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Performance of 'Modi®' apple trees on several Geneva rootstocks managed organically: Five-year results from the 2015 NC-140 Organic Apple Rootstock Trial

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Abstract

In 2015, an orchard trial of ten apple rootstocks was established at ten locations in the United States and Canada using 'Modi®' as the scion cultivar. Trees were managed in accordance with United States organic standards to expose these rootstocks to the nutrient conditions and biome typically associated with organic tree-fruit production. Rootstocks included nine named Cornell-Geneva clones [Geneva® 11 (G.11), Geneva® 30 (G.30), Geneva® 41 (G.41), Geneva® 202 (G.202), Geneva® 214 (G.214), Geneva® 222 (G.222), Geneva® 890 (G.890), Geneva® 935 (G.935), and Geneva® 969 (G.969)] and M.9 NAKBT337. All trees were spaced 1 x 3.5 m and trained using the tall spindle system. After 5 years, the greatest mortality was for trees on M.9 NAKBT337 (14%). Rootstocks separated into size classes from large semi-dwarf to small dwarf. G.890 resulted in large semi-dwarf trees, and G.202 produced moderate semi-dwarfs. G.41 and G.30 resulted in small semi-dwarf trees, and trees on G.935 were large dwarfs. G.11, G.214, G.969 and M.9 NAKBT337 resulted in trees that were moderate dwarfs, and G.222 resulted in small dwarf trees. The most yield efficient (cumulatively, 2016-19) trees in the trial were on G.935, G.11, and G.969, and the least efficient trees were on G.202 and G.890. The largest fruit (2016-19) were harvested from trees on G.30, G.41, G.890, and M.9 NAKBT33, and the smallest were harvested from trees on G.202.

NC-140 is a Multi-state Research Project organized by state agricultural experiment stations, USDA, and agencies in Mexico and Canada. During the 45 years of its existence, it has evaluated nearly all new temperate, tree-fruit rootstocks utilizing uniform trials in diverse locations in North America (Cowgill et al., 2017). All prior NC-140 trials were managed with "conventional", i.e., non-organic, programs. This nomenclature of "organic" vs. "conventional' suggests that there are standard management practices applied across each system, when in reality, there are a large number of practices and intensities of management that are applied within and across systems. Because of this potential variation in management, in this paper we refer to "organic" compared to "non-organic" systems, as conventions may vary among each system across regions and cooperators. In 2019, 947 million pounds (~430,000 mt) of certified organic apples were produced in the U.S., with about 93% of that production located in Washington state (NASS, 2020). While relatively small-scaled compared to overall apple orchard land use, organic production still constitutes substantial commercial activity in diverse apple producing states throughout the U.S., and organic orchards may be found in all apple-producing states.

Organic production presents several potential limitations to overall orchard performance. In the U.S., organic apple production is more common in western states that have

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less summer precipitation than in the more humid mid-west and eastern U.S. A trial in California comparing organic to conventional production found few differences between the systems, and although trees were slightly smaller, and profitability was greater for the organically-managed orchard (Swezey et al., 1998). In Washington, apple yields under organic management were generally comparable with non-organic apples in multiyear studies (Peck et al., 2006; Reganold et al., 2001), which explains the relatively greater proportion of organically-grown fruit in that state than in most other U.S. states or Canadian provinces. Because of increased precipitation and humidity that leads to greater disease pressure and more insect pest species present, organic apple production is substantially more difficult in the eastern U.S. than in drier western states. In a long-term evaluation of organic apple production in Vermont, cumulative crop yield was far below economically acceptable conventional yields for nearly all cultivars trialed, and newly established trees were all unprofitable (Bradshaw et al., 2016a; Bradshaw et al., 2016b). In Kentucky, yield in a long-term trial of organically-managed, scab-resistant apple cultivars (SRCs) was substantially lower than what is typical for non-organic, commercial apples in the state, and only 43-64% of fruit were considered marketable primarily due to insect and disease damage (Williams et al., 2015). Evaluation of organic apple production in New York has shown greater success. In one study, the SRC 'Liberty' was evaluated over four seasons in comparative organic and integrated (a hybrid of organic and conventional) management systems and overall, organic management was competitive with integrated fruit production for yield and tree growth, although pest incidence was generally greater (Peck et al., 2010). In a separate trial that compared two intensities of organic management with a non-treated control in an orchard consisting of multiple SRCs, similar levels of pest and disease incidence to the prior New York and Vermont studies were observed (Agnello et al., 2017). However, higher prices received for certified-organic fruit would likely offset a lower percentage of clean fruit under organic management, so long as yield is sufficient as outlined by Bradshaw et. al. (2016b).

Over the last several years, several new rootstocks have been released from the Cornell-Geneva breeding program (managed jointly by Cornell University and the United States Department of Agriculture-Agricultural Research Service). Many of these Geneva series rootstocks have been previously evaluated in other NC-140 trials (Autio et al., 2013; Autio et al., 2017a; Autio et al., 2020a; Autio et al., 2017b; Autio et al., 2020b; Autio et al., 2011b; Autio et al., 2011c; Marini et al., 2014; Robinson et al., 2007). The objectives of this current trial were to assess and compare performance of several Cornell-Geneva rootstocks managed using organic management procedures at multiple sites in North America.

