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

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Abstract

In 2014, a multi-year orchard experiment of apple *Malus domestica* (Borkh) was established at 14 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 five years and averaged over all locations, G.11 and G.41 were 6% smaller and 5% larger, respectively, than M.9-T337. G.935 and B.10 were 9% and 5% smaller, respectively, than M.26 EMLA, whereas G.214 and G.969 were 3% and 10% larger, respectively. V.1 and G.30 were 52% and 60% larger, respectively, than M.26 EMLA, whereas V.7, G.890, V.6, and V.5 were the largest genotypes in the trial, ranging from 77-95% larger than M.26 EMLA. G.202 performance was unusual and therefore was omitted from data analysis. Generally, cumulative yields per tree were greater on trees with the highest vigor. On average, 10 of the 16 rootstocks produced higher yields than M.9-T337 and M.26 EMLA; the newer rootstocks B.10, V.5, V.6, V.7 and all of the Geneva series rootstocks, with the exception of G.41, had cumulative yields that exceeded M.9-T337 and M.26 EMLA. Averaged over all locations, cumulative yield efficiency was greatest for G.935, G.214, M.9-T337, G.11, G.890, and G.969. 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 only reflective of the orchard establishment years; additional research must be completed before apple producers can make more informed decisions concerning rootstock selection for their orchard training systems and planting locations.

'Honeycrisp' is a high-value popular apple cultivar that has seen a substantial increase in planting acreage across North America over the past two decades. 'Honeycrisp' is characterized by low vigor and weak growth (Cline and Gardner, 2005) and a propensity for the calcium-related disorder bitter pit (Valverdi and Kalcsits, 2021) that requires matching with an appropriate rootstock to optimize fruit quality and long-term orchard productivity. It is also very precocious. If cropped before its canopy fully fills its allotted space, tree growth can be stunted, resulting in 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).

Clones of M.9 and M.26 are the most widely planted apple rootstocks in North America. 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 as well as being 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 trees breaking if not adequately supported (Cline and Gardner, 2009).

There remains a need for highly productive rootstocks that confer a range of tree vigor and can withstand a range of abiotic and biotic stresses. The NC-140 Multistate Research Project is the primary coordinated effort for North American evaluation of 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 project cooperators evaluate these trees for up to 10 years representing many sites and climates across North America.

The 2014 'Honeycrisp' rootstock trial was established to evaluate new rootstocks from the University of Michurinsk (Russia), joint Cornell-USDA (USA) and Vineland (Canada) breeding programs. Several Cornell-Geneva rootstocks (G.11, G.202, G.214, G.30, G.41, G.890, G.935, and G.969) were tested, with varying degrees of size control, productivity, yield efficiency, ease of nursery propagation, fire blight resistance, tolerance to extreme temperatures, and resistance to soil pathogens. The reported order of increasing vigor of the Cornell-Geneva rootstocks tested in this trial, as reported by the breeding program, is G.11, G.41 (M.9-T337 size), G.214 (M.9/M.26 size), G.935, G.202 (M.26 size), G.30, G.890 and G.969 (M.7 size) (Fazio, 2018). All the Geneva rootstocks are reported to be resistant to fire blight, tolerant to crown and root rots (*Phytophthora* sp.), winter hardy, and have low propensity to suckering and burrknot development, while G.11 and G.935 are susceptible 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 reportedly very cold hardy and resistant to fire blight and has been of increasing interest to growers. V.1 from the Vineland program is a semi-dwarfing rootstock with cold hardiness and fire blight resistance (Cline et al., 2001). It was tested in a previous NC-140 trial (Marini et al., 2006a) but has not been tested in a NC-140 study with '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, personal communication). 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.

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. The purpose of this study was to evaluate the performance of 'Honeycrisp' grafted on new apple rootstocks across a range of environments.

Material and Methods

'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 14 locations (Table 1) in the spring of 2014. They 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}).

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	Irrigated ?
(CH) Cuauhtémoc, Chihuahua, Mexico	R. Parra-Quezada.	Universidad Autónoma de Chihuahua	106º58'58"W	28º28'32"N	2143	Clay loam	yes
(ID) Parma, Idaho	E. Fallahi	University of Idaho	116°56'40"W	43°48'5"N	703	Sandy 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, W. Cowgill and R. Magron	Rutgers University	74°57'24"W	40°33'38"N	188	Silt loam	yes
(NY) Geneva, New York	T. Robinson, J. Lordan, and P. Francescatto	Cornell University	77°01'48"W	42°51'45"N	224	Silt loam	yes
(ON-R) Blenheim, 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	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

All trees were propagated at Willow Drive Nursery, Ephrata, WA and shipped to the cooperators in the spring of 2014. At each site, irrigation, fertilization, pest and disease management followed local guidelines. The experimental design was a completely randomized design with 10 replications of single trees 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 much 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, and in the autumn, root suckers were counted and removed, and tree mortality and harvest date, yield (total fruit weight) and total fruit number per tree were recorded. Crop density per tree was calculated by dividing the total number of fruit by the TCA, and average fruit weight (FW) was calculated by dividing total fruit weight by total number of fruit per tree. Cumulative yield was calculated as the sum of yield from 2015 to 2018. Cumulative yield efficiency (CYE) was calculated by dividing cumulative yield by TCA in 2018. Overall average fruit weight was calculated as the mean of FW for each year of cropping (2015-2018). Following harvest and prior to pruning in 2018, the height and spread of the canopy was recorded. Each winter, the data were sent to the senior author for summarization and statistical analysis.

