSA)	Tree height (m)	Tree spread (m)	Cumulative suckers (no/tree)	Cumulative yield (year 2-10) (kg/tree)[y]	Cumulative yield efficiency (year 2-8) (kg/tree/cm^2 TCSA)[y]	Average fruit weight (g) (year 2-8)	Biennial bearing index (year 2-8) (0=annual; 1=biennial)	Notable characteristics
Rootstock										
B.10	100	23	2.9	1.6	2	86	4.0	221	0.49	M.26 size category, low suckering, low bienniality
G.11	93	18	3.0	1.5	3	82	4.7	219	0.52	M.9 size category, low suckering
G.214	96	23	3.1	1.7	30	84	3.8	214	0.52	M.26 size category, moderate suckering
G.30	86	37	3.5	1.9	21	128	3.5	239	0.49	MM.106 size category, moderate suckering, low bienniality
G.41	86	22	3.0	1.6	6	86	3.9	226	0.54	M.26 size category, low suckering
G.890	98	45	3.6	2.0	67	170	3.8	231	0.52	MM.106 size category, high suckering, very high productivity
G.935	92	21	3.0	1.5	23	79	4.0	207	0.52	M.26 size category, low productivity
G.969	94	26	3.0	1.6	11	102	4.2	203	0.48	M.26 size category, high productivity, low bienniality
M.26 EMLA	96	24	2.9	1.5	8	70	3.2	212	0.52	M.26 size category, low productivity
M.7	100	40	3.3	1.8	103	33	0.8	292	0.62	High suckering, very low productivity, very low yield efficiency, high bienniality, low productivity
M.9-T337	92	19	2.8	1.4	18	73	4.2	205	0.53	Very low productivity, low suckering, very low yield efficiency, high bienniality
MM.106	90	41	3.3	1.6	0	52	1.3	285	0.57	MM.106 size category,
V.1	98	35	3.2	1.8	15	92	2.8	211	0.56	MM.106 size category, high productivity
V.5	97	46	3.4	1.9	14	125	2.8	238	0.50	MM.106 size category, high productivity
V.6	88	44	3.4	1.9	9	121	2.9	238	0.55	MM.106 size category, high productivity
V.7	89	41	3.4	1.8	14	118	3.1	232	0.52	

Cont. on following page.

Table 11. Continued.

Rootstock/ Location	Tree survival	Vigor (cm^2 TCSA)	Tree height (m)	Tree spread (m)	Cumulative suckers (no/tree)	Cumulative yield (year 2-10) (kg/tree)[y]	Cumulative yield efficiency (year 2-8) (kg/tree/cm^2 TCSA)[y]	Average fruit weight (g) (year 2-8)	Biennial bearing index (year 2-8) (0=annual; 1=biennial)	Notable characteristics
Location										
MA	98	26	3.8	1.8	33	92	3.8	304	0.58	Tall trees, moderate tree suckers, high fruit weight, moderate bienniality, low suckering
ME	91	25	2.7	1.6	NA[x]	86	3.8	206	0.39	
MEX	58	28	2.8	1.2	2	116	4.4	221	0.55	Low tree survival for some rootstocks
MI	91	18	3.0	1.3	NA	66	3.9	218	0.54	Low suckering
MN	92	27	2.7	2.2	5	70	2.7	119	0.71	High bienniality, low fruit weight
NJ	97	35	3.0	1.7	NA	NA	NA	NA	0.52	High vigor, low suckering
NY	99	37	3.4	1.6	2	142	4.2	226	0.50	High vigor, low suckering, high tree survival
ON-R	67	30	2.8	1.4	NA	NA	NA	NA	NA	Lower tree survival for some rootstocks, low suckering
ON-S	96	34	3.3	1.6	10	64	2.1	288	0.50	Low productivity, large fruit weight
PA	100	37	3.4	1.9	58	138	4.0	208	0.37	Excellent tree survival, high suckering
VA	99	29	NA	NA	19	85	3.2	188	0.45	Low fruit weight
WA	100	28	3.1	1.5	NA	105	4.0	213	0.67	Low suckering, high bienniality
WI	98	36	3.4	2.1	15	140	4.2	232	0.50	Good tree survival, excellent productivity, good fruit size

[z]These summary characteristics need to be interpreted with caution because of the statistically significant 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.

[x]NA represents data not available.