Materials and Methods

In spring, 2015, an orchard trial of 10 apple rootstocks was established at 10 sites in North America (Table 1) under the coordination of the NC-140 Multi-State Research Committee. 'Modi®' [a U.S. trademark of 'CIVG198'(Leis et al., 2008)] was used as the scion cultivar, and trees were propagated by Wafler Nursery (Wolcott, NY, USA). 'Modi®' is a 'Gala' x 'Liberty' hybrid SRC bred in Italy. This cultivar was selected for its reported high fruit quality, consistent yield, and resistance to fire blight. Rootstocks included nine named Cornell-Geneva clones [Geneva® 11 (G.11), Geneva® 30 (G.30), Geneva® 41 (G.41), Geneva® 202 (G.202), Geneva® 214 (G.214), Geneva® 222 (G.222), Geneva® 890 (G.890), Geneva® 935 (G.935), and Geneva® 969 (G.969)] and M.9 NAKBT337.

The trial was planted in California, Colorado, Idaho, Massachusetts, Michigan, New Mexico, Nova Scotia (Canada), New York (Geneva and Ithaca), and Vermont. In eight

Table 1. Cooperators and sites in the 2015 NC-140 Organic Apple Rootstock Trial.

Site	Planting location	NC-140 Cooperator	Cooperator affiliation and address
California (CA)	Lakeport	Rachel Elkins	UC Cooperative Extension, University of California Davis, 883 Lakeport Blvd., Lakeport, CA 95453
Colorado (CO)	Grand Junction	Ioannis Minas	Western Colorado Research Center - Orchard Mesa, Colorado State University, 3168 B 1/2 Road, Grand Junction, CO 81503-9621
Idaho (ID)	Parma	Esmaeil Fallahi	Parma Research & Extension Center, University of Idaho, 29603 U of I Lane, Parma, ID 83660
Massachusetts (MA)	Amherst	Jon Clements/Wesley Autio	Stockbridge School of Agriculture, 205 Paige Laboratory, University of Massachusetts, Amherst, MA 01003 USA
Michigan (MI)	East Lansing	Todd Einhorn	Department of Horticulture, 1066 Bouge St., Room A338-C, Michigan State University, East Lansing, MI 48824
New Mexico (NM)	Alcalde	Shengrui Yao	Sustainable Agriculture Science Center, New Mexico State University, 371 County Road 40, Alcalde, NM 87511
Nova Scotia (NS)	Kentville	Suzanne Blatt	Kentville Research & Development Centre, Agric. & Agri-Food Canada, 32 Main St, Kentville, Nova Scotia, B4N 1J5 Canada
New York (NYG)	Geneva	Terence Robinson	Department of Horticulture, Cornell University, NYSAES, Geneva, NY 14456 USA
New York (NYI)	Ithaca	Gregory Peck	School of Integrative Plant Science, 121 Plant Sciences Building, Cornell University, Ithaca, NY 14853
Vermont (VT)	South Burlington	Terence Bradshaw	Department of Plant & Soil Sciences, 210 Jeffords Hall, University of Vermont, Burlington, VT 05405

of the plantings (excluding California and Nova Scotia). Geneva® 16 (G.16) was included in the experiment. Cooperators, their contact information, and specific locations for this trial are listed in Table 1. The experiment was arranged as a randomized complete block design with 12 replications at each location. Within each location, blocks were determined by initial trunk cross-sectional area (TCA). For example, the largest tree for each rootstock was grouped in block 1 and smallest trees in block 12. Each replication included one tree per rootstock treatment. Trees were spaced 1 m x 3.5 m and trained in the tall spindle orchard system (Robinson et al., 2011). At planting, only minimal pruning was performed to remove broken or poorly-located lateral shoots, and shoots remaining after this pruning were counted. The height of graft union above the soil line after planting was also measured. Pest management, irrigation, fertilization, and crop-load management were consistent among all trees within a site. All fertilizer and pesticide inputs followed USDA National Organic Program standards (USDA National Organic Program, 2008) but specific management practices were based on the needs at each location.

Trunk circumference was measured annually at 25 cm above the bud union and in Oct. 2019 used to calculate TCA. After harvest in the fifth year (Oct. 2019), tree height was measured, and canopy spread was assessed by averaging the in-row and across-row canopy widths. Root suckers were counted and removed when trees were dormant each year. Yield was assessed in 2016 through 2019; however, very few sites had fruit to harvest in 2016. Cumulative yield efficiency (kg·cm-2 TCA) was calculated using cumulative yield

(2016-19) and 2019 TCA. All fruit were counted, and the total crop yield weighed for each tree in each year, and average fruit weight for 2019 and for 2016-19 were calculated from total fruit weight harvested and number of fruit harvested per tree.

Data were subjected to analysis of variance with the MIXED procedure of the SAS statistical analysis software (SAS Institute, Cary, NC). In the analyses, fixed main effects were rootstock and site. Block (within site) was a random, nested effect. In nearly all cases, the interaction of rootstock and site was significant. Rootstock differences within site were assessed (for all sites individually and including all rootstocks, also by the MIXED procedure) for survival (through 2019), TCA (2019), cumulative yield per tree (2016-19), cumulative yield efficiency (2016-19), and average fruit weight (2016-19). Because not all sites included G.16 rootstock, analyses comparing rootstocks across all sites excluded that rootstock. However, G.16 was included in comparisons of rootstocks within states in which it was included in the trial. Mean separations among rootstocks in all cases were performed by Tukey's HSD (P = 0.05).