Data were analyzed by the GLIMMIX procedure of SAS (version 9.4, SAS Institute, Inc., Cary, NC) and mean separation performed using Tukey's HSD test to separate means with treatments as fixed effects. The data were initially analyzed with all locations together. However, due to the high frequency of rootstock and location interaction, and missing rootstocks for some locations, each location was analyzed separately. Shapiro-Wilk test was used to test the assumption that the residuals were normally distributed. Scatterplots of studentized residuals were visually observed to test the assumption that the errors were homogeneous. 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

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

Rootstock	ID	MA	ME	MEX	MI	MN		NJ		NY	ON-R	ON-S	PA	VA	WA	WI	Mean
B.10					100			100	a	100		100		100		100	100
G.11		100	100	70	90	100	a[z]	100	a	100	100	100		90	100	100	96
G.214		100	90		100	90	a	100	a	100		100		100	100	100	98
G.30	100	100	90	50	100	100	a	100	a	100	88	100		90	100	100	94
G.41		90		70	90	100	a	100	a	90	90	80		90	100	90	90
G.890		100				89	a			100			100		100	100	98
G.935		100	89		73	100	a	100	a	100	100	90		100	100	100	96
G.969	100	100	70	80	100	100	a	100	a	100	100	100	100	100	100	100	96
M.26 EMLA	100	100	100	78	89	100	a	100	a	100	100	100	100	89	100	100	97
M.7												100					100
M.9-T337		100		40	90	100	a	100	a	100	100	100	100	100	100	100	94
MM.106												90					90
V.1	100	100	100		90	100	a	100	a	90			100	100	100	100	98
V.5		100	100		89	100	a	100	a	100	100	100	100	100	100	100	99
V.6		100		75	89	67	b	78	b	100	100	100	100	100	100	100	92
V.7		100	86		88	78	b	88	ab	100	88	88	100	100	100	87	92
Mean	100	99	92	66	91	94		97		99	97	96	100	97	100	98	96
P-value	NA	0.497	0.350	0.446	0.740	0.015		0.040		0.584	0.545	0.296	NA	0.722	NA	0.415	

of the two factors was significant (P<0.0001) (Table 2). Tree survival was significantly affected by rootstock at only two of the 14 locations. Tree survival was lowest in MEX, followed by MI, ME, MN, and NJ. Pooled over all locations, tree survival was highest for B.10 and lowest for V.6 and V.7. However, rootstocks had a significant effect on tree survival only in MN and NJ. In MN, V.5 and V.6 had the lowest survival (P=0.015). Similarly, in NJ, V.5 and V.6 also had the lowest survival (P=0.04). 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. Since more than five years is required to fully evaluate tree survival (Marini et al., 2006a), these data should be considered preliminary.

TCA. Tree vigor, as indicated by TCA, was influenced by location and rootstock, and the interaction of the two factors was significant (P<0.001) (Table 3; Figure 1). Therefore, generalizations of rootstock's effect on vigor were difficult to make. Pooled over all locations, G.11 and G.41 were 6% smaller and 5% larger than M.9-T337, respectively (Figure 1). G.935 and B.10 were 9% and 5% smaller, respectively, than M.26 EMLA, while G.214 and G.969 were 3% and 10% larger, respectively. V.1 and G.30 were 52% and 60% larger than M.26 EMLA, respectively, while V.7, G.890, V.6, and V.5

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

Rootstock	ID		MA		ME		MEX		MI		MN		NJ		NY		ON-R		ON-S		PA		VA		WA		WI		Mean
B.10									6.2	d			12.5	e	10.4	def			15.8	abc			10.5	ef			13.5	de	11.5
G.11			7.5	ef	7.0	d	10.9	bc	5.3	d	9.4	d	10.7	e	8.3	f	9.2	d	8.2	g			9.9	f	9.5	f	11.8	e	9.0
G.214			11.2	d	9.0	d			7.9	cd	9.9	d	14.4	e	12.5	de			13.4	cde			14.2	de	12.4	ef	15.7	de	12.1
G.30	34.5	a	16.2	c	16.7	a	18.4	a	11.9	b	12.7	cd	25.7	cd	18.8	b	15.4	b	18.1	a			18.5	bc	20.1	a-e	23.3	bc	19.3
G.41			9.6	def			11.2	bc	6.7	d	10.9	d	12.8	e	9.8	def	8.2	d	9.0	efg			9.5	f	9.9	f	12.8	e	10.0
G.890			21.2	a							22.0	a			23.7	a					23.1	b			20.3	a-d	26.8	ab	22.8
G.935			9.6	def	7.9	d			7.6	cd	10.2	d	17.0	de	9.3	ef	14.2	bc	7.5	g			10.2	ef	13.2	def	14.3	de	11.0
G.969	16.2	b	12.1	d	9.8	cd	10.5	bc	6.1	d	12.1	cd	25.7	cd	11.3	def	12.4	bcd	10.9	d-g	15.3	c	15.3	cd	12.0	c-f	14.9	de	13.2
M.26 EMLA	13.4	b	10.3	de	8.4	d	8.4	c	7.1	cd	10.5	d	18.7	de	11.2	def	14.6	bc	12.6	c-f	15.3	c	11.9	def	12.2	ef	14.0	de	12.0
M.7																			12.7	c-f									12.7
M.9-T337			6.9	f			9.7	bc	5.9	d	9.2	d	14.9	e	7.4	f	10.3	cd	9.1	fg	11.8	c	10.7	ef	9.3	f	9.8	e	9.6
MM.106																			13.7	bcd									13.7
V.1	23.0	ab	12.5	d	12.4	bc			9.8	bc	16.0	bc	33.5	bc	13.8	cd					22.2	b	19.6	b	19.3	b-e	19.2	cd	18.3
V.5			17.1	bc	17.4	a			15.4	a	23.0	a	40.6	ab	21.5	ab	24.4	a	18.6	a	25.1	ab	19.8	ab	27.5	a	31.4	a	23.5
V.6			19.6	ab			14.1	ab	10.7	b	18.5	ab	49.7	a	17.7	bc	23.1	a	18.3	a	28.6	a	23.7	a	22.1	abc	28.1	ab	22.8
V.7			17.0	bc	14.0	ab			11.7	b	18.3	ab	43.0	ab	19.7	ab	23.2	a	18.3	ab	21.7	b	20.1	ab	24.7	ab	24.3	bc	21.3
Mean	21.8		13.1		11.4		11.9		8.6		14.0		24.6		14.0		15.5		13.3		20.4		14.9		16.4		18.5		15.2
P-value	0.0009		<0.0001		<0.0001		0.0002		<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.

