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Budagovsky, Geneva, Pillnitz, and Malling Apple Rootstocks Affect 'Fuji' Performance Over Eight Years in the 2010 NC-140 'Fuji' Apple Rootstock Trial

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Abstract

In 2010, an orchard trial of apple rootstocks was established at seven locations in the United States and Mexico using 'Zhen® Fuji Aztec[c.o.v.]' as the scion cultivar. Rootstocks included two named clones from the Budagovsky series (B.9, B.10), five unreleased Budagovsky clones (B.7-3-150, B.64-194, B.67-5-32, B.70-6-8, and B.71-7-22), four named Cornell-Geneva clones [Geneva® 11 (G.11), Geneva® 41 (G.41), Geneva® 202 (G.202), and Geneva® 935 (G.935)], nine unreleased Cornell-Geneva clones (CG.2034, CG. 3001, CG.4003, CG.4004, CG.4013, CG.4214, CG.4814, CG.5087, and CG.5222), one named clone from the Pillnitz series (Supp.3) and one unreleased Pillnitz clone (PiAu 51-11), and three Malling clones as controls (M.9 NAKBT337, M.9 Pajam 2, and M.26 EMLA). For G.41 and G.935, there were both stool-bed-produced (N) and tissue-culture-produced (TC) rootstock liners used for trees. All trees were trained to a Tall Spindle. After 8 years, the greatest mortality was for trees on Supp.3 (22%), M.9 NAKBT337 (21%), M.9 Pajam 2 (19%), B.71-7-22 (19%), and M.26 EMLA (16%). Rootstocks were partitioned into size classes from sub-dwarf to large semi-dwarf. B.7-3-150, B.70-6-8, B.67-5-32, B.64-194, and PiAu 51-11 resulted in large semi-dwarf trees with comparably low cumulative yield efficiency and projected cumulative yield per ha. CG.4004, CG.3001, CG.5222, and M.26 EMLA produced moderate semi-dwarf trees. The most yield efficient and highest yielding trees in this group were on CG.4004, CG.3001, and CG.5222. The large dwarf category included G.935N, G.935TC, CG.4814, G.41N, and M.9 Pajam 2. Trees on G.935N and G.935TC were the most yield efficient, and G.935N had the highest projected per-hectare cumulative yield for their size category. Trees on CG.4214, M.9 NAKBT337, G.11, G.202, B.10, G.41TC, and Supp.3 were moderate dwarfs. Trees on CG.4214, M.9 NAKBT337, G.11, G.202, and B.10 were the most yield efficient and had the highest potential yield per hectare in this size category. The small dwarf category included CG.2034, B.9, and CG.4003. These three rootstocks produced trees which were similarly yield efficient and had similar projected per-hectare yields. B.71-7-22 was classified as a sub-dwarf, and produced a tree which was highly yield efficient, with a relatively low projected per-hectare yield.

For more than 40 years, the NC-140 Multi-State Research Project has involved researchers from throughout North America to evaluate fruit-tree performance on different rootstocks utilizing uniform trials at diverse locations, with the principle goal of helping orchardists optimize their rootstock selection (Cowgill et al., 2017). Apple rootstocks from the United States, Canada, the United Kingdom, Japan, Russia, Poland, Germany, and the Czech Republic, have been evaluated under the direction of NC-140.

A number of new rootstocks have become available from the Budagovsky, Cornell-Geneva, and Pillnitz breeding programs. Budagovsky rootstocks, from the Michurinsk State Agrarian University in Michurinsk, Tambov Region, Russia, have been evaluated in a number of NC-140 trials (Autio et al., 2001a; 2001b; 2013; Marini et al., 2001a; 2001b; 2006; 2014; NC-140, 1996; Robinson et al., 2007). Many Cornell-Geneva apple rootstocks, from a breeding program managed jointly by Cornell University and the United States Department of Agriculture-Agricultural Research Service, have been evaluated by NC-140 (Autio et al., 2011a; 2011b, 2013; Marini et al., 2014; Robinson et al., 2007). Likewise, a number of Pillnitz rootstocks, from the Institut für Obstforschung

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Dresden-Pillnitz, Germany (Fischer, 1997), have been evaluated by NC-140 (Autio et al., 2011a; 2011b; 2013; Marini et al., 2014).

The objectives of this trial were to assess and compare the performance of several Budagovsky, Cornell-Geneva, and Pillnitz rootstocks at multiple sites in North America, exposing the rootstocks to diverse climate, soil, and management conditions. A second objective was to compare the method of rootstock propagation (stoolbed vs. tissue culture) on the performance of two Geneva rootstocks.

Materials and Methods

In spring, 2010, an orchard trial of 27 apple rootstocks was established at seven sites in North America (Table 1) under the coordination of the NC-140 Multi-State Research Committee. 'Zhen® Fuji Aztec$^{c.o.v.}$' was used as the scion cultivar, and trees were propagated by Willow Drive Nursery (Ephrata, WA, USA). Rootstocks included two named clones from the Budagovsky series (B.9, B.10), five unreleased Budagovsky clones (B.7-3-150, B.64-194, B.67-5-32, B.70-6-8, and B.71-7-22), four named Cornell-Geneva clones [Geneva® 11 (G.11), Geneva® 41 (G.41), Geneva® 202 (G.202), and Geneva® 935 (G.935)], nine unreleased Cornell-Geneva clones (CG.2034, CG. 3001, CG.4003, CG.4004, CG.4013, CG.4214, CG.4814, CG.5087, and CG.5222), one named clone from the Pillnitz series (Supp.3), one unreleased Pillnitz clone (PiAu 51-11), and three Malling series clones to serve as controls (M.9 NAKBT337, M.9 Pajam 2, and M.26 EMLA). Additionally, there were both stool-bed-produced (denoted with an N following the rootstock name) and tissue-culture-produced (denoted with a TC following the rootstock name) rootstock liners used for trees on G.41 and G.935. The trial initially included four additional rootstocks. B.70-20-20 was maintained in the trial through the first 5 years but was deemed too vigorous, similar to a standard seedling rootstock. B.7-20-21 remained in the trial throughout, but it clearly was incorrectly identified, producing a subdwarf tree, when it should have produced a semidwarf. PiAu 9-90, likewise, was kept in the trial, but extreme variability among trees suggested that there was a mistake in the propagation of the trees or the rootstocks. The trial initially had G.202 from both stool-bed-produced liners and tissue-cultured liners. A dramatic difference between the two sources resulted in genetic testing that identified the stool-bed-liner trees as not true G.202. B.7-20-21, PiAu 9-90, and G.202 (stool-bed liners) were eliminated from the data set prior to the analyses presented here. Please note that this trial is very similar in nature to the 2010 NC-140 'Honeycrisp' Apple Rootstock Trial (Autio et al., 2020), except for the cultivar, planting locations, and tree spacing.