Table 2. At-planting characteristics (2015) of Modi® trees in the 2015 NC-140 Organic Apple Rootstock Trial. All data are least-squares means adjusted for missing subclasses.[z]

	Trunk cross-sectional area at planting (cm^2)		Branches at planting after initial pruning (no.)		Graft union height (cm)	
Rootstock						
G.11	1.4	c	1.2	ab	12.3	ab
G.30	1.2	d	0.8	bcd	11.2	bc
G.41	1.6	b	1.1	b	12.6	ab
G.202	1.8	a	1.2	ab	12.4	ab
G.214	0.9	e	0.4	de	12.4	ab
G.222	0.2	f	0.1	e	13.3	a
G.890	1.8	a	1.5	a	12.3	ab
G.935	1.7	b	0.9	bc	13.0	a
G.969	1.3	d	0.6	cde	11.3	bc
M.9 NAKBT337	1.3	d	0.7	bcd	10.4	c
Location						
CA	1.2	a	0.3	c	---	
CO	1.3	a	---		---	
ID	---		1.7	b	11.2	de
MA	1.4	a	0.0	c	10.7	de
MI	1.2	a	0.3	c	7.4	f
NM	1.3	a	0.4	c	12.3	cd
NS	1.2	a	3.0	a	13.9	bc
NYG	1.5	a	1.5	b	14.9	ab
NYI	1.3	a	0.3	c	16.4	a
VT	1.4	a	0.3	c	10.2	e

[z]Values within a column for location or rootstock which share a letter do not differ at α=0.05 using Tukey's HSD adjustment for multiple comparisons.

Results

Tree Characteristics at and Soon after Planting. TCA at planting varied by rootstock.Trees on G.202 and G.890 were the largest and those on G.222 were the smallest (Table 2). The number of branches remaining after the initial pruning also varied by rootstock. Trees on G.890 had the most branches, and those on G.222 had the fewest. Graft union height varied somewhat by rootstock, with the highest unions for trees on G.222 and G.935 and the lowest for trees on M.9 NAKBT337 (Table 2).

Among sites, there were no significant differences in TCA at planting, but cooperators left differing numbers of lateral branches after the initial pruning (Table 2). Nova Scotia left the largest number, and New Mexico, California, Michigan, New York (Ithaca), Vermont, and Massachusetts had the fewest. Cooperators also differed in their approach to graft union height above the soil line after planting (Table 2). Graft unions were highest in New York (Ithaca), and lowest in Michigan.

Site Effects on Tree Performance. Over the 5 years of this trial, sites differed in all aspects of tree performance (Table 3). Among sites, survival was significantly lower in California (64%), than all other sites, and for the other nine locations, sur-

Table 3. Tree and fruiting characteristics (2019) of Modi trees in the 2015 NC-140 Organic Apple Rootstock Trial. All data are least-squares means adjusted for missing subclasses.[z]

	Survival (%, 2015-19)		Trunk cross-sectional area (cm^2, 2019)		Tree height (cm, 2019)		Canopy width (cm, 2019)		Root suckers (no./tree, 2015-19)		Yield per tree (kg, 2019)		Cumulative yield per tree (kg, 2016-19)		Yield efficiency (kg/cm^2 TCA, 2019)		Cumulative yield efficiency (kg/cm^2 TCA, 2016-19)		Fruit weight (g, 2019)		Average fruit weight (g, 2016-19)	
Location																						
CA	64	b	3.7	e	225	h	146	bc	2.1	bc	0.6	f	1.7	c	0.14	f	0.42	d	60	e	66	f
CO	97	a	6.3	d	266	ef	86	e	0.9	cd	0.8	f	1.9	c	0.14	f	0.32	d	169	a	149	c
ID	98	a	9.3	b	290	cd	138	bcd	4.9	a	10.8	a	13.2	a	1.26	a	1.51	a	145	abc	149	c
MA	95	a	7.4	cd	272	def	137	bcd	1.5	cd	0.7	f	1.7	c	0.09	f	0.25	d	108	d	116	e
MI	100	a	10.8	a	321	ab	170	a	1.6	cd	6.1	bc	13.1	a	0.56	cd	1.24	bc	151	ab	202	a
NM	95	a	9.4	ab	285	cde	142	bcd	3.1	b	2.7	def	9.4	b	0.29	def	1.00	c	110	d	85	f
NS	98	a	7.3	cd	254	fg	151	b	1.1	cd	6.8	b	10.4	ab	0.96	b	1.46	ab	140	bc	142	cd
NYG	95	a	9.9	ab	301	bc	125	d	3.3	b	4.2	cde	10.5	ab	0.47	de	1.17	bc	150	ab	139	cd
NYI	99	a	7.9	c	331	a	145	bc	0.7	cd	1.8	ef	7.7	b	0.20	ef	0.99	c	158	ab	170	b
VT	90	a	6.6	cd	232	gh	130	cd	0.3	d	5.1	bcd	10.9	ab	0.81	bc	1.72	a	121	cd	124	de
Rootstock																						
G.11	93	ab	6.7	d	268	c	139	b	1.0	d	4.3	abc	8.3	bcd	0.58	a	1.14	ab	128	a	133	ab
G.30	91	ab	8.8	b	294	b	140	b	1.8	cd	4.1	bc	8.9	bc	0.45	a	1.01	bc	137	a	141	a
G.41	96	a	8.9	b	289	b	148	b	0.8	d	4.1	bc	9.1	b	0.42	a	0.96	bcd	139	a	140	a
G.202	98	a	9.6	b	297	b	148	b	3.1	ab	3.7	c	7.4	bcde	0.36	a	0.73	d	130	a	126	b
G.214	90	ab	5.9	d	273	c	138	b	0.9	d	3.0	c	6.4	ef	0.49	a	1.04	bc	132	a	132	ab
G.222	93	ab	4.3	e	241	d	103	d	4.0	a	3.0	c	4.4	f	0.66	a	0.98	bcd	125	a	130	ab
G.890	96	a	13.6	a	328	a	171	a	3.4	ab	5.7	a	11.5	a	0.40	a	0.82	cd	133	a	138	a
G.935	93	ab	7.8	c	273	c	143	b	2.5	bc	5.4	ab	11.0	a	0.63	a	1.33	a	129	a	132	ab
G.969	95	a	6.4	d	266	c	126	c	1.0	d	3.1	c	7.1	cde	0.47	a	1.10	ab	130	a	133	ab
M.9 NAKBT337	86	b	6.4	d	248	d	113	d	0.8	d	3.1	c	6.6	def	0.44	a	0.97	bcd	130	a	138	a