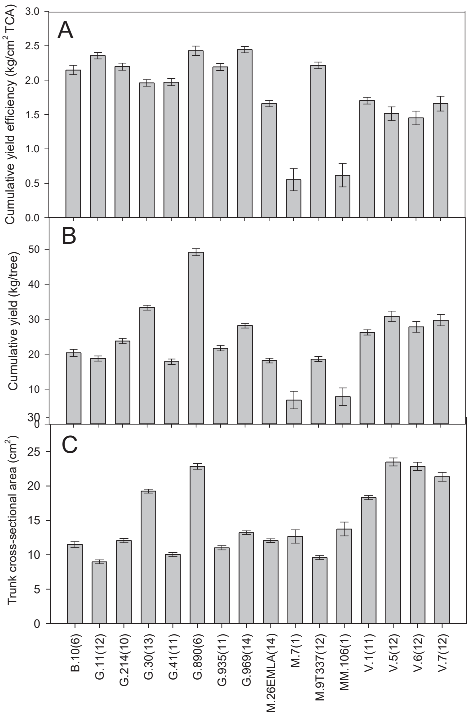

Figure 1. Trunk cross sectional area (TCA, A), cumulative yield per tree (CY, B), and cumulative yield efficiency (CYE, C) of 'Honeycrisp' trees on 16 rootstocks. TCA was taken in 2018, 5 years after planting, and CY and CYE represent yields from 2015-2018. Data represent the lsmeans of rootstocks pooled across all planting locations. The number within the brackets beside the rootstock indicates the number of locations the rootstock was tested. Error bars represent the standard error of the lsmean taken from the GLMMIX mixed model analyses.

were the largest of all, ranging from 77-95% larger than M.26 EMLA. Pooled over all rootstocks, tree vigor was greatest in NJ, ID, PA, WI, and WA, and lowest in MEX, ME, and MI. 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 properties, environmental conditions, tree nutrition, and whether the site was fumigated prior to planting; examining the interaction of these factors with rootstock is beyond the scope of this study.

For all locations that had trees on G.11, G.41, and G.935, vigor of trees on these rootstocks (based on TCA) was consistently similar to M.9-T337. These data agree with Fazio (2018) and Autio et al. (2020), who classified these rootstocks in the 'dwarfing' category. In a New York study comparing the performance of 'Honeycrisp' on several Geneva rootstocks with two orchard systems (Slender Axis, Tall Spindle), Reig et al. (2019) found that G.11 and G.41 were similar in TCA to M.9-T337 after 10 years. At all locations that tested B.10 (MI, NJ, NY, ON-S, VA, and WI), it was statistically similar in TCA, albeit variable in absolute values. In a 'Honeycrisp' rootstock experiment in NY, G.935 conferred vigor similar to M.26 (Robinson et al., 2008), which is consistent with all locations in the present study except ON-S, where G.935 was smaller than M.26 EMLA. 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 a 'Honeycrisp' study conducted in NY (Lordan et al., 2019), but inconsistent with another study in the same region that categorized G.214 as a dwarfing rootstock most similar to M.9 (Robinson et al., 2012). The semi-dwarfing rootstock G.969 was previously classified in the M.7 size range (Cummins et al., 2013a). In MA, ME, MEX, MN, NJ, VA, and WI, G.969 was consistently larger than M.26 EMLA. However, in MI, NY, ON-R, ON-S, PA, and WA G.969 was similar or smaller than M.26 EMLA. Robinson et al. (2014) categorized G.969 between M.26 and M.7 size. Rootstock genotype differences in vigor can be attributed to differences in scion, soil texture and other soil physio-chemical properties, 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). G.30 has shown high vigor in other studies including one in NY where it was 48-68% more vigorous than M.26 EMLA (Robinson et al., 2006; Reig et al., 2019) 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 was 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 the largest or among the largest rootstocks, except in PA. This is the first study evaluating V.5 and V.6 genotypes. They both had TCA twice the size of M.26 EMLA; therefore, they are considered 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.

Canopy Size. Tree height and width was 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 at all but one location (ON-R). Pooled across rootstocks, tree height was lowest in ME, MEX, and MN (all below 3 m) and greatest at ID, MA, NJ, NY, PA, and WA. Cooperators were requested to restrict tree height to 3.5 m by pruning, based on the protocol for the Tall Spindle training system. At several locations, tree height exceeded 3.5 m on several rootstocks by the fifth leaf: these included G.890, V.5, V.7, G.30, G.969, and V.1. Early development of the tree canopy and maximizing tree height are important to maximize precocity and yield. Clearly, with 'Honeycrisp' as the scion, some rootstocks such as G.890, V.5, V.7, and G.30 are too vigorous for the Tall Spindle system and