The trial was planted in Chihuahua (Mexico), Idaho, Kentucky, New York, North Carolina, Pennsylvania, and Utah. 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 at each location, with four replications. Blocks were defined by physical location in the field, and trees were allocated to blocks by initial TCA (largest trees in block 1 and smallest in block 4). Each replication included one plot per rootstock, and each rootstock plot included one to three trees. Trees were spaced 1.8 x 4.3

Table 1. Cooperators and sites in the 2010 NC-140 Fuji Apple Rootstock Trial.

Site	Planting location	NC-140 Cooperator	Cooperator affiliation and address
	No planting	Wesley Autio	Stockbridge School of Agriculture, 205 Paige Laboratory, University of Massachusetts, Amherst, MA 01003 USA
	No planting	Terence Robinson	Department of Horticulture, Cornell University, NYSAES, Geneva, NY 14456 USA
Chihuahua (CH)	Cuauhtémoc	Rafael Parra Quezada	Universidad Autonoma de Chihuahua, Facultad de Ciencias Agrotecnologicas, Cuauhtémoc, Chih. 31527, Mexico
Idaho (ID)	Parma	Esmaeil Fallahi	University if Idaho Parma Research & Extension Center, 29603 U of I Lane, Parma, ID 83660 USA
Kentucky (KY)	Princeton	Dwight Wolfe	University of Kentucky Research & Education Center, 1205 Hopkinsville Street, Princeton, KY 42445 USA
New York (NY)	Highland	Gemma Reig, Stephen Hoying	Hudson Valley Research Laboratory, Cornell University, P.O. Box 727, Highland, NY 12528 USA
North Carolina (NC)	Mills River	Michael Parker	Department of Horticultural Science, North Carolina State University, Campus Box 7609, Raleigh, NC 27695 USA
Pennsylvania (PA)	Rock Springs	Robert Crassweller	Department of Plant Science, The Pennsylvania State University, 7 Tyson Building, University Park, PA 16802 USA
Utah (UT)	Kaysville	Brent Black	Plant, Soil, and Climate Department, Utah State University, Logan, UT 84322 USA

m and trained as tall spindles (Robinson and Hoying, 2011). Pest management, irrigation, fertilization, and crop-load management were consistent among all trees at a site and followed local recommendations.

Trunk circumference, 25 cm above the bud union, was measured in Oct. 2017 and used to calculate trunk cross-sectional area (TCA). Also in Oct. 2017, 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 each year

Yield was assessed in 2011 through 2017; however, very few sites harvested any fruit in 2011. Biennial Bearing Index (BBI) was calculated with yields from 2012-17 using the approach of Hoblyn et al. (1936). To present an estimate of mature yield per tree, 2016 and 2017 annual yields per tree were averaged as a way of overcoming the variation caused by a high degree of biennial bearing.

Cumulative yield efficiency ($kg \cdot cm^{-2}$ TCA) was calculated using cumulative yield (2011-2017) and 2017 TCA. However, to give an indication of mature tree yield efficiencies, yield efficiency of the last two years of the project was calculated in 2016 and 2017, and the average is presented to avoid variation due to biennial bearing. Yield efficiency, however, may not adequately predict relative orchard yield because of the wide range in tree vigor represented in this trial, and the fact that once tree canopies fill their allotted orchard space, rootstock effects on yield efficiency are modified differentially by pruning severity. To at least partially address this concern, recommended tree densities were estimated for each tree, and potential cumulative yield was estimated on a per-hectare basis. As a first step, it was assumed that rootstocks categorized as subdwarf could be spaced at 0.8 x 3.3 m, small dwarfs at 1.0 x 3.5 m, moderate dwarfs at 1.2 x 3.7 m, large dwarfs at 1.5 x 4.0 m, small semi-dwarfs at 1.8 x 4.3 m, moderate semi-dwarfs at 2.0 x 4.5 m, and large semi-dwarfs at 2.3 x 4.8 m. A quadratic regression relationship was built for TCA's less than 90 cm^2 and projected density from the spacing noted above ($Y = 4666.7 - 85.314X + 0.4688X^2$). Because the TCAs ranged well above the average for the most vigorous tree category, a different linear relationship was fit for trees with TCA greater than 90 cm^2 ($Y = 1246.3 - 5.1805X$). This two-part regression relationship was used to estimate a planting density for every tree based on its TCA. The product of predicted planting density and the cumulative yield per tree gave the projected cumulative yield per ha.

As part of the measurement of yield in 2011-17, total number of fruit was counted. These data were used to assess average fruit weight. Because of the effects of biennial bearing, and therefore crop load, on fruit size, fruit weight from a mature tree is presented as the average of 2016 and 2017. Average fruit weight was also calculated for the life of the trial. In both cases the average was calculated as the total weight of fruit divided by the total number of fruit over the assessment period, i.e. 2016 and 2017 or 2011 through 2017.