[z]Values within a column for location or rootstock which share a letter do not differ at $\alpha=0.05$ using Tukey's HSD adjustment for multiple comparisons.

vival was 90% or better (Table 3). The largest trees by TCA were in Michigan, and smallest were in California (Table 3). Statistical separation for tree height among sites ranged on a gradient where the greatest height was in New York (Ithaca), followed by Michigan, and New York (Geneva), and lowest in California, followed by Vermont (Table 3). Similarly, canopy width varied by site, with greatest in Michigan, lowest in Colorado followed by New York (Geneva), and other sites intermediate (Table 3). Cumulative yield per tree (2016-19) was greatest in Michigan and Idaho and least in Colorado, Massachusetts, and California (Table 2). Yield efficiency (2016-19) was highest in Vermont and Idaho and lowest in Massachusetts, Colorado, and California (Table 3). On average (2016-19), fruit were largest in Michigan and smallest in California and Nova Scotia (Table 3).

Rootstock Effects on Tree Performance. Tree survival was affected by the combination of site and rootstock (Tables 3-5). Trees on M.9 NAKBT337 had significantly lower survival in California, New Mexico, and Nova Scotia than trees on G.41, G.202, G.890, and G.969 (Table 4). Rootstock did not significantly affect survival in Colorado, Idaho, Massachusetts, Michigan, New York (Geneva), or New York (Ithaca). Tree death was greater for G.30 in Vermont, where only 55% of trees survived through 2019 (Table 4), and causes listed included vole, dogwood borer, and winter damage (Table 5). In California, only 25% and 33% of the trees on M.9 NAKB337 and G.214, respectively, remained alive after five years (Table 4). Survival was relatively good only for trees on one rootstock, G.202. The reasons for tree loss were not consistent (Table 5). For instance, trees on M.9 NAKBT337 died due to weed competition (13%), fire blight infection (33%), and 53% were lost to unknown causes.

As is most often the case in NC-140 trials, TCA, tree height, and canopy spread were affected similarly by rootstock across the sites (Table 3). At all sites except California, the largest trees were on G.890, and at five of the 10 sites the smallest were on G.222 (Table 6). Where G.16 was included at a location, trees were equally small to those on G.222. Also, in California, trees on G.41 were the largest, but not significantly larger than those on G.30, G.202, G.214, G.890, or G.935. Trees on G.890, were consistently larger than those on G.222 and G.16 (where included in the trial) (Table 6). Root suckering was affected by rootstock (Table 3). G.222 produced the most root suckers, and G.969, G.11, G.214, G.41, and M.9 NAKBT337 produced the fewest root suckers. Location also affected root suckering, with the most produced from trees in Idaho and fewest from trees in Vermont.

The greatest yields per tree (2019 and cumulatively 2016-19) were harvested from trees on G.890 and G.935, and the lowest

Table 4. Survival (%, 2015-19) of Modi®® trees after five years in the 2015 NC-140 Organic Apple Rootstock Trial.[z]

Rootstock	CA		CO		ID		MA		MI		NM		NS		NYG		NYI		VT	
G.11	58	abc	100	a	100	a	83	a	100	a	100	a	100	a	92	a	100	a	100	a
G.16	---		97	a	86	a	100	a	100	a	100	a	---		79	a	100	a	92	a
G.30	67	abc	100	a	100	a	100	a	100	a	92	ab	100	a	100	a	100	a	55	b
G.41	83	ab	100	a	92	a	92	a	100	a	100	a	100	a	100	a	100	a	91	a
G.202	92	a	100	a	100	a	100	a	100	a	100	a	100	a	100	a	100	a	92	a
G.214	33	bc	100	a	92	a	92	a	100	a	100	a	100	a	92	a	100	a	92	a
G.222	51	abc	99	a	100	a	100	a	100	a	99	a	100	a	85	a	100	a	91	a
G.890	83	ab	92	a	100	a	100	a	100	a	92	ab	100	a	100	a	100	a	92	a
G.935	75	abc	83	a	92	a	92	a	100	a	100	a	100	a	92	a	100	a	95	a
G.969	75	abc	100	a	100	a	92	a	100	a	100	a	100	a	92	a	92	a	100	a
M.9 NAKBT337	25	c	100	a	100	a	91	a	100	a	66	b	78	b	100	a	100	a	93	a

[z] Values within a column for location or rootstock which share a letter do not differ at α=0.05 using Tukey's HSD adjustment for multiple comparisons.

