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

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Abstract

In 2010, an orchard trial of apple rootstocks was established at six locations in the United States and Mexico using 'Aztec Fuji' as the scion cultivar. Rootstocks included two named clones from the Budagovsky series (B.9, B.10), seven unreleased Budagovsky clones (B.7-3-150, B.7-20-21, B.64-194, B.67-5-32, B.70-6-8, B.70-20-20, 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), two unreleased Pillnitz clones (PiAu 9-90 and PiAu 51-11), and three Malling clones as controls (M.9 NAKBT337, M.9 Pajam 2, and M.26 EMLA). All trees were trained a Tall Spindle. After 5 years, the greatest mortality was for trees on M.9 NAKBT337 (22%). Trees on four rootstocks (M.9 Pajam 2, Supp.3, B.71-7-22, and B.70-20-21) experienced 11-20% mortality, and all others averaged10% or less. Tree size after 5 years allowed for a preliminary partitioning of these rootstocks in to size classes from sub-dwarf to semi-standard. B.70-20-20 was a semi-standard, and PiAu 9-90 was a large semi-dwarf. B.64-194, B.67-5-32, B.70-6-8, and PiAu 51-11 were moderate semi-dwarfs. B.7-3-150, CG.3001, CG.4004, CG.5222, and M.26 EMLA were small semi-dwarfs. G.202N (N = liners from stool beds), G.935 N, G.935TC (TC = liners from tissue culture), CG.4814, and M.9 Pajam 2 were large dwarfs. B.10, G.11, G.41N, G.41TC, G.202TC, Supp.3, and M.9 NAKBT337 were moderate dwarfs. B.9, CG.2034, CG.4003, CG.4013, CG.4214, and CG.5087 were small dwarfs, and B.7-20-21 and B.71-7-22 were sub-dwarfs. Trees on B.70-20-20, PiAu 9-90, PiAu 51-11, B.67-5-32, B.70-6-8, and B.64-194 were too vigorous for a high-density system, and conversely, trees on B.71-7-22 and B.7-20-21 were not vigorous enough. Among the five small semi-dwarf rootstocks, CG.4004 performed best, using cumulative (2011-14) yield efficiency as the primary determinant of performance. Among the five large dwarf rootstocks, G.935N performed best. Of the seven rootstocks characterized as moderate dwarfs, M.9 NAKBT337, G.11, and G.202TC resulted in the greatest cumulative yield efficiency. Of the six rootstocks in the small-dwarf class, CG.4003, B.9, CG.5087, and CG.2034 performed best.

The 40-year-old NC-140 Multi-State Research Project is comprised of researchers from 29 U.S. states, three Canadian provinces, Mexico, and Chile. It evaluates fruit-tree performance on different rootstocks, with the principle goal of helping orchardists optimize their orchard system through rootstock selection. NC-140 greatly enhances the evaluation process through uniform trials at many locations including a diversity of soils and climates.

New apple rootstocks are made available regularly from numerous sources worldwide. The Budagovsky, Cornell-Geneva, and Pillnitz breeding programs are some of the most prolific producers of new apple rootstocks. Budagovsky rootstocks are from the Michurinsk State Agrarian University in Michurinsk, Tambov Region, Russia (Cummins and Aldwinckle, 1983) and have been included in numerous NC-140 trials since 1984 (Autio et al., 2001; 2013; Marini et al., 2001a; 2001b; 2006; 2014; NC-140, 1996; Robinson et al., 2007). The Cornell-Geneva Apple Rootstock Breeding Program has released numerous rootstocks with a high de-

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gree of disease resistance, particularly to the fire blight bacterium (*Erwinia amylovora*), and many of these rootstocks have been evaluated by NC-140 since 1992 (Autio et al., 2011a; 2011b, 2013; Marini et al., 2014; Robinson et al., 2004; 2007). The Pillnitz series of rootstocks (PiAu and Supporter) are from the Institut für Obstforschung Dresden-Pillnitz, Germany, (Fischer, 1997) and have been in numerous NC-140 trials since 1999 (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 to Malling industry standards at multiple sites in North America, exposing the rootstocks to diverse climate, soil, and management conditions.