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 2014), TCA (2017), cumulative yield per tree (2011-17), cumulative yield efficiency (2011-17), BBI (2011-17), and average fruit size (2012-17). Because of the large number of treatments included and the variation in the number of observations per treatment, average Tukey's HSD values ($P = 0.05$) were calculated using the error MS from PROC GLM and the average number of observations per rootstock. Statistically, this approach is inadequate, but it is very conservative in assessing dif-

Table 2. Site means for trunk cross-sectional area, root suckers, yield per tree, yield efficiency, and fruit size of Fuji apple trees in the 2010 NC-140 Fuji Apple Rootstock Trial. Means are based on data from ID, KY, NC, NY, PA, and UT. All values are least-squares means, adjusted for missing subclasses.[z]

Location	Survival (2010-17, %)	Trunk cross-sectional area (2017, cm^2)	Tree height (2017, cm)	Canopy width (2017, cm)	Cumulative root suckers (2010-17, no./tree)	Yield per tree (average, 2016-17, kg)	Cumulative yield per tree (2011-17, kg)	Biennial Bearing Index (0-1)	Yield efficiency (average 2016-17, kg/cm^2 TCA)	Cumulative yield efficiency (2011-17, kg/cm^2 TCA)	Fruit weight (2016-17, g)	Average Fruit weight (2012-17, g)
ID	100	48.4	366	175	0.5	33.4	166	0.46	0.81	3.77	221	231
KY	83	62.5	357	236	20.5	24.3	70	0.56	0.52	1.34	158	162
NC	90	45.7	366	276	8.5	13.3	64	0.66	0.37	1.77	195	203
NY	100	37.7	535	180	3.8	32.6	121	0.78	1.14	3.74	171	174
UT	97	58.4	391	247	20.4	18.9	88	0.62	0.43	1.69	220	207
Estimated HSD	9	9.2	26	16	3.2	3.2	10	0.06	0.16	0.24	15	12

[z] Mean separation in columns by Tukey's HSD ($P = 0.05$). HSD was calculated based on the average number of observations per mean.

ferences and allows for a reasonable look at rootstock effects.

Results

Site Effects on Tree Performance. Over the 8 years of this trial, site affected all aspects of tree performance (Table 2). Table 2 includes data only from the five sites with a complete set of rootstocks (excluding CG.4013 and CG.5087). Chihuahua and Pennsylvania were involved in the trial but did not end with a complete set of rootstocks and therefore are not included in the results presented in Tables 2 and 3. Results from Chihuahua and Pennsylvania, however, are included in the tree performance data presented by location in Tables 4-10.

Among all sites, survival was least in Ken-

Table 3. Rootstock means for trunk cross-sectional area, root suckers, yield per tree, yield efficiency, and fruit size of Fuji apple trees in the 2010 NC-140 Fuji Apple Rootstock Trial. Means are based on data from ID, KY, NC, NY, and UT. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	Survival (2010-17, %)	Trunk cross-sectional area (2017, cm^2)	Tree height (2017, cm)	Canopy width (2017, cm)	Projected tree density (no./ha)	Cumulative root suckers (2010-17, no./tree)	Yield per tree (average, 2016-17, kg)	Cumulative yield per tree (2011-17, kg)	Biennial Bearing Index (0-1)	Yield efficiency (average, 2016-17, kg/cm^2 TCA)	Cumulative yield efficiency (2011-17, kg/cm^2 TCA)	Projected cumulative yield (2011-17, MT/ha)	Fruit weight (2016-17, g)	Average Fruit weight (2012-17, g)
B.9	97	17.9	280	153	3331	14.0	12.8	59	0.58	0.76	3.23	177	159	167
B.10	91	37.6	372	205	2160	2.8	23.8	94	0.62	0.74	2.66	199	201	199
B.7-3-150	100	83.0	487	261	984	3.4	26.7	109	0.58	0.41	1.55	114	198	200
B.64-194	94	84.9	480	259	947	13.4	28.4	106	0.58	0.44	1.42	102	207	208
B.67-5-32	98	82.3	462	245	979	5.9	28.8	108	0.61	0.43	1.43	104	198	200
B.70-6-8	100	88.3	493	262	915	2.2	27.4	113	0.58	0.40	1.48	108	197	199
B.71-7-22	81	11.1	242	154	3808	7.5	7.3	32	0.64	0.83	3.43	117	175	175
G.11	97	41.6	391	225	2005	4.1	24.7	105	0.63	0.73	2.83	217	204	205
G.41N	101	48.3	420	235	1781	3.4	29.1	123	0.62	0.74	2.49	184	205	211
G.41TC	99	43.0	422	238	1848	10.4	25.6	103	0.56	0.67	2.32	183	195	205
G.202	100	36.9	371	206	2242	17.8	23.1	98	0.63	0.70	2.82	210	183	180
G.935N	94	47.1	420	237	1787	11.2	32.8	143	0.59	0.81	3.35	257	200	198
G.935TC	95	48.8	388	222	1884	30.1	25.1	111	0.60	0.70	2.81	209	200	200
CG.2034	88	20.9	301	169	3015	9.1	15.1	68	0.62	0.82	3.28	208	190	189
CG.3001	100	63.5	462	249	1234	8.4	31.0	134	0.66	0.57	2.20	161	201	207
CG.4003	100	23.2	322	181	2939	3.6	14.3	67	0.55	0.70	3.10	197	162	163
CG.4004	100	59.9	453	248	1388	13.4	35.0	149	0.65	0.69	2.63	198	211	214
CG.4214	100	32.5	373	211	2445	14.1	23.6	93	0.60	1.16	3.16	224	191	193
CG.4814	95	47.8	397	233	1787	20.1	28.5	111	0.61	0.72	2.61	201	182	187
CG.5222	100	60.6	464	254	1317	19.5	28.9	124	0.64	0.55	2.14	160	196	201
Supp.3	78	37.4	343	199	2165	3.9	18.6	77	0.66	0.58	2.20	165	169	174
PiAu 51-11	94	88.7	481	258	938	3.9	27.9	104	0.66	0.41	1.39	101	213	214
M.9 NAKBT337	79	39.4	380	213	2159	15.2	24.2	100	0.65	0.60	2.88	215	191	195
M.9 Pajam 2	81	46.4	400	204	1818	29.6	23.5	108	0.62	0.74	2.48	189	193	196
M.26 EMLA	84	72.6	476	249	1088	1.9	26.7	113	0.66	0.45	1.68	122	203	210
Estimated HSD	20	13.0	42	30	346	15.7	6.3	23	0.12	0.35	0.65	41	23	17

[z] Mean separation in columns by Tukey's HSD ($P = 0.05$). HSD was calculated based on the average number of observations per mean.