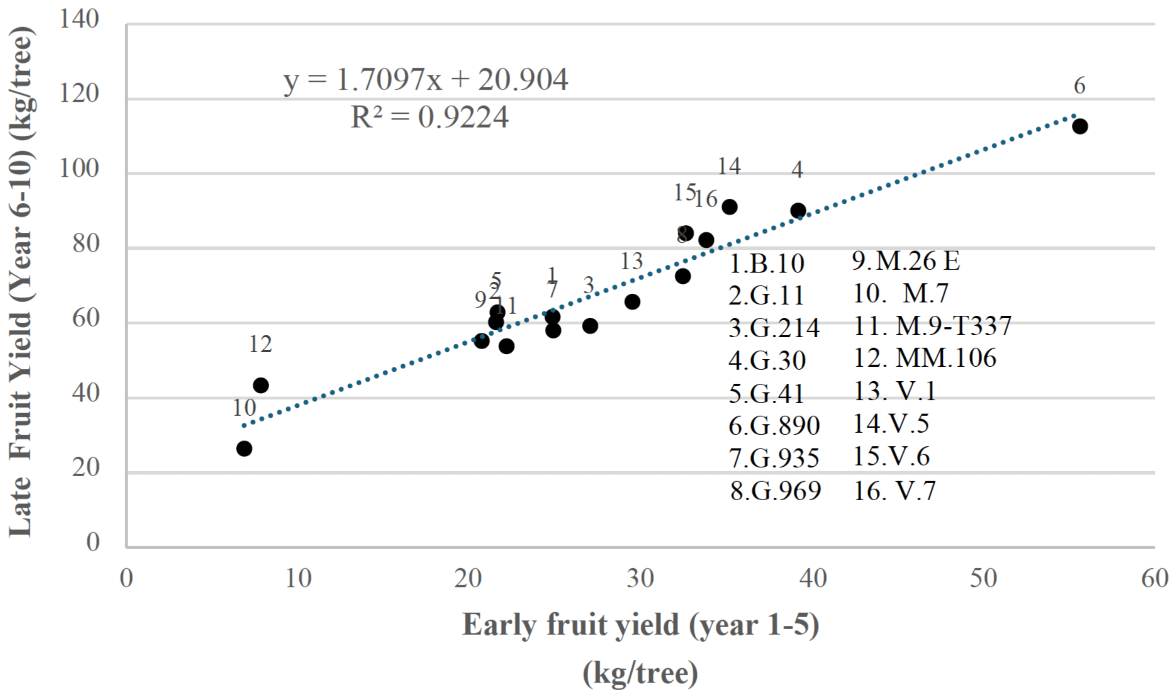

Figure 4. Regression of cumulative yield of Honeycrisp trees (kg/tree) in years 1-5 (2014-2018) vs. years 6-10 (2019-2023) of 'Honeycrisp' trees on 13 rootstocks. Data represent the lsmeans of rootstocks pooled across all planting locations.

resistance to fire blight and other abiotic and biotic stressors (Fazio et al. 2018), the Geneva and Vineland series demonstrates potential as an alternative to the Malling series in North American apple-producing regions.

Pooled over all locations, rootstock vigor separated into three rather distinct rootstock classes: those similar to M.9-T337 (G.11), those similar to M.26 EMLA (G.935, G.41, B.10, G.214, G.969), and those more vigorous than M.26 EMLA (V.1, G.30, M.7, V.7, MM.106, V.6, G.890, V.5). Lawrence et al. (2025) compared rootstocks across five cultivars over 17 years and showed that 'Honeycrisp' is a relatively weak grower on many rootstocks, and that intermediate vigor stocks are more likely to fill the space and provide high long-term yields. In the present study that would include those stocks similar to M.26 or slightly larger. The group that are significantly more vigorous than M.26 is likely too vigorous for sustained yields when trained to the tall spindle training system using 'Honeycrisp'. CYs were greater on trees with the highest vigor. On average, all 12 Geneva, Vineland, and Budagovsky rootstocks tested in this trial had CYs higher than the industry standards M.9-T337 and M.26 EMLA. The newer rootstocks B.10, V.5, V.6, V.7 and all the Geneva rootstocks, had good to excellent CYs. G.890 had exceptional CY and stood out among all the rootstock genotypes evaluated. CYE is also an important metric when considering a rootstock as it provides a measure of yield over several years adjusted for tree vigor. In this study, CYE was highest for M.9-T337 and all the Geneva rootstocks, as well as B.10. Tree vigor, canopy width, and branch size are some of the key factors in determining the suitability of a particular rootstock-scion combination for using the tall spindle orchard system with tree densities ranging from 1,000–1,500 trees/acre (Robinson et al. 2006; Robinson and Hoying 2011). By year five in the present study, G.969, V.6, V.7, and V.5 were particularly vigorous

(Cline et al. 2021a) for tall spindle systems, and by year 10, G.11, G.30, G.935, G.969, M.26 EMLA, V.1, V.5, V.6 and V.7 had become too vigorous for the tall spindle orchard system; however, this depended on location and pruning practices at each location. When the tree canopy exceeds its allotted space of 1.2 x 3.6 m for the tall spindle, excessive pruning can lead to losses in productivity because of an imbalance in reproductive growth.

Rootstock selection can profoundly impact orchard profitability and return on investment (Dallabetta et al. 2021; Gonzalez Nieto et al. 2023). Knowledge of abiotic and biotic stresses, including soil properties (replant disease, Phytophthora root rot, woolly apple aphid, replant disease, soil texture, water holding capacity, fertility, irrigation), location (winter temperature, environmental factors, length of growing season, propensity to sucker), scion cultivar (vigor, fire blight susceptibility), orchard design (training system, tree density, tree height, single vs. multi-leader), and impact on calcium nutrition and bitter pit are all factors that must be considered when selecting a rootstock.

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