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

Rootstock	ID	MA	ME	MEX	MI	MN	NJ	NY	ON-R	ON-S	PA	VA	WA	WI	Mean
B.10					2.5 f		2.8 d	3.0 cde		3.0 bcd		2.6 cd		3.0 c-f	2.8
G.11		2.9 e	2.4 c	2.3 ab	2.8 b-f	3 bcd	2.9 cd	3.1 cde	3.0	2.9 cd		2.9 a-d	3.2 ab	2.9 ef	2.8
G.214		3.7 ab	2.6 bc		3.5 a	3 bcd	3.4 abc	3.3 bcd		3.4 ab		3.2 a	3.3 ab	3.2 a-e	3.2
G.30	3.9 a	3.5 abc	3.1 a	2.5 a	3.4 ab	3 abc	3.5 ab	3.5 ab	3.0	3.6 a		3.2 a	3.5 a	3.5 a	3.3
G.41		3.1 cde		2.2 b	2.8 c-f	3 a-d	2.9 cd	3.1 b-e	3.0	3.1 bcd		2.7 bcd	3.1 ab	3.1 b-f	2.9
G.890		3.8 a				3 a		3.7 a			3.7 ab		3.5 a	3.4 abc	3.5
G.935		3.3 bcd	2.5 c		3.2 a-e	2 bcd	3.2 a-d	2.9 ef	3.2	2.7 d		2.9 abc	3.2 ab	2.8 ef	2.9
G.969	3.2 b	3.4 abc	2.6 bc	2.3 ab	2.9 b-f	3 ab	3.7 a	3.2 b-e	3.1	3.0 cd	3.2 cd	3.1 a	3.3 ab	3.1 b-f	3.1
M.26 EMLA	2.5 c	2.9 de	2.4 c	2.0 b	2.7 def	2 d	3.0 bcd	3.0 de	3.0	2.8 d	3.0 d	2.5 d	2.9 b	2.8 ef	2.7
M.7										3.0 bcd					3.0
M.9-T337		2.7 e		2.2 ab	2.5 ef	2 cd	3.0 bcd	2.6 f	3.0	2.8 d	2.9 d	2.6 bcd	3.0 b	2.8 f	2.7
MM.106										3.0 bcd					3.0
V.1	3.2 b	3.0 de	2.5 c		2.8 c-f	3 abc	3.4 abc	2.8 ef			3.3 bcd	3.0 ab	3.6 a	3.0 def	3.0
V.5		3.6 ab	2.9 ab		3.7 a	3 ab	3.8 a	3.5 ab	3.1	3.4 ab	3.6 abc	3.1 a	3.5 a	3.4 ab	3.4
V.6		3.7 a		2.2 b	3.4 a-d	3 ab	3.7 a	3.4 abc	3.1	3.3 abc	4.0 a	3.1 a	3.4 ab	3.3 a-d	3.3
V.7		3.6 abc	2.9 ab		3.4 abc	3 abc	3.8 a	3.5 ab	3.4	3.4 abc	3.5 bc	3.0 abc	3.6 a	3.1 a-f	3.3
Mean	3.2	3.3	2.7	2.2	3.0	2.6	3.3	3.2	3.1	3.1	3.4	2.9	3.3	3.1	3.1
P-value	<0.0001	<0.0001	<0.0001	0.0008	<0.0001	<0.0001	<0.0001	<0.0001	0.0815	<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 5. Canopy spread (m) of 'Honeycrisp' trees after five years as influenced by rootstock and location[z]

Rootstock	ID	MA	ME	MEX	MI	MN	NJ	NY	ON-R	ON-S	PA	VA	WA	WI	Mean
B.10					1.1 def		1.2 e	1.8 cd		1.5 a-d		1.6 e		1.9 d	1.5
G.11		1.7 cd	1.7 b	1.3 ab	1.1 def	1.8 abc	1.2 cde	2.0 a-d	1.5 c	1.4 bcd		1.8 cde	0.9 de	1.9 d	1.5
G.214		2.1 abc	1.6 b		1.4 bcd	1.5 d	1.4 a-e	2.1 a-d		1.5 a-d		2.2 ab	1.1 cde	2.0 bcd	1.7
G.30	1.6 a	2.1 abc	2.2 a	1.4 a	1.7 a	1.8 a-d	1.3 b-e	2.3 ab	1.8 abc	1.6 ab		2.3 ab	1.2 abc	2.3 a	1.8
G.41		1.9 bcd		1.2 ab	1.2 cde	1.7 a-d	1.4 a-e	1.9 bcd	1.5 c	1.4 a-d		1.8 cde	1.0 cde	2.0 cd	1.5
G.890		2.5 a				1.9 ab		2.4 a			2.4 a		1.2 abc	2.3 ab	2.1
G.935		1.8 bcd	1.6 b		1.4 a-d	1.6 a-d	1.5 abc	1.9 bcd	1.6 c	1.4 bcd		2.0 bcd	1.1 b-e	1.9 d	1.6
G.969	1.2 bc	2.1 abc	1.7 ab	1.3 ab	1.1 ef	1.8 a-d	1.5 a-d	1.8 cd	1.8 abc	1.4 bcd	1.9 bc	2.0 a-d	0.9 cde	2.0 bcd	1.6
M.26 EMLA	0.9 c	1.8 cd	1.3 b	1.1 b	1.2 c-f	1.6 bcd	1.2 de	1.7 de	1.6 bc	1.4 a-d	1.7 c	1.7 de	1.0 cde	1.8 d	1.4
M.7										1.4 a-d					1.4
M.9-T337		1.5 d		1.2 ab	0.9 f	1.5 cd	1.3 b-e	1.3 e	1.6 c	1.3 cd	1.7 c	1.6 e	0.9 e	1.8 d	1.4
MM.106										1.3 d					1.3
V.1	1.2 b	1.8 cd	1.4 b		1.3 cde	1.7 a-d	1.5 a-d	1.8 cde			2.0 bc	2.1 abc	1.1 a-d	1.9 d	1.6
V.5		2.1 abc	1.8 ab		1.7 ab	1.8 abc	1.6 a	2.2 abc	2.0 a	1.6 a	2.3 a	2.3 ab	1.3 ab	2.3 ab	1.9
V.6		2.1 abc		1.2 ab	1.5 abc	1.8 a-d	1.6 ab	2.2 a-d	2.0 ab	1.6 a	2.3 a	2.3 a	1.3 a	2.3 abc	1.9
V.7		2.3 ab	1.7 ab		1.4 a-d	1.9 a	1.7 a	2.2 a-d	2.0 a	1.6 abc	2.2 ab	2.1 abc	1.2 abc	2.1 a-d	1.9
Mean	1.2	2.0	1.7	1.2	1.3	1.7	1.4	2.0	1.8	1.5	2.1	2.0	1.1	2.0	1.6
P-value	<0.0001	<0.0001	<0.0001	0.0173	<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.