Table 4. Survival (2010-17, %) of Fuji apple trees at individual planting locations in the 2010 NC-140 Fuji Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	CH	ID	KY	NC	NY	PA	UT
B.9	100	100	92	92	100	100	100
B.10	100	100	92	70	100	100	92
B.7-3-150	100	100	100	100	100	100	100
B.64-194	100	100	71	100	100	100	100
B.67-5-32	100	100	92	100	100	100	100
B.70-6-8	100	100	100	100	100	92	100
B.71-7-22	100	100	70	56	89	100	90
G.11	100	100	88	100	100	100	100
G.41N	---	100	100	100	100	50	100
G.41TC	100	100	100	100	100	---	100
G.202	100	100	100	100	100	100	100
G.935N	100	100	90	90	100	88	90
G.935TC	100	100	75	100	100	75	100
CG.2034	---	100	50	100	100	100	100
CG.3001	0	100	100	100	100	100	100
CG.4003	100	100	100	100	100	100	100
CG.4004	67	100	100	100	100	---	100
CG.4013	---	---	100	67	100	67	100
CG.4214	100	100	100	100	100	100	100
CG.4814	40	100	100	100	100	33	75
CG.5087	100	100	100	100	---	---	50
CG.5222	100	100	100	100	100	100	100
Supp.3	75	100	40	67	100	67	83
PiAu 51-11	100	100	91	80	100	75	100
M.9 NAKBT337	75	100	33	60	100	90	100
M.9 Pajam 2	100	100	44	63	100	100	100
M.26 EMLA	100	100	45	83	100	100	92
Estimated HSD	40	---	65	75	26	65	47

[z] Mean separation in columns by Tukey's HSD ($P = 0.05$). HSD was calculated based on the average number of observations per mean.

tucky and greatest in Idaho, New York, and Utah. NC, PA, and CH were intermediate (Table 4).

The largest trees by TCA were in Kentucky and Utah, and smallest were in New York. Root suckering was most in Kentucky and Utah and least in Idaho.

Yield per tree in 2016/17 was greatest in Idaho and, cumulatively (2011-17), was greatest in Idaho and least in North Carolina and Kentucky. Biennial bearing was most in New York and least in Idaho. In 2016/17, the most yield efficient trees were in New York, and the least were in North Carolina and Utah. Cumulatively (2011-17), the most yield efficient trees were in Idaho and New York, and the least were in Kentucky. Largest fruit in 2016/17 were harvested in Idaho and Utah, and smallest were harvested in New York and Kentucky. Over the life of the trial, largest fruit were in Idaho, and smallest were in Kentucky and New York.

Rootstock Effects on Tree Performance. Survival was affected by rootstock (Tables 3-5), with the lowest for trees on Supp.3, M.9 NAKBT337, B.71-7-22, M.9 Pajam 2, and M.26 EMLA. Nearly 80% of these tree deaths were attributed to fireblight. Overall, 20 (3.8%) of 520 trees on Budagovsky rootstocks died during the trial, three (0.6%) to graft union breakage, nine (1.7%) to fireblight, and eight (1.5%) to unknown causes. Twenty-two (4.4%) out of 499 trees on Cornell-Geneva rootstocks died, three (0.6%) to graft union breakage, three (0.6%) to fireblight, one (0.2%) to winter injury, and 16

Table 5. Cause of tree death (2010-17, no.) of Fuji apple trees at individual planting locations in the 2010 NC-140 Fuji Rootstock Trial.

Location	Rootstock	Graft union breakage (no.)	Fireblight (no.)	Winter injury (no.)	Unknown cause (no.)	Trees at the beginning of the trial (no.)
CH	CG.3001				1	1
	CG.4004		1			3
	CG.4814		2		1	5
	Supp.3				1	4
	M.9 NAKBT337		1		2	12
KY	B.9	1				12
	B.10	1				12
	B.64-194		2			7
	B.67-5-32	1				12
	B.71-7-22		3			10
	G.11				1	8
	G.935N	1				10
	G.935TC			1		4
	CG.2034	1				2
	Supp.3		3			5
	PiAu 51-11		1			11
	M.9 NAKBT337		6	1	1	12
	M.9 Pajam 2		4	1		9
	M.26EMLA		5	1		11
NC	B.9				1	12
	B.10				3	10
	B.71-7-22		4			9
	G.935N				1	10
	CG.4013				1	3
	Supp.3		2			6
	PiAu 51-11		2			10
	M.9 NAKBT337		4			10
	M.9 Pajam 2		3			8
	M.26EMLA		2			12
NY	B.71-7-22				1	9
	G.202N				1	5
PA	B.70-6-8				1	12
	G.41N				1	2
	G.41TC				1	8
	G.935TC				1	4
	CG.4013				1	3
	CG.4814				4	6
	Supp.3				1	3
	PiAu 51-11				3	12
	M.9 NAKBT337				1	10
UT	B.10				1	12
	B.71-7-22				1	10
	G.935N				1	10
	CG.4814				2	8
	CG.5087	1				2
	Supp.3				1	6
	M.26EMLA				1	12

(3.2%) to unknown causes. Fourteen (12.2%) of 115 trees on Pillnitz rootstocks died during the trial, eight (7.0%) due to fireblight and six (5.2%) to unknown causes. Greatest losses were noted for trees on Malling rootstocks, with 33 (14.7%) of 225 lost during the trial. Twenty-five (11.1%) died due to fireblight, three (1.3%) due to winter injury, and five (2.2%) due to unknown causes.