Materials and Methods

In spring, 2010, an orchard trial of 31 apple rootstocks was established at six sites in North America (Table 1) under the coordination of the NC-140 Multi-State Research Committee. 'Aztec Fuji' 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), seven unreleased Budagovsky clones (B.7-3-150, B.7-20-21, B.64-194, B.67-5-32, B.70-6-8, B.70-20-20, 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), two unreleased Pillnitz clones (PiAu 9-90 and 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) liners used for trees on G.41, G.202, and G.935. Please note that this trial is very similar in nature to the 2010 NC-140 'Honeycrisp' Apple Rootstock Trial (Autio et al., 2017), except for the cultivar, planting locations, and tree spacing.

The trial was planted in Chihuahua (Mexico), Idaho, Kentucky, 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. Each replication included one plot per rootstock, and each rootstock plot included one to three trees. Trees were spaced 1.8 x 4.3 m and trained as a tall spindle (Robinson and Hoying, 2011). Pest management, irrigation, and fertilization followed local recommendations at each site.

Trunk circumference, 25 cm above the bud union, was measured in October, 2014 and used to calculate trunk cross-sectional area (TCA). Also in October, 2014, 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 2014; however, very few sites harvested any fruit in 2011. Yield efficiency (kg·cm^{-2} TCA) in 2014 and on a cumulative basis were calculated using 2014 TCA. Fruit weight was assessed on a 50-apple sample (or available crop) in 2012, 2013, and 2014.

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 (2014), cumulative yield per tree (2011-14), cumulative yield efficiency (2011-14), and average fruit size (2012-14). Because of the

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 of Idaho Parma Research & Extension Center, 29603 U of I Lane, Parma, ID 83660
Kentucky (KY)	Princeton	Dwight Wolfe	University of Kentucky Research & Education Center, 1205 Hopkinsville Street, Princeton, KY 42445
North Carolina (NC)	Mills River	Michael Parker	Department of Horticultural Science, North Carolina State University, Campus Box 7609, Raleigh, NC 27695
Pennsylvania (PA)	Rock Springs	Robert Crassweller	Department of Plant Science, The Pennsylvania State University, 7 Tyson Building, University Park, PA 16802
Utah (UT)	Kaysville	Brent Black	Plant, Soil, and Climate Department, Utah State University, Logan, UT 84322 USA

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 differences and allows for a reasonable look at rootstock effects.

Results

Cold Damage in the Nursery. Prior to digging from the nursery in 2009, the trees used for this trial experienced an unseasonable freeze, with temperatures on Oct. 10 and 11 dropping to about -7°C. When planted at the research sites, most trees performed very well, but about 10% either leafed out and died very soon after planting in 2010 or they never leafed out. Rootstocks expressed differences in what we expect is a response to the nursery cold of Oct. 2009. More than 50% of the trees on CG.2034, CG.4013, and PiAu 9-90 never leafed out or died very soon after planting (data not shown). About 33% of the trees on CG.4814 and CG.5087, similarly, did not leaf out or leafed out and soon died (data not shown). Only between 0 and 15% of the trees on the other rootstocks showed a similar response. The interesting exceptions are G.41, G.202, and G.935. For each of these rootstocks, there was a set of trees produced from stool-bed liners and a set from tissue-cultured liners. In all cases, the trees on the tissue-cultured liners responded better after planting (data not shown). Specifically, 66% of trees on G.41N and 0% of trees on G.41TC failed to leaf out and grow normally. Similarly, 22% of trees on G.202N and 0% of trees on G.202TC failed to leaf out and grow normally. With the difference less dramatic, 20% of trees on G.935N and 10% of trees on G.935TC did not leaf out or leafed out and soon died. Trees in the nursery were not arrayed in a replicated trial, so some of the differences observed may be related to factors other than rootstock.