would require excessive pruning to maintain the canopy within the allotted space (1.2 x 3.6 m). Tree width was significantly affected by rootstock at all 14 locations (Table 5). Pooled across rootstocks, tree width was lowest in ID, MEX, MI, and WA (< 1.3 m) and greatest in MA, NY, PA, VA, 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. Because of high tree vigor, in several locations tree width exceeded 1.2 m on several rootstocks by the fifth leaf. This was most apparent for G.969, V.6, V.7, and V.5 rootstocks; however, it was dependent on location and pruning practices at each location. Excessive pruning can lead to losses in productivity as a result of an imbalance in reproductive growth.

Rootstock Suckers. Quantity of cumulative root suckers (CRS) (2015-18) was influenced by location and rootstock, and the interaction of the two factors was significant ($P<0.0001$) (Table 6). CRS were significantly affected by rootstock in 9 of 14 locations. Pooled across rootstocks, there were fewest CRS in ME, MI, MN, NY, ON-R, ON-S, and WI, and the most CRS (> 4 suckers per tree) in ID, MA, NJ, and PA. Pooled over all locations, the most CRS were observed for M.7, G.890, G.214, and G.30, and the least for MM.106, B.10, and G.41. Rootstocks had a significant effect on CRS in ID, MA, MEX, MI, NY, ON-S, PA, VA, and WI and was highest in MA, PA, NJ, VA. In ID, CRS was highest on G.30. CRS for some rootstocks ranged widely depending on location. For example, for G.30, there were no suckers at MI, while at MA, there were 22.6 suckers per tree for G.30; both sites are sandy loam soils. In MA, CRS was highest on G.214, G.30, and G.890 (> 15 suckers per tree). CRS was highest on G.890 in PA and NY. Although there were significant rootstock effects on CRS in MEX, MI, NY, and ON-S, the overall amount of rootstock suckering was relatively

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

Rootstock	ID	MA	ME	MEX	MI	MN	NJ	NY	ON-R	ON-S	PA	VA	WA	WI	Mean
B.10					0.0 b		0.1	0.0 b		0.0 b		1.2 bc		0.2 b	0.2
G.11		1.1 b	0.1	0.0 a	0.0 b	1.1	0.4	0.0 b	0.0	0.0 b		0.1 c	0.4	1.5 b	0.4
G.214		15.7 a	0.0		0.0 b	2.8	6.3	0.2 ab		2.0 b		7.9 ab	2.8	6.9 a	4.1
G.30	13.4 a	22.6 a	0.3	1.7 a	0.0 b	0.7	7.6	0.3 ab	0.2	0.2 b		5.4 abc	2.7	1.0 b	4.0
G.41		2.2 b		0.0 a	0.0 b	0.3	0.9	0.0 b	0.1	0.1 b		2.5 bc	1.7	0.5 b	0.7
G.890		15.4 a				2.6		1.0 a			18.2 a		6.3	1.8 b	6.6
G.935		6.0 b	0.0		0.6 a	0.4	7.3	0.2 ab	0.1	0.0 b		10.1 a	5.7	3.5 ab	2.8
G.969	2.5 ab	3.1 b	0.3	3.1 a	0.1 ab	0.5	4.6	0.1 b	0.0	0.1 b	3.8 b	3.4 abc	3.6	0.1 b	1.7
M.26 EMLA	0.3 b	4.0 b	0.3	0.8 a	0.0 b	1.0	6.2	0.0 b	0.2	0.0 b	1.5 b	0.6 c	0.0	1.5 b	1.1
M.7										7.0 a					7.0
M.9-T337		5.9 b		0.6 a	0.0 b	2.4	5.3	0.0 b	0.1	0.1 b	5.1 b	7.0 abc	1.6	0.7 b	2.2
MM.106										0.0 b					0.0
V.1	0.6 b	2.5 b	0.0		0.1 ab	0.3	5.0	0.1 b			7.2 ab	1.1 bc	1.5	1.0 b	1.6
V.5		2.4 b	0.0		0.0 ab	0.2	3.3	0.1 b	0.2	0.1 b	10.0 ab	1.9 bc	1.9	0.1 b	1.6
V.6		3.1 b		3.7 a	0.0 ab	0.2	5.9	0.1 b	0.6	0.0 b	4.0 b	1.4 bc	2.1	0.2 b	1.6
V.7		4.7 b	0.3		0.0 ab	0.3	4.6	0.6 ab	0.6	0.3 b	9.5 ab	1.6 bc	1.0	0.4 b	1.9
Mean	4.2	6.8	0.1	1.4	0.1	1.0	4.4	0.2	0.2	0.7	7.4	3.4	2.4	1.4	2.3
P-value	0.0294	<0.0001	0.8073	0.0198	0.0488	0.2828	0.1206	0.0047	0.6970	<0.0001	0.0023	<0.0001	0.0537	<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.

low (< 3 suckers per tree) compared to the other locations. The strong rootstock by location interaction on suckers observed in this trial also was observed in previous NC-140 trials (Marini et al., 2006a). The amount of variation in rootstock suckers is related to tree vigor and also was observed in other NC-140 studies (Autio et al., 2020; Marini and Fazio, 2018). Other factors such as 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 infection sites for fire blight (Marini and Fazio, 2018), 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).