TCA, tree height, and canopy spread were

Table 6. Trunk cross-sectional area (2017, cm^2) of Fuji apple trees at individual planting locations in the 2010 NC-140 Fuji Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	CH	ID	KY	NC	NY	PA	UT
B.9	10.6	27.2	16.9	10.3	12.9	22.1	22.2
B.10	22.4	41.2	46.1	29.8	25.4	48.7	45.5
B.7-3-150	36.5	57.2	118.1	79.9	65.1	97.1	94.9
B.64-194	33.6	81.3	106.4	88.5	52.7	95.5	95.1
B.67-5-32	25.3	82.6	97.5	82.2	55.3	84.2	94.1
B.70-6-8	29.7	62.8	113.4	101.4	74.4	109.1	89.3
B.71-7-22	5.0	10.6	11.6	9.6	6.1	10.0	17.4
G.11	22.7	36.3	57.3	33.8	29.6	31.6	51.3
G.41N	---	72.9	33.0	45.2	38.5	88.2	51.8
G.41TC	24.5	49.6	39.2	38.2	39.4	---	48.4
G.202	25.4	38.7	53.9	27.7	30.8	36.0	33.2
G.935N	16.1	42.6	62.7	36.8	35.0	46.0	58.5
G.935TC	20.6	37.3	80.8	31.6	30.0	42.9	64.1
CG.2034	---	18.1	21.8	17.6	16.1	14.8	30.7
CG.3001	---	72.5	64.7	55.3	49.1	41.3	76.1
CG.4003	14.3	15.0	31.4	20.2	22.0	19.9	27.6
CG.4004	19.2	71.5	57.4	41.4	45.6	---	83.8
CG.4013	---	---	43.7	35.0	16.0	33.4	39.7
CG.4214	11.2	31.8	48.0	22.5	23.3	22.0	36.6
CG.4814	11.7	41.6	65.2	54.7	32.3	42.9	45.5
CG.5087	12.7	29.2	46.7	6.8	---	---	49.6
CG.5222	25.3	69.0	73.7	49.7	46.1	50.1	64.6
Supp.3	19.7	30.2	43.6	37.0	26.4	39.8	49.2
PiAu 51-11	25.7	71.3	105.9	103.8	58.8	101.0	103.7
M.9 NAKBT337	13.7	33.5	56.4	32.9	31.1	44.8	43.2
M.9 Pajam 2	14.4	47.4	63.2	27.9	36.8	47.5	56.9
M.26 EMLA	25.1	67.5	93.7	64.6	59.5	74.2	77.7
Estimated HSD	17.4	21.6	44.7	37.3	18.9	26.4	32.0

[z] Mean separation in columns by Tukey's HSD ($P = 0.05$). HSD was calculated based on the average number of observations per mean.

affected similarly by rootstock (Table 3). Largest trees were on PiAu 51-11, B.70-6-8, B.64-194, B.7-3-150, and B.67-5-32, and smallest were on B.71-7-22. The relative rootstock effects on TCA were similar across sites (Table 6) with a few exceptions. In ID, trees on G.41N, CG.3001, and CG.5222 were unexpectedly large. Compared to other rootstocks, trees on CG.5087 were smaller than expected in NC. Projected planting densities ranged from 947 to 3808 trees per hectare (Table 3).

Root suckering was affected by rootstock (Table 3), with most resulting in relatively little suckering. Greater than average rootstock suckering was induced by G.935TC and M.9 Pajam 2.

The greatest yields per tree (2016-17 average and cumulatively 2011-17) were harvested from trees on CG.4004, G.935N, CG.3001, CG.5222, and G.41N, and the smallest yields were from trees on B.71-7-22 (Table 3). Cumulative yields were reasonably consistent across site (Table 7).

Biennial bearing was high for all rootstocks, with BBI ranging from a low of 0.55 to a high of 0.66 (Table 3). Averaged across the core locations, no statistically significant differences were present among rootstocks. Within location (Table 8), some significant differences among rootstocks were noted, but those differences were not

Table 7. Cumulative yield per tree (2011-17, kg) of Fuji apple trees at individual planting locations in the 2010 NC-140 Fuji Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	CH	ID	KY	NC	NY	PA	UT
B.9	16.4	128.0	33.8	30.0	55.3	46.0	47.3
B.10	26.3	151.9	71.8	51.0	108.2	88.6	85.7
B.7-3-150	37.6	163.7	80.0	55.0	144.1	103.8	100.8
B.64-194	27.1	179.3	63.2	57.0	125.1	109.3	105.7
B.67-5-32	26.4	183.0	68.7	64.2	117.1	123.4	107.6
B.70-6-8	33.1	184.5	66.0	63.7	142.8	127.7	106.2
B.71-7-22	8.9	45.8	21.7	17.9	41.1	20.4	32.6
G.11	37.0	156.8	68.9	72.6	126.5	111.3	101.6
G.41N	---	253.6	75.6	74.9	119.5	98.7	89.7
G.41TC	28.1	191.9	76.7	50.3	124.8	---	72.4
G.202	34.2	154.2	78.1	61.5	119.0	81.8	76.0
G.935N	19.5	230.7	103.1	93.4	156.5	135.6	130.4
G.935TC	29.3	153.4	72.3	72.4	147.7	96.2	108.6
CG.2034	---	102.3	46.3	37.7	81.9	49.2	72.3
CG.3001	---	252.8	54.7	84.4	174.4	120.8	105.2
CG.4003	20.0	67.4	56.7	56.1	97.5	46.9	58.0
CG.4004	28.2	255.5	105.9	105.7	173.2	---	105.0
CG.4013	---	---	69.5	55.0	99.4	55.8	59.8
CG.4214	15.6	162.0	67.9	48.6	120.7	57.2	64.2
CG.4814	22.2	183.0	90.0	66.9	130.2	95.5	84.9
CG.5087	30.4	122.6	80.9	33.9	---	---	94.0
CG.5222	41.6	207.4	81.6	90.2	137.0	113.0	104.7
Supp.3	24.5	88.4	68.0	57.8	94.0	86.8	77.2
PiAu 51-11	28.4	170.5	72.1	65.1	128.3	96.5	86.2
M.9 NAKBT337	16.0	150.0	71.0	75.3	123.0	112.8	82.8
M.9 Pajam 2	12.8	164.0	77.9	72.6	119.5	120.2	104.8
M.26 EMLA	30.6	182.1	71.8	83.8	126.8	125.0	101.8
Estimated HSD	17.1	73.2	46.4	48.5	47.6	77.7	49.2

[z] Mean separation in columns by Tukey's HSD ($P = 0.05$). HSD was calculated based on the average number of observations per mean.

consistent from location to location. In CH, all trees were very biennial, with those on G.11, G.41TC, G.202, G.935N, G.935TC, CG.4003, CG.4214, CG.5087, CG.5222, and Supp.3 significantly more biennial than trees on CG.4004. In ID, trees on M.26 EMLA were more biennial than those on CG.4003. In NY, trees on Supp.3 were more biennial than those on B.9 and B.64-194, and in PA trees on G.11 and CG.2034 were more biennial than those on CG.4814 and Supp.3. In UT, trees on Supp.3 and CG.3001 were more biennial than those on CG.5087.