Site and Rootstock Differences at Planting. The trunk cross-sectional area (TCA) at planting was similar across the four core sites (Table 2). Cooperators left a similar number of branches per tree in Idaho, Kentucky, and Utah, but in North Carolina, about twice the number of branches remained per tree (Table 2).Likewise, planting depth varied with location, with the average graft union height greater in Kentucky and North Carolina than in Idaho and Utah (Table 2).

Rootstock resulted in significant differences in the TCA at planting, with the largest trees on PiAu 9-90 and the smallest on G.41TC and B.71-7-22 (Table 3). The greatest number of branches CG.4004, PiAu 9-90, and G.935N, and the fewest branches were on G.41TC and B.71-7-22 (Table 3). Graft-union height at planting was generally similar among rootstocks, with a few exceptions likely related to the length of the rootstock shank, both of which were very small in a few cases (Table 3). The average graft-union height for nearly all rootstocks was between 80 and 104 mm. Trees on G.935TC and CG.3001 had unions which were 77 and 74 mm, respectively above the soil surface. The most notable deviations from average, however, were trees on G.41TC, with an average graft-union height of only 33 mm, due to a very short rootstock shank on these trees propagated with tissue-culture produced liners.

Site Effects on Tree Performance. Over the first 5 years, site (Table 4) and rootstock (Table 5) affected all aspects of tree performance. Table 4 includes data only from the four sites with a complete set of 30 rootstocks (note that CG.4013 was missing from too many sites to be included in the core). Chihuahua planted a complete set of rootstocks, but three (CG.2034, CG.4013, and G.41N) did not leaf out following planting. Pennsylvania was missing one at planting (G.41TC), and in 2012, declared 16 others (B.64-194, B.71-7-22, B.7-20-21, CG.2034, CG.3001, CG.4003, CG.4004, CG.4013, CG.4214, CG.4814, CG.5087, G.202N, G.41N, G.935TC, PiAu 9-90, and Supp.3) to be unsuitable trees for data collection. Subsequent tree death resulted in the loss of one

Table 2. Site means for trunk cross-sectional area, number of branches, and height of the graft union at planting of Fuji apple trees in the 2010 NC-140 Fuji Apple Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Site	Trunk cross-sectional area at planting (2010, cm^2)	Number of branches at planting	Height of graft union at planting (mm)
ID	2.0	6.7	57
KY	1.8	4.8	124
NC	1.9	10.0	119
UT	1.7	5.1	53
Average HSD	1.0	3.6	9

[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 3. Rootstock means for trunk cross-sectional area, number of branches, and height of the graft union at planting of Fuji apple trees in the 2010 NC-140 Fuji Apple Rootstock Trial. Means are based on data from ID, KY, NC, and UT. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	Trunk cross-sectional area at planting (2010, cm^2)	Number of branches at planting	Height of graft union at planting (mm)
B.9	1.4	4.0	91
B.10	1.8	6.4	93
B.7-3-150	2.2	5.3	92
B.7-20-21	1.0	2.4	102
B.64-194	1.5	4.6	94
B.67-5-32	1.5	3.6	97
B.70-6-8	2.2	5.8	95
B.70-20-20	2.6	10.2	82
B.71-7-22	0.8	1.7	81
G.11	1.6	7.5	100
G.41N	2.2	5.8	81
G.41TC	0.3	0.1	33
G.202N	2.7	10.5	95
G.202TC	2.2	10.0	88
G.935N	2.6	11.0	95
G.935TC	2.1	8.7	77
CG.2034	1.2	2.2	80
CG.3001	2.1	9.5	74
CG.4003	1.4	6.2	94
CG.4004	1.9	12.6	84
CG.4214	1.4	4.4	104
CG.4814	2.2	10.3	82
CG.5087	1.4	4.8	83
CG.5222	2.6	8.5	81
Supp.3	1.5	4.8	98
PiAu 9-90	3.0	11.7	104
PiAu 51-11	2.4	8.1	86
M.9 NAKBT337	1.6	5.0	92
M.9 Pajam 2	1.8	5.9	98
M.26 EMLA	2.0	8.9	93
Average HSD	0.9	2.7	23

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

more in Chihuahua. Data from these two sites were excluded from the analyses presented in Tables 4 and 5. Results from Chihuahua and Pennsylvania, however, are included in the tree performance data presented by location in Tables 6-10.