Cumulative Yield. Cumulative yield was influenced by location and rootstock, and the interaction of the two factors was significant (P<0.001) (Table 7; Figure 1). With the exception of M.7 and MM.106 (which were planted at only one location – ON-S), the lowest yields were observed on G.41, M.9-T337, and M.26 EMLA and the highest on G.890. Locations with high yields included ID, MA, NY, PA, WA, and WI. At some locations, cumulative yields exceeded 50 kg/tree on V.1, G.935, V.5, V.7, G.969, V.6, G.30, and G.890 rootstocks – even though at other locations, yields were considerably lower for the same rootstock. It is unclear why cumulative yields in WI exceeded every other site except PA. WI is a more northerly location, but this may be offset by the reported high vigor of this site. Generally, cumulative yields were greater on trees with the highest vigor. On average, M.9-T337 and M.26 EMLA had similar yields (18.7 and 18.6 kg/tree, respectively), and 9 of the 16 rootstocks outperformed these two standard rootstocks. The newer rootstocks B.10, V.5, V.6, V.7, and all the Geneva rootstocks,

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

Rootstock	ID	MA	ME	MEX	MI	MN	NJ	NY	ON-R	ON-S	PA	VA	WA	WI	Mean
B.10					18.1 cd		19.1	36.3 b-f		9.5 ab		9.5 abc		37.4 g	19.6
G.11		19.5 d	20.5 bcd	5.8 bc	19.5 cd	17.9 a-e	19.4	32.8 def	25.1 abc	5.8 b		7.3 c	22.8 c	36.7 g	18.3
G.214		29.3 bcd	14.6 cd		24.0 bcd	15.0 de	24.5	34.1 c-f		8.3 ab		18.7 a	32.9 abc	39.0 efg	22.4
G.30	55.4 a	43.7 a	46.8 a	11.9 ab	33.1 ab	25.6 ab	27.5	51.0 ab	23.8 abc	7.0 ab		15.6 abc	46.0 a	75.8 a	33.6
G.41		20.4 d		2.8 c	16.7 cd	16.3 cde	20.5	38.1 b-f	17.4 c	7.3 ab		6.8 c	16.1 c	51.4 c-f	18.1
G.890		39.4 abc				24.9 abc		61.6 a			79.3 a		51.4 a	72.5 ab	49.2
G.935		22.8 d	22.9 bc		16.1 cd	15.6 de	25.6	25.4 f	23.3 abc	7.7 ab		7.4 c	32.3 abc	52.2 cde	21.2
G.969	42.2 ab	40.7 ab	29.1 b	12.7 a	21.3 cd	22.3 a-d	23.9	45.6 bcd	18.8 bc	8.6 ab	61.2 bc	17.6 ab	18.3 c	53.1 cd	28.2
M.26 EMLA	27.9 b	18.6 d	10.9 d	7.2 abc	16.0 cd	14.6 de	21.2	30.6 ef	23.6 abc	5.8 b	29.1 e	6.8 c	20.0 c	31.5 g	17.9
M.7										6.4 ab					6.4
M.9-T337		17.8 d		10.8 ab	14.0 d	12.7 e	20.1	25.0 f	20.6 bc	8.0 ab	39.8 de	9.2 bc	24.9 bc	38.3 fg	18.8
MM.106										6.8 ab					6.8
V.1	37.2 b	26.0 d	15.5 cd		22.4 bcd	21.1 a-d	22.1	31.9 def			52.1 bcd	10.4 abc	34.4 abc	40.1 d-g	26.2
V.5		27.8 cd	26.0 bc		40.2 a	26.6 a	24.5	44.1 b-e	34.0 a	10.6 a	47.1 cd	15.0 abc	44.5 ab	54.7 c	30.6
V.6		29.7 bcd		5.9 bc	24.2 bcd	23.1 a-d	21.5	41.2 b-e	28.7 ab	9.7 ab	66.2 ab	13.6 abc	33.9 abc	56.6 c	27.5
V.7		27.0 cd	22.7 bc		27.2 bc	19.4 a-e	16.5	48.6 abc	34.3 a	7.9 ab	56.3 bc	14.4 abc	43.6 ab	58.5 bc	29.2
Mean	40.7	27.9	23.2	8.1	22.5	19.6	22.0	39.0	25.0	7.8	53.9	11.7	32.4	49.8	23.4
P-value	0.0005	<0.0001	<0.0001	0.0003	<0.0001	<0.0001	0.1601	<0.0001	<0.0001	0.003	<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.

exception for G.41, had cumulative yields that exceeded M.9-T337 and M.26 EMLA.

Overall, the strong rootstock by location interaction on cumulative yield observed in this trial indicates the importance of testing rootstocks at a regional level. Whether these rootstock differences will continue as the trees mature and continue to grow is unclear. However, it is likely that several rootstocks with high vigor will become less productive as more pruning is required to restrict them to their orchard space. On average, trees on G.890, G.30, and G.969 were 161%, 78%, and 50% more productive, respectively, than on M.9-T.337, while V.1, V.6, V.7, and V.5 were 39%, 46%, 55%, and 62% more productive, respectively, than M.9-T.337. B.10, G.935, and G.214 were 4%, 13%, and 19% 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 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). The cumulative yield data are more indicative of the early 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 realized.