Averaged over 2016 and 2017, the most yield efficient trees were on CG.4214, and the least efficient trees were on B.7-3-150, B.64-194, B.67-5-32, B.70-6-8, PiAu51-11, and M.26 EMLA (Table 3). Cumulatively (2011-17), the most yield efficient trees were on B.71-7-22, G.935N, B.9, CG.2034, CG.4214, and CG.4003, and the least efficient were on B.7-3-150, B.64-194, B.67-5-32, B.70-6-8, PiAu51-11, and M.26 EMLA (Table 3). Differences in cumulative yield efficiency among rootstocks within sites (Table 9) were similar to the overall core differences. The most consistent rootstocks with high yield efficiency were B.71-7-22, CG.2034, CG.4214, CG.4814, and CG.5087. Trees on G.11, G.935N, CG.4003, and M.9 NAKBT337 were less consistent from site to site but were generally very yield efficient. Among locations, B.7-3-150, B.64-194, B.67-5-32, B.70-6-8, Supp.3, PiAu 51-11,

Table 8. Biennial Bearing Index (2011-17) of Fuji apple trees at individual planting locations in the 2010 NC-140 Fuji Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	CH	ID	KY	NC	NY	PA	UT
B.9	0.95	0.37	0.52	0.61	0.67	0.64	0.71
B.10	0.93	0.53	0.50	0.82	0.73	0.57	0.53
B.7-3-150	0.88	0.40	0.56	0.68	0.78	0.59	0.48
B.64-194	0.95	0.46	0.59	0.73	0.68	0.54	0.45
B.67-5-32	0.90	0.49	0.60	0.55	0.78	0.54	0.62
B.70-6-8	0.95	0.36	0.53	0.67	0.82	0.63	0.51
B.71-7-22	0.95	0.48	0.66	0.63	0.75	0.83	0.70
G.11	0.98	0.47	0.49	0.69	0.82	0.66	0.68
G.41N	---	0.48	0.55	0.65	0.86	0.47	0.55
G.41TC	1.00	0.34	0.58	0.50	0.74	---	0.64
G.202	1.00	0.36	0.59	0.74	0.79	0.60	0.66
G.935N	0.99	0.44	0.52	0.68	0.72	0.50	0.56
G.935TC	0.99	0.40	0.67	0.67	0.77	0.45	0.52
CG.2034	---	0.48	0.61	0.75	0.79	0.66	0.48
CG.3001	---	0.40	0.53	0.70	0.90	0.47	0.78
CG.4003	1.00	0.28	0.52	0.61	0.71	0.63	0.64
CG.4004	0.73	0.58	0.56	0.65	0.81	---	0.66
CG.4013	---	---	0.42	0.56	0.76	0.60	0.56
CG.4214	0.99	0.48	0.54	0.60	0.69	0.51	0.67
CG.4814	0.94	0.54	0.53	0.61	0.75	0.40	0.64
CG.5087	1.00	0.58	0.44	0.71	---	---	0.45
CG.5222	0.99	0.57	0.54	0.65	0.85	0.64	0.58
Supp.3	1.00	0.49	0.50	0.62	0.92	0.39	0.79
PiAu 51-11	0.96	0.56	0.67	0.65	0.74	0.56	0.69
M.9 NAKBT337	0.95	0.38	0.54	0.70	0.84	0.58	0.66
M.9 Pajam 2	0.92	0.54	0.66	0.62	0.85	0.59	0.57
M.26 EMLA	0.97	0.63	0.53	0.70	0.80	0.53	0.62
Estimated HSD	0.22	0.30	0.29	0.27	0.23	0.24	0.32

[z] Mean separation in columns by Tukey's HSD ($P = 0.05$). HSD was calculated based on the average number of observations per mean.

and M.26 EMLA resulted in trees consistently in the least efficient category.

The highest estimated cumulative yield per hectare (based on projected tree density and measured yield per tree) was from trees on G.935N, CG.4214, and G.11 (in descending order) (Table 3). The lowest estimated cumulative yield per hectare was for trees on M.26 EMLA, B.71-7-22, B.7-3-150, B.70-6-8, B.67-5-32, B.64-194, and PiAu 51-11 (in descending order).

Average fruit weight in 2016-17 and over the life of this trial (2012-17) was affected significantly by rootstock (Table 3). Largest fruit were harvested from trees on PiAu 51-11, M.26 EMLA, B.64-194, G.41N, CG.4004, CG.3001, and G.11, and the smallest were harvested from trees on B.9, B.71-7-22, CG.4003, and Supp.3. Considerable variability in rootstock effect existed among locations (Table 10). Trees on G.41N produced the largest fruit in ID and fruit in the largest statistical category in five of six locations. G.41TC resulted in the largest fruit in NC and ones in the largest category in four of six locations. Trees on PiAu 51-11 produced the largest fruit in PA and UT and fruit in the largest category in five of seven locations. M.26 resulted in the largest fruit in KY and ones in the largest category in five of seven locations. CG.4003 resulted in the smallest fruit in ID and PA and ones in the smallest statistical category at all locations. Supp.3 resulted in the smallest fruit in NC and NY