Table 5. Cause of tree death (2015-19, no.) of Modi® apple trees at individual planting locations in the 2015 NC-140 Organic Apple Rootstock Trial.

					Causes of tree death (tree no.)						
Loc	Root	Initial tree count (no.)	Tree death (no.)	Tree death (%)	Weed competition	Breakage	Voles	Fire blight	Dogwood borer	Winter injury	Unknown cause
CA	G.011	12	5	42	1						4
CA	G.030	12	4	33	3						1
CA	G.041	12	2	17							2
CA	G.202	12	1	8							1
CA	G.214	12	8	67	2						6
CA	G.222	7	3	43							3
CA	G.890	12	2	17	1						1
CA	G.935	12	3	25							3
CA	G.969	12	4	33	1	2					1
CA	M.9T337	12	9	75	2						7
CO	G.890	12	1	8			1				
CO	G.935	12	2	17			2				
ID	G.016	6	1	17		1					
ID	G.041	12	1	8							1
ID	G.214	12	1	8		1					
ID	G.935	12	1	8							1
MA	G.011	12	2	17							2
MA	G.041	12	1	8							1
MA	G.214	12	1	8							1
MA	G.935	12	1	8							1
MA	M.9T337	9	1	11							1
NM	G.030	12	1	8				1			
NM	G.890	12	1	8				1			
NM	M.9T337	9	3	33				3			
NS	M.9T337	9	2	22				2			
NYG	G.011	12	1	8				1			
NYG	G.016	5	1	20		1					
NYG	G.214	12	1	8		1					
NYG	G.222	7	1	14			1				
NYG	G.935	12	1	8				1			
NYG	G.969	12	1	8		1					
NYI	G.969	12	1	8							1
VT	G.030	11	5	45			1		2	2	
VT	G.041	11	1	9					1		
VT	G.202	12	1	8				1			
VT	G.214	12	1	8				1			
VT	G.890	12	1	8				1			

yields were from trees on G.222 and G.214 (Table 3). For the main effect of location, the highest yields were harvested in Idaho, and the lowest were from California, Colorado, and Massachusetts (Table 3). Cumulative yields were mostly consistent across site (Table 7). Trees on G.890 and G.935 were among the highest yielding rootstocks, and trees on G.222 and G.16 (where planted) were among the lowest yielding rootstocks.

The effect of rootstock on yield efficiency in 2019 was consistent across sites (Table 3), but trees in Idaho were most yield efficient and those in California, Colorado, and Mas-

Table 6. Trunk cross-sectional area (cm^2, 2019) of Modi® trees after five years in the 2015 NC-140 Organic Apple Rootstock Trial.[z]

Rootstock	CA	CO	ID	MA	MI	NM	NS	NYG	NYI	VT
G.11	3.3 bcd	6.3 bc	8.5 cd	6.3 def	9.0 cde	7.4 ef	6.3 cd	7.9 c	6.4 cd	5.6 cde
G.16	---	1.1 e	5.3 de	3.5 f	7.1 def	5.3 f	---	5.0 c	3.7 d	3.5 e
G.30	4.2 abc	6.8 b	11.8 ab	8.5 bc	10.2 c	11.2 b	7.8 bc	12.6 b	8.2 bc	6.6 bcd
G.41	5.1 a	6.7 b	10.5 abc	7.9 bcd	13.6 b	9.9 bcd	8.3 b	9.8 bc	9.2 b	8.1 b
G.202	4.9 ab	7.8 ab	10.8 abc	9.4 b	13.1 b	10.7 bc	9.3 b	12.5 b	9.3 b	8.0 b
G.214	3.5 abcd	3.7 cde	7.4 de	6.9 cde	7.1 ef	6.9 ef	5.4 d	7.1 c	5.9 cd	5.6 cde
G.222	1.5 d	2.4 de	4.3 e	4.5 ef	6.0 f	6.0 f	5.3 d	5.3 c	4.6 d	3.5 e
G.890	4.6 abc	10.6 a	13.2 a	14.1 a	21.6 a	15.7 a	11.5 a	18.2 a	14.8 a	12.0 a
G.935	4.0 abc	7.0 b	9.2 bcd	5.6 def	10.1 c	9.9 bcd	8.2 b	8.1 c	9.5 b	6.9 bc
G.969	3.2 cd	5.0 bcd	9.0 bcd	6.4 de	7.6 def	8.8 cde	5.8 d	7.6 c	6.2 cd	4.8 cde
M.9 NAKBT337	2.7 cd	6.2 bc	8.6 bcd	4.6 ef	9.5 cd	7.4 def	5.5 d	9.4 bc	5.0 d	4.6 de

[z] Values within a column for location or rootstock which share a letter do not differ at α=0.05 using Tukey's HSD adjustment for multiple comparisons.