Cumulative Yield Efficiency. CYE was calculated using the sum of four years of yield (2015-2018) and the TCA in year 4 (2018). This method is used to normalize yields amongst rootstocks that range in tree vigor. In this study, CYE was influenced by location and rootstock, and the interaction of the two factors was significant (P<0.0001) (Table 8; Figure 1). CYE was significantly affected by rootstock at all 14 locations. Pooled across rootstocks, CYE were lowest in MEX, MN, NJ, ON-S, and VA, and greatest (> 2.5 kg/TCA) in MI, NY, PA, and WI. Pooled over all locations, CYE was highest (≥ 2.0 kg·cm^{-2} TCA) for G.969, G.890, G.11, M.9-T337, G.214, G.935, B.10, G.41 and G.30 and lowest (<2.0 2.0 kg·cm^{-2} TCA) for M.7, MM.106, V.6, V.5, M.26 EMLA, V.7, and V.1. Across locations, CYE was highest on G.11 in NY, on G.41 in WI and NY, and on G.969 in MA, MI, and PA. Some rootstocks ranged widely in CYE across locations. For example, the CYE for G.969 was 1.0 kg·cm^{-2} TCA in NJ but 4.1 kg·cm^{-2} TCA in NY. 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. Although the results thus far in this experiment are inconsistent with previous observations, e.g., the semi-dwarfing rootstocks G.30 and especially G.890 were as efficient as their dwarfing counterparts, the data in this study only comprise the first four years of yields. Consequently, our CYE data may not adequately predict cumulative yields of mature orchards. Once tree canopies fill their allotted space, rootstock effects on yield efficiency are modified differentially by pruning severity (Autio et al., 2017).

Fruit weight. FW (2015-18) 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 MEX, NJ, ON-R, and VA. Pooled across rootstocks, FW ranged from 146 g in MN to 288 g in NY. In general, FW was lowest in MEX, MN, ON-S, and VA, and highest in NJ, NY, and OR-R. Pooled across locations, trees on G.890, B.10, V.5, and G.30

Table 8. Cumulative yield efficiency (2015-2018; kg/cm^2 TCA) of 'Honeycrisp' trees as influenced by rootstock and location[z].

Rootstock	ID	MA	ME	MEX	MI	MN	NJ	NY	ON-R	ON-S	PA	VA	WA	WI	Mean
B.10					3.0 abc		1.6 ab	3.6 abc		1.0 b-e		0.9 abc		2.8 b-e	2.1
G.11		2.5 a-d	3.0 ab	0.5 bcd	3.7 a	2.0 ab	1.9 a	4.1 a	2.9 a	1.4 ab		0.8 abc	2.3 abc	3.2 a-d	2.4
G.214		2.6 abc	2.4 bc		3.0 abc	1.6 ab	1.7 ab	2.8 bcd		1.3 bc		1.3 a	2.7 a	2.5 de	2.2
G.30	1.8 b	2.7 ab	2.8 ab	0.7 a-d	2.8 abc	2.1 a	1.1 a-d	2.7 bcd	1.5 bcd	0.7 de		0.8 abc	2.3 abc	3.3 a-d	2.0
G.41		2.1 bcd		0.3 d	2.5 abc	1.5 ab	1.7 ab	3.9 ab	2.2 b	1.2 bcd		0.7 abc	1.6 bc	4.1 a	2.0
G.890		1.9 bcd				1.2 ab		2.6 cd			3.6 ab		2.5 abc	2.8 b-e	2.4
G.935		2.4 a-d	3.2 a		2.2 c	1.5 ab	1.6 ab	2.7 bcd	1.7 bcd	1.9 a		0.7 bc	2.5 abc	3.7 ab	2.2
G.969	2.6 a	3.4 a	3.0 ab	1.2 a	3.5 ab	1.9 ab	1.0 bcd	4.1 a	1.5 bcd	1.4 ab	4.0 a	1.2 ab	1.9 abc	3.6 abc	2.4
M.26 EMLA	2.1 ab	1.8 bcd	1.4 d	1.0 abc	2.3 bc	1.6 ab	1.2 a-d	2.7 bcd	1.6 bcd	0.8 cde	1.9 c	0.5 bc	1.8 abc	2.3 de	1.7
M.7										0.6 e					0.6
M.9-T337		2.6 a-d		1.2 ab	2.4 bc	1.4 ab	1.5 abc	3.4 abc	2.0 bc	1.3 b	3.4 ab	0.9 abc	2.6 ab	3.9 a	2.2
MM.106										0.6 e					0.6
V.1	1.7 b	2.1 bcd	1.2 d		2.3 bc	1.4 ab	0.7 cd	2.3 cd			2.4 c	0.5 c	1.8 abc	2.2 e	1.7
V.5		1.6 cd	1.5 d		2.6 abc	1.2 b	0.6 cd	2.1 d	1.4 cd	0.8 cde	2.0 c	0.8 abc	1.6 c	1.8 e	1.5
V.6		1.5 d		0.4 cd	2.3 bc	1.4 ab	0.5 d	2.6 cd	1.3 d	0.7 de	2.4 c	0.6 bc	1.7 bc	2.2 e	1.5
V.7		1.7 bcd	1.9 cd		2.3 bc	1.1 b	0.4 d	2.5 cd	1.5 bcd	0.9 b-e	2.6 bc	0.7 abc	1.8 abc	2.6 cde	1.7
Mean	2.1	2.2	2.3	0.8	2.7	1.5	1.2	3.0	1.8	1.0	2.8	0.8	2.1	2.9	1.8
P-value	0.0150	<0.0001	<0.0001	<0.0001	0.0002	0.0028	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0007	<0.0001	<0.0001	