Table 9. Cumulative yield efficiency (2011-17, kg/cm^2 trunk cross-sectional area) of Fuji apple trees at individual planting locations in the 2010 NC-140 Fuji Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	CH	ID	KY	NC	NY	PA	UT
B.9	1.54	4.90	2.11	2.78	4.25	2.07	2.13
B.10	1.16	3.80	1.55	1.67	4.38	1.83	1.92
B.7-3-150	1.07	2.99	0.72	0.73	2.24	1.11	1.07
B.64-194	0.81	2.23	0.62	0.69	2.42	1.22	1.15
B.67-5-32	1.11	2.29	0.77	0.80	2.14	1.48	1.17
B.70-6-8	1.19	2.99	0.63	0.62	1.97	1.21	1.21
B.71-7-22	1.87	4.42	1.81	1.77	7.22	2.20	1.93
G.11	1.77	4.36	1.28	2.21	4.30	3.51	1.99
G.41N	---	3.40	2.08	1.91	3.26	1.20	1.78
G.41TC	1.07	3.75	1.75	1.41	3.26	---	1.47
G.202	1.40	4.10	1.50	2.22	3.97	2.25	2.30
G.935N	1.26	5.53	1.69	2.63	4.67	3.11	2.23
G.935TC	1.41	3.94	0.97	2.38	4.98	2.18	1.78
CG.2034	---	5.50	1.63	1.93	4.91	2.78	2.44
CG.3001	---	3.53	0.88	1.52	3.68	3.06	1.37
CG.4003	1.60	4.39	1.80	2.72	4.50	2.14	2.12
CG.4004	1.45	3.63	1.86	2.56	3.85	---	1.23
CG.4013	---	---	1.54	1.82	6.26	1.65	1.46
CG.4214	1.46	5.06	1.37	2.21	5.31	2.67	1.89
CG.4814	2.01	4.41	1.40	1.24	3.99	2.11	2.01
CG.5087	2.66	4.33	1.75	2.90	---	---	1.86
CG.5222	1.67	3.00	1.14	1.83	3.01	2.24	1.71
Supp.3	1.30	2.96	1.49	1.59	3.40	2.11	1.58
PiAu 51-11	1.14	2.39	0.75	0.74	2.21	0.95	0.85
M.9 NAKBT337	1.13	4.52	1.55	2.40	4.12	2.57	1.84
M.9 Pajam 2	0.85	3.49	1.37	2.40	3.28	2.52	1.89
M.26 EMLA	1.23	2.79	0.78	1.31	2.18	1.70	1.32
Estimated HSD	0.84	1.71	1.13	1.18	2.27	1.40	0.75

[z] Mean separation in columns by Tukey's HSD ($P = 0.05$). HSD was calculated based on the average number of observations per mean.

and fruit in the smallest category in six of seven locations. Trees on B.9 produced the smallest fruit in KY and UT and fruit in the smallest category in five of seven locations.

Effects of Rootstock Propagation Technique. Across all tree characteristics assessed (Tables 3-11), only a few differences were detected between stoolbed-sourced and tissue-culture-sourced rootstocks for G.41 and G.935. Averaged across the core locations, tree characteristics for G.41N and G.41TC were not significantly different (Table 3). G.41N in ID, however, resulted in trees with a larger TCA (Table 6) and greater fruit size (Table 10) than did G.41TC. Averaged across the core locations, trees on G.935N were similar to those on G.935TC, except trees on G.935TC produced more root suckers and had lower yield and fruit size (Table 3). Among sites, only in ID was that difference in cumulative yield significant when comparing G.935N and G.935TC (Table 7).

Discussion

Trees were grouped into vigor class by TCA. The distribution among classes, TCA, projected tree density, estimated spacing, cumulative yield efficiency, and projected cumulative yield per hectare are presented in Table 11. Groupings were as follows (with ranges as percent of the TCA of trees on M.9 NAKBT337): large semi-dwarf (200+%), moderate semi-dwarf (150-200%), large dwarf (110-130%), moderate dwarf

Table 10. Average fruit size (2011-17, g) of Fuji apple trees at individual planting locations in the 2010 NC-140 Fuji Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	CH	ID	KY	NC	NY	PA	UT
B.9	148	208	130	181	148	194	168
B.10	136	223	168	213	179	223	211
B.7-3-150	127	228	167	201	191	223	212
B.64-194	131	241	170	207	199	216	222
B.67-5-32	139	245	167	203	175	215	211
B.70-6-8	129	230	169	202	179	219	214
B.71-7-22	153	173	163	176	158	183	203
G.11	129	236	168	226	177	209	220
G.41N	---	296	155	215	178	218	212
G.41TC	135	245	160	232	182	---	209
G.202	129	202	153	194	170	191	179
G.935N	145	236	166	210	170	216	208
G.935TC	139	210	181	221	177	213	211
CG.2034	---	210	158	207	164	194	205
CG.3001	---	270	170	205	176	223	211
CG.4003	144	148	144	191	157	150	172
CG.4004	128	277	172	202	186	---	231
CG.4013	---	---	153	185	284	195	196
CG.4214	139	222	164	210	171	184	201
CG.4814	158	222	152	200	171	200	192
CG.5087	136	272	163	198	---	---	191
CG.5222	122	267	159	204	177	205	200
Supp.3	130	213	145	175	136	155	203
PiAu 51-11	130	265	167	199	199	236	241
M.9 NAKBT337	142	222	167	214	176	219	198
M.9 Pajam 2	135	240	155	191	176	207	215
M.26 EMLA	125	253	184	210	182	227	219
Estimated HSD	29	50	33	31	53	35	42

[z] Mean separation in columns by Tukey's HSD ($P = 0.05$). HSD was calculated based on the average number of observations per mean.

(80-110%), small dwarf (40-80%), and subdwarf (0-40%).

B.7-3-150, B.70-6-8, B.67-5-32, B.64-194, and PiAu 51-11 produced trees in the large semi-dwarf category (200+% of M.9 NAKBT337). These rootstocks were estimated to be suitable for densities of 915-984 trees per hectare. Projected yields per hectare were statistically similar and ranged from 101 to 114 MT.

CG.4004, CG.3001, CG.5222, and M.26 EMLA produced trees in the moderate semi-dwarf size category. Projected densities ranged from 1088 to 1388 trees per hectare, with a projected cumulative yield per hectare of 122 to 198 MT. In this group, trees on CG.4004, CG.3001, and CG.5222 were the highest yielding. Robinson et al. (2011) found that 'Honeycrisp' trees on CG.4004, after 6 years, were similar in size to those on M.7 and were significantly more yield efficient.