Table 7. Cumulative yield per tree (kg, 2016-19) of Modi® trees after five years in the 2015 NC-140 Organic Apple Rootstock Trial.[z]

Rootstock	CA	CO	ID	MA	MI	NM	NS	NYG	NYI	VT
G.11	1.3 a	2.1 abc	20.0 a	1.4 ab	13.9 bcd	7.9 cde	9.1 c	10.3 abcd	8.7 ab	8.4 bc
G.16	---	0.5 c	1.4 b	0.5 b	5.0 e	4.8 de	---	4.6 e	2.0 c	4.4 c
G.30	1.8 a	2.2 abc	11.7 ab	1.9 ab	13.3 cd	11.2 bc	10.8 bc	13.1 abc	7.5 b	15.3 a
G.41	2.5 a	1.6 abc	10.0 ab	1.8 ab	18.7 ab	9.2 cd	10.4 bc	13.6 ab	9.3 ab	14.2 a
G.202	2.7 a	1.7 abc	11.5 ab	1.7 ab	15.5 abc	6.5 de	9.2 c	9.5 cde	6.2 bc	9.3 bc
G.214	1.6 a	1.1 bc	6.2 b	1.8 ab	8.0 e	9.1 cd	8.7 c	8.7 de	6.2 bc	12.1 ab
G.222	0.0 a	0.6 c	13.2 ab	1.1 ab	4.0 e	4.2 e	6.0 c	5.2 e	2.7 c	6.9 c
G.890	1.5 a	2.3 abc	15.2 ab	2.3 a	20.2 a	17.7 a	15.9 a	14.3 a	12.0 a	13.8 a
G.935	2.9 a	2.2 abc	16.8 ab	1.9 ab	19.6 a	13.3 b	15.1 ab	12.2 abcd	12.0 a	14.0 a
G.969	1.9 a	2.9 a	12.8 ab	2.4 a	8.9 de	7.5 cde	9.7 c	9.8 bcde	6.5 bc	8.8 bc
M.9 NAKBT337	0.7 a	2.7 ab	14.3 ab	0.7 b	9.5 de	7.3 cde	9.3 c	8.2 de	6.5 bc	6.5 c

[z] Values within a column for location or rootstock which share a letter do not differ at α=0.05 using Tukey's HSD adjustment for multiple comparisons.

Table 8. Cumulative yield efficiency (kg/cm2, 2016-19) of Modi® trees in the 2015 NC-140 Organic Apple Rootstock Trial.[z]

Rootstock	CA	CO	ID	MA	MI	NM	NS	NYG	NYI	VT
G.11	0.39 ab	0.31 ab	2.34 a	0.24 ab	1.57 ab	1.02 ab	1.43 ab	1.31 ab	1.30 a	1.54 abc
G.16	---	0.38 ab	0.57 a	0.13 b	0.76 d	0.94 abc	---	1.06 ab	0.57 c	1.37 abc
G.30	0.47 ab	0.32 ab	1.03 a	0.27 ab	1.29 bcd	1.02 ab	1.41 ab	1.11 ab	0.95 abc	2.22 a
G.41	0.48 ab	0.23 b	0.89 a	0.23 ab	1.43 bc	0.93 bc	1.29 ab	1.43 a	0.98 abc	1.73 abc
G.202	0.53 ab	0.22 b	1.06 a	0.19 b	1.17 bcd	0.61 c	1.02 b	0.76 b	0.66 c	1.14 c
G.214	0.45 ab	0.32 ab	0.83 a	0.27 ab	1.12 bcd	1.36 a	1.61 ab	1.26 ab	1.06 ab	2.13 a
G.222	0.05 b	0.27 ab	2.88 a	0.27 ab	0.81 d	0.71 bc	1.19 ab	1.11 ab	0.60 c	1.91 ab
G.890	0.29 ab	0.24 b	1.15 a	0.17 b	0.94 d	1.14 ab	1.45 ab	0.82 b	0.78 bc	1.18 bc
G.935	0.71 a	0.32 ab	1.90 a	0.33 ab	1.90 a	1.35 a	1.91 a	1.62 a	1.27 a	1.99 a
G.969	0.56 ab	0.57 a	1.42 a	0.40 a	1.18 bcd	0.85 bc	1.70 a	1.31 ab	1.07 ab	1.92 a
M.9 NAKBT337	0.29 ab	0.41 ab	1.56 a	0.17 b	1.03 cd	0.98 abc	1.61 ab	0.98 ab	1.18 a	1.43 abc

[z] Values within a column for location or rootstock which share a letter do not differ at α=0.05 using Tukey's HSD adjustment for multiple comparisons.

sachusetts were lowest. Cumulatively (2016-19), trees on G.935 were the most yield efficient, and those on G.202 were the least efficient. Trees in Vermont and Idaho had the greatest cumulative yield efficiency, and those in California, Colorado, and Massachusetts were the lowest. Although the location by rootstock interaction was significant, the relative differences among rootstocks did not vary greatly with location (Table 8).

Across all sites, average fruit weight in 2019 did not vary significantly with rootstock (Table 3), but the largest fruit were harvested in Colorado, and the smallest fruit were harvested in California. Averaged over all fruiting years and sites, trees on G.30, G.41, G.890, and M.9 NAKBT337 produced the largest fruit, and those on G.202 produced the smallest (Table 3). Averaged across all rootstocks and years, the largest fruit were from Michigan, and the smallest were from California (Table 3). Within the Massachusetts, Michigan, and the two New York locations, rootstock did not affect average fruit weight (Table 9).