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

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

Rootstock[y]	ID	MA	ME	MEX	MI	MN	NJ	NY	ON-R	ON-S	PA	VA	WA	WI	Mean
B.10					197 bc		308	274		228 a-d		206		269 ab	258
G.11		265 ab	247 a	234	226 abc	163 a	257	301	289	255 abc		206	262 a	253 a-d	247
G.214		254 ab	225 a		257 a	102 b	239	276		271 a		202	247 a	216 d	232
G.30	281 a	263 ab	237 a	218	252 ab	147 a	270	298	264	266 ab		191	278 a	265 abc	252
G.41		259 ab		220	260 a	151 a	271	297	265	231 a-d		208	244 a	265 abc	247
G.890		280 a				154 a		301			261 a		270 a	282 a	264
G.935		233 b	207 a		253 ab	137 ab	252	257	270	216 cd		214	263 a	217 d	233
G.969	192 b	229 b	210 a	209	210 abc	149 a	282	270	258	224 a-d	230 b	203	225 a	229 cd	225
M.26 EMLA	248 a	253 ab	213 a	216	216 abc	133 ab	298	301	302	241 a-d	257 a	223	236 a	277 a	249
M.7										199 d					199
M.9-T337		229 b		217	194 c	149 a	289	278	281	227 a-d	236 ab	224	244 a	236 bcd	234
MM.106										200 d					200
V.1	242 a	244 ab	216 a		214 abc	142 ab	271	280			238 ab	209	265 a	251 a-d	238
V.5		268 ab	255 a		263 a	149 a	284	305	274	221 bcd	249 ab	227	264 a	280 a	254
V.6		280 a		204	243 abc	160 a	290	299	265	233 a-d	256 ab	223	263 a	275 a	250
V.7		258 ab	215 a		236 abc	160 a	255	297	281	240 a-d	249 ab	222	253 a	265 abc	246
Mean	241	255	225	217	232	146	274	288	275	232	247	212	255	256	239
P-value	<0.0001	<0.0001	0.0116	0.4811	<0.0001	0.0015	0.0606	0.0616	0.0870	<0.0001	0.0037	0.1274	0.0360	<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.

had the highest FW, while trees on G.969, G.214, G.935, and M.9-T337 had the lowest. However, FW ranged widely within several locations, and rootstock effect on FW was quite inconsistent. To minimize biennial bearing and improve fruit quality, co-operators were requested to reduce crop load each year to 5-6 fruits/cm^2 TCA. Due to circumstances beyond the control of the co-operator, in some cases, fruit set was light and well below this threshold. This would have led to crop load differences between trees on different rootstocks in the same location and across locations, resulting in differential impact on FW. In previous studies, FW was influenced by crop load, rootstock, and location (Marini and Barden, 2004; Marini et al., 2014), therefore, covariance analysis is likely required to properly adjust FW for crop density (Marini et al., 2012a, 2012b). Conducting covariance analysis to adjust and test for rootstock differences in fruit weight based on crop load for each year of the study and the large number of rootstocks and locations is a sizeable undertaking and beyond the scope of this study.

Conclusions

In this study, several newer Geneva and Vineland series rootstocks were tested using the scion 'Honeycrisp' across 14 locations in North America. After five years, there was significant interaction between rootstocks and locations in the metrics used to measure rootstock performance (survival, vigor, suckering, cumulative yield, cumulative yield, and fruit size). As a result of the interaction, rootstocks performed differently across locations, which is common among multi-location rootstock studies that have tested several rootstocks. While the pooled rootstock means have been presented for comparative purposes, these data must be interpreted with caution as generalizations of rootstock's effect on vigor are difficult to make. Pooled over all locations, G.11 and

G.41 were similar in size to M.9-T337, while G.935, B.10, G.214, and G.969 were similar in size to M.26 EMLA. V.1, V.5, V.6, V.7, G.890 and G.30 were all larger than M.26 EMLA and therefore are likely too vigorous for sustained yields when trained to the tall spindle training system using 'Honeycrisp'. Cumulative yields were generally greater on trees with the highest vigor. On average, 10 of the 16 rootstocks tested 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, with the exception for G.41, had good to excellent cumulative yields. Cumulative yield efficiency 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 G.969, G.890, G.11, M.9-T337, G.214, G.935, B.10, G.41 and G.30. Overall, B.10, G.11, G.214, G.41, G.935, and G.969 are likely to perform the best using the tall spindle training system based on the first five years of production.

These data and those from a companion study (Cline et al., 2021) will help inform apple producers of the characteristics of these rootstocks to enable better rootstock selection for their orchard training systems and planting locations. While beyond the scope of this paper, translating these results to the apple industry will impact producer behaviour and improve outcomes. 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); and orchard design (training system, tree density, tree height, single vs. multi-leader) are all factors that must be considered when selecting a rootstock. Rootstock selection can profoundly impact orchard profitability and return on investment (Dallabetta et al., 2021). Therefore, apple producers should be aware of new and novel rootstock opportunities when establishing a new orchard.

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About the Cover:

Chestnuts are native to Asia, Europe, and North America and belong to a group of 13 different types of deciduous trees in the genus *Castanea*. European, Chinese, and Japanese chestnuts and hybrids are cultivated commercially with world-wide production of about 2.4 million tons. Chestnut species differ in nut quality, growth habit and resistance to pests. Genotypes from several breeding programs are being evaluated in different locations to determine adaptability to local growing conditions.

Photo provided by Dr. Burak Akyūz.