G.935N, G.935TC, CG.4814, G.41N, and M.9 Pajam 2 produced trees in the large dwarf size category. Projected density ranged from 1781 to 1884 trees per hectare, and projected cumulative yield per hectare ranged from 184 to 257 MT. Trees of G.935N were the best yield performers. Several other studies (Autio et al., 2011a; Autio et al., 2013; Lordan et al., 2018; Marini et al., 2014; Robinson et al., 2011) found that trees of multiple varieties on G.935 were similar in size to comparable trees on M.26, generally larger than trees on

Table 11. Rootstocks were distributed among seven vigor classes. Distribution among categories were made relative to the trunk cross-sectional area of trees on M.9 NAKBT337: 0-40% sub-dwarf, 40-80% small dwarf, 80-110% moderate dwarf, 110-130% large dwarf, 130-150% small semi-dwarf, 150-200% moderate semidwarf, and 200+% large semidwarf. Within class, rootstocks are ordered highest to lowest based on cumulative (2011-17) yield efficiency. Also presented are projected tree density and per-hectare cumulative yields (2011-17). These 2010 NC-140 Fuji Apple Rootstock Trial data are from ID, KY, NC, NY, and UT. All values are least-squares means, adjusted for missing subclasses.[z]

Vigor class	Rootstock	Trunk cross-sectional area (2017, cm^2)	Projected tree density (no./ha)	Projected in-row by across-row spacing (m)	Cumulative yield efficiency (2011-17, kg/cm^2 TCA)	Projected cumulative yield (2011-17, MT/ha)
Large semi-dwarf	B.7-3-150	83.0	984	2.17 x 4.67	1.55	114
	B.70-6-8	88.3	915	2.28 x 4.78	1.48	108
	B.67-5-32	82.3	979	2.18 x 4.68	1.43	104
	B.64-194	84.9	947	2.23 x 4.73	1.42	102
	PiAu 51-11	88.7	938	2.25 x 4.75	1.39	101
Moderate semi-dwarf	CG.4004	59.9	1388	1.71 x 4.21	2.63	198
	CG.3001	63.5	1234	1.86 x 4.36	2.20	161
	CG.5222	60.6	1317	1.78 x 4.28	2.14	160
	M.26 EMLA	72.6	1088	2.03 x 4.53	1.68	122
Large dwarf	G.935N	47.1	1787	1.43 x 3.93	3.35	257
	G.935TC	48.8	1884	1.37 x 3.87	2.81	209
	CG.4814	47.8	1787	1.43 x 3.93	2.61	201
	G.41N	48.3	1781	1.43 x 3.93	2.49	184
	M.9 Pajam 2	46.4	1818	1.41 x 3.91	2.48	189
Moderate dwarf	CG.4214	32.5	2445	1.13 x 3.63	3.16	224
	M.9 NAKBT337	39.4	2159	1.24 x 3.74	2.88	215
	G.11	41.6	2005	1.32 x 3.82	2.83	217
	G.202	36.9	2242	1.20 x 3.70	2.82	210
	B.10	37.6	2160	1.24 x 3.74	2.66	199
	G.41TC	43.0	1848	1.39 x 3.89	2.32	183
	Supp.3	37.4	2165	1.24 x 3.74	2.20	165
Small dwarf	CG.2034	20.9	3015	0.96 x 3.46	3.28	208
	B.9	17.9	3331	0.89 x 3.39	3.23	177
	CG.4003	23.2	2939	0.97 x 3.47	3.10	197
Sub-dwarf	B.71-7-22	11.1	3808	0.80 x 3.30	3.43	117
Estimated HSD		13	346		0.65	41

[z] Mean separation in columns by Tukey's HSD ($P = 0.05$). HSD was calculated based on the average number of observations per mean.

M.9 and smaller than those on M.7. Generally, trees on G.935 were more yield efficient than those on M.26 and similar to those on M.9. Lordan et al. (2018) found that 'Honeycrisp' trees on CG.4814 were larger than those on M.9 NAKBT337.

CG.4214, M.9 NAKBT337, G.11, G.202, B.10, G.41TC, and Supp.3 produced trees in the moderate dwarf category. Projected densities ranged from 1848 to 2445 trees per hectare, and projected cumulative yields per hectare ranged from 165 to 224 MT. The best yield performance was from trees on CG.4214, M.9 NAKBT337, and G.11. In a New York trial, 'Golden Delicious' trees on CG.4214 were similar to trees on M.26 in size and yield efficiency (Robinson et al, 2011). 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. 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 and similarly or more yield efficient.

CG.2034, B.9, and CG.4003 produced trees in the small dwarf size category. Projected density ranged from 2939 to 3331 trees per hectare, and projected cumulative yield per hectare ranged from 177 to 208 MT. It is interesting to note that B.9 produced a tree that ranks fourth out of 25 rootstocks in the trial for cumulative yield efficiency, but only fifteenth out of 25 rootstocks for projected cumulative yield hectare.

B.71-7-22 produced trees in the sub-dwarf category. Projected density was 3808 trees per hectare, and projected cumulative yield was 117 MT per hectare.

The calculation of estimated cumulative yield per hectare should help users of this information estimate the economic impact of selecting one rootstock over another. The above mentioned result with B.9 where it had the fourth highest yield efficiency, but because of its lack of growth, it had intermediate estimated cumulative yield. The differences in cumulative yield over 8 years or even over a projected orchard life of 20 years can result in large differences in cumulative economic crop value. Lordan et al. (2019) estimated these economic effects due to rootstock with Honeycrisp for one location in New York. The magnitude of these effects indicate that the selection of rootstock that is optimally matched with the climate, soil, and cultivar can have significant economic benefit (Robinson et al. 2019).

Among rootstocks from the various breeding programs, Budagovsky rootstocks showed very little commercial promise. Several were too vigorous and nonproductive. B.71-7-22 was too weak. B.10 produced a reasonable tree, but there were more productive choices in its moderate dwarf category. The two Pillnitz rootstocks (PiAu 51-11 and Supp.3) performed poorly and have little commercial promise. Several of the Cornell-Geneva rootstocks performed very well and were the top performers in the moderate semi-dwarf, large dwarf, moderate dwarf, and small dwarf categories.

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