Discussion

Trees were generally of commercially acceptable size at planting, but the caliper range was relatively large for some rootstocks, which was the initial justification for using tree size as the blocking factor in the experimental design. However, blocking by initial TCA may not have been necessary and may have complicated statistical analysis. If location within a planting, rather than initial TCA, was used as the blocking factor , initial tree size could have been used as a covariate. At planting, G.202 trees had substantially smaller TCA than the other rootstocks. We would expect trees approaching maturity, i.e., after their fifth season of growth, to catch up in size, and as discussed below, trees grafted onto G.202 do not appear to have suffered from long-term vigor deficiency as a result of being smaller than other trees at planting.

The primary differences that existed at trial establishment were in the number of retained shoots and the planted height of the graft union above ground level. While differences in retained shoots attributable to rootstock would be explained by relative vigor and branching habit in the nursery, differences attributable to site factors likely stem from cooperators' management practices, as all trees were sourced from the same nursery and ostensibly would have arrived at each location with relatively the same number of shoots. Differences in graft union height above the soil line among the plantings could be attributed to specific conditions at each site and cooperators' use of union height to adjust relative dwarfing effect to compensate for soil or other conditions. For example, trees in Vermont are planted

Table 9. Average fruit weight (g, 2016-19) of Modi® trees in the 2015 NC-140 Organic Apple Rootstock Trial.[z]

Rootstock	CA		CO		ID		MA		MI		NM		NS		NYG		NYI		VT	
G.11	75	ab	151	ab	148	abc	113	a	182	a	79	bc	144	ab	136	a	174	a	127	ab
G.16	---		145	ab	130	c	101	a	208	a	78	bc	---		138	a	172	a	137	a
G.30	74	ab	144	ab	161	a	116	a	205	a	90	ab	148	ab	139	a	197	a	136	a
G.41	77	ab	187	a	146	abc	115	a	204	a	91	ab	144	ab	149	a	162	a	127	ab
G.202	55	ab	134	b	146	abc	127	a	175	a	76	c	136	ab	134	a	157	a	115	b
G.214	43	b	157	ab	143	bc	114	a	206	a	88	abc	139	ab	136	a	175	a	122	ab
G.222	51	ab	143	ab	135	c	112	a	218	a	86	abc	133	ab	136	a	163	a	126	ab
G.890	58	ab	150	ab	155	ab	123	a	192	a	92	a	167	a	140	a	176	a	125	ab
G.935	66	ab	137	b	156	ab	109	a	205	a	93	a	145	ab	132	a	166	a	113	b
G.969	84	a	135	b	145	bc	120	a	210	a	79	bc	132	b	141	a	159	a	124	ab
M.9 NAKBT337	79	ab	152	ab	152	abc	111	a	223	a	76	c	134	ab	147	a	178	a	124	ab

[z] Values within a column for location or rootstock which share a letter do not differ at α=0.05 using Tukey's HSD adjustment for multiple comparisons.

on a sandy soil with low inherent vigor and organic matter, so that cooperator typically plants trees lower to reduce overall relative dwarfing effect. On the other hand, trees in Ithaca, New York were planted in heavy clay, in which deeper planting is more difficult and trees settle less after planting compared to sandier soils. A comparison of graft union height from the soil line and overall tree vigor may be of interest, but the differences in soil type and subsequent management are likely to minimize any effects observed from that one variable.

Site and rootstock differences in this trial may likely be exacerbated more so than other NC-140 trials because organic management practices were specific to each site. Additionally, the cooperators in this trial have varying levels of experience with organic management, and plantings established on commercial partners' farms that were subject to local management may have deviated from ideal conditions. For example, weed competition was cited as a major cause of tree death in CA, and vole damage, which is often a result of suboptimal weed management, was cited in three other states. Given the increased labor and/or input requirements of organic management to maintain adequate weed control, we might expect that this factor alone could have affected overall tree performance as much as site or rootstock factors.

All trees in this trial had smaller TCA when measured at the end of the fifth season of growth than what has previously been reported for other comparable NC-140 trials using conventional, non-organic management practices. For example, in the 2010 NC-140 'Honeycrisp' and 'Fuji' rootstock trials, TCA of trees on M.9 NAKBT337 was 50% and 180% larger, respectively, after 5 years than the 'Modi®' trees in this trial, despite being the same size at planting (Autio et al., 2017a; Autio et al., 2017b). This comparison however, is limited by the different scion cultivar and especially by the overlap of only one state between the trials, but the difference is substantial and further supports the conclusion that organically-managed trees in this trial were under-sized after 5 years compared to their potential when grown under non-organic management.

It is possible that differences observed in this trial that deviate from past trials conducted under non-organic management reflect differences in the ability of rootstocks to uptake nutrients when grown using organic practices. Reig et al. (2018) showed significant differences in leaf and fruit tissue concentrations of virtually all mineral nutrients among rootstocks. Therefore, rootstock performance may vary with different management programs, such as organic vs. non-organic systems, due to different abilities to acquire and utilize nutrients. In comparisons of organic and non-organic management, even on the same rootstocks, mineral nutrient concentrations commonly vary by management system. In a Washington State study, leaf mineral concentrations were lower for N, S, Mg, and B in organic compared to non-organic treatments (Peck et al., 2006). In a New York trial, however, leaf concentrations for several mineral nutrients were higher for trees grown with organic than non-organic management (Peck et al., 2010). These references are included not to suggest that trees with organic management are better or worse suited to mineral nutrient uptake, but rather that substantial differences in orchard management can have significant impact on rootstock performance. Growers practicing organic management may likely require rootstocks with greater nutrient and water use efficiency than for trees in non-organic systems, and these results for the orchard establishment phase of the trial provide initial data for that consideration. In this trial, soil fertility management was the same for all rootstocks within each site. Therefore, differences in a rootstocks' ability to uptake nutrients will be confounded in site differences and thus are not able to be analyzed under the present experimental design. To better evaluate nutrient and water use efficiency under organic management, increased tree numbers and more complex experimental design would be required to add in a variable nutrient treatment that could better study these factors.

Using the approach described by Autio et al. (2020a), trees were grouped into vigor class by TCA. Groupings were as follows (with ranges as percent of the TCA of trees on M.9 NAKBT337): trees on G.890 were large semi-dwarfs (200+%), trees on G.202 were moderate semi-dwarfs (150-200%), trees on G.41 and G.30 were small semi-dwarfs (130-150%), trees on G.935 were large dwarfs (110-130%), trees on G.11, G.214, and G.969 were moderate dwarfs (80-110%), and trees on G.222 were small dwarfs (40-80%). These size class rankings are generally consistent with prior trials, with some caveats. In an eight-year summary of eleven dwarf rootstocks with 'Liberty' as scion, G.202 trees were 20% larger than those grafted on M.9 (Robinson et al., 2003), yet in a later trial with 'McIntosh' as scion across nine sites in northern or mid-Atlantic states, G.202 trees were approximately 200% the size of trees on M.9 after five years (Autio et al., 2011a). In a similar five-year summary of a 1999 NC-140 trial with 'Fuji' and 'McIntosh' scions, G.41 trees had similar TCA to M.9, which is inconsistent with the results of this study. Several other studies have similarly reported G.41 trees to be similar in TCA to M.9 (Dallabetta et al., 2018; Lordan et al., 2018; Marini et al., 2014).

In several NC-140 studies trees on G.30 were relatively vigorous compared with M.9 or the small semidwarf M.26, which is consistent with its TCA ranking among rootstocks in this trial (Hirst, 2000; Marini et al., 2006; Robinson et al., 2004). Likewise, in earlier trials, trees on G.935 had similar TCA compared to M.9 clones (Autio et al., 2017a; Autio et al., 2017b; Marini et al., 2006). Grafted to the scion cultivars 'Honeycrisp' and 'Fuji', trees on G.11 were classified by as moderate dwarf, but trees grafted to G.214 varied in size by scion cultivar, producing large dwarf and small dwarf trees, respectively (Autio et al., 2017a; Autio et al., 2017b). Despite being the smallest trees in this study, trees on G.222 have been variable in terms of TCA. For example, Autio et al. (2017b) reported that trees on G.222 ranked eighth largest of twenty-five for TCA after ten years, and it was classified moderate semi-dwarf rootstock. The practical implication associated with sorting into these size classes would be to vary spacing of trees within a trial or a production orchard based upon this relative vigor scale. As such, some rootstocks are likely planted too close together in the row in this trial, while others would perform more optimally with a closer planting distance. These plantings will continue to produce during the next five production years, and complete analysis of their performance should include optimal spacing as a metric for potential crop yield.

In this trial, G.202 and G.16 had the lowest cumulative yield efficiency, whereas G.935 and G.11 had the highest efficiency. These results are similar to the ranking in the five-year performance of those rootstocks grafted to 'Honeycrisp' and 'Fuji' (except for G.16, which was not in those trials), although there was little statistically relevant separation between the rootstocks for yield efficiency or fruit weight (Autio et al., 2017a; Autio et al., 2017b). However, compared to those two trials, cumulative yield in the fifth year for this organically-managed trial is about one-third that for non-organically managed trees. Despite differences in cultivars and sites, the magnitude of difference suggests that yield may not yet be sufficient to judge performance of these rootstocks.

Fruit weight is another factor in this trial that differed substantially from previous studies managed under non-organic conditions and including the same rootstocks. Cultivar has significant effect on fruit weight, so comparing 'Modi®' to other cultivars is impossible. In this trial, fruit weight averaged over all years and rootstocks ranged from 202 g in MI to 60 g in CA, with no consistent ranking among the rootstocks and no differences among rootstocks in five of the states. Five states also had mean fruit weight less than 140 g—the threshold often used for grading into the low-priced processing category (Bradshaw et al., 2016b) or outright culled (Wargo et al., 2003). Even if applying a less stringent cutoff of 122 g for fresh market as opposed to lower-value cider fruit as proposed by Peck (2010), four states in this trial would still have mean fruit weight in the lower-value category. By comparison, in other NC-140 trials mean fruit weight for the first five years ranged from 210 g to 238 g for 'Fuji' to 164 g to 322 g for 'Honeycrisp' (Autio et al., 2017a; Autio et al., 2017b). It is important to consider that, under USDA-NOP organic certification, most plant growth regulator thinning products are disallowed. This means that crop load adjustment must be carried out by using caustic materials (such as liquid lime sulfur) or hand thinning, and it is not likely that this was performed consistently across all sites. Average fruit weight is strongly and negatively correlated with crop density, and analysis of covariance considering both rootstock and crop density will be evaluated in future publications about this trial.

Given the relatively smaller tree and fruit size and concomitant poor performance of trees under organic management in this trial compared to other NC-140 trials, the data presented should be considered preliminary. As with prior NC-140 trials, this trial will continue through the tenth growing season, after which a more thorough evaluation will be presented. The lead author, and project coordinator, is working with participants to develop more robust organic management systems that better reflect the regionally used best management practices.

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