Obviously, the lowest survival was noted in Chihuahua and Pennsylvania (Table 6), but among the 4 sites included in Table 4, survival in Kentucky and North Carolina was approximately 90% and in Idaho and Utah was about 100% (Table 4).

Site-related tree characteristics are presented in Table 4. After 5 years, the largest TCA was recorded for trees in Kentucky and the smallest for trees in North Carolina.

Table 4. Site means for trunk cross-sectional area, root suckers, tree height, canopy spread, yield per tree, yield efficiency, and fruit size of Fuji apple trees in the 2010 NC-140 Honeycrisp Apple Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Site	Survival (2014, %)	Trunk cross-sectional area (2014, cm^2)	Cumulative root suckers (2010-14, no./tree)	Tree height (cm)	Canopy spread (cm)	Yield per tree (2014, kg)	Cumulative yield per tree (2011-14, kg)	Yield efficiency (2014, kg/cm^2 TCA)	Cumulative yield efficiency (2011-14, kg/cm^2 TCA)	Fruit weight (2014, g)	Average Fruit weight (2012-14, g)
ID	100	30.1	0.1	339	108	33.8	61.6	1.2	2.2	238	238
KY	91	38.7	6.8	336	216	3.1	12.7	0.1	0.4	213	170
NC	89	25.9	---	342	183	10.8	20.2	0.6	1.1	210	202
UT	99	32.6	4.6	332	214	21.7	34.7	0.7	1.2	210	197
Average HSD	10	7.4	1.7	17	16	2.4	4.6	0.1	0.1	13	13

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

Tree height was similar across sites, but canopy spreads in Kentucky and Utah were double the spread in Idaho. Yield per tree in 2014 and cumulatively (2011-14) was greatest in Idaho and least in Kentucky. Yield efficiency in 2014 and cumulatively (2011-14) was likewise highest in Idaho and lowest in Kentucky. Average fruit weight in 2014 and overall (2012-14) was highest in Idaho. Lowest average fruit weight overall (2012-14) was in Kentucky.

Rootstock Effects on Tree Performance. Survival was affected by rootstock (Tables 5 and 6). Percent survival was lowest for trees on M.9 NAKBT337 (78% within the four core sites). Since tree loss affected the inclusion of data from the other sites in the core, it is important to look at tree loss over all sites. Across all sites, trees on eight rootstocks experienced losses of 10% or more (data not shown in tables): M.26 EMLA (10%), M.9 Pajam 2 (13%), B.7-20-21 (15%), B.71-7-22 (15%), M.9 NAKBT337 (18%), Supp.3 (19%), CG.4013 (29%), and CG.4814 (29%). Among these eight rootstocks, 58 trees were lost in total, and 37 of those losses were attributed to fireblight. The loss of more than 75% of the trees on M.26 EMLA, M.9 Pajam 2, M.9 NAKBT337, Supp.3, and B.71-7-22 was caused by fireblight. Of the nine trees on CG.4814 that died, only three of the losses were attributed to fireblight. Of the nine trees on B.7-20-21, only one loss was attributed to fireblight, and the cause of death of the two trees lost on CG.4013 was not thought to be fireblight. Among the other 23 rootstocks, 28 trees died. Four deaths were attributed to fireblight, one to voles, and one to deer. The remaining 22 were undetermined. Fireblight was the primary reason for tree loss in Kentucky and North Carolina accounting for 81% and 57% of the deaths, respectively. With the exception of four trees lost to fireblight in Chihuahua, the reasons for losses at the other sites were unknown. It is important to note that Pennsylvania had only a partial planting. Seven rootstock treatments experienced total loss, but five of those were represented initially by only a single tree, one started with two trees, and two started with three trees.

Table 5. Rootstock means for trunk cross-sectional area, root suckers, tree height, canopy spread, yield per tree, yield efficiency, and fruit size of Fuji apple trees in the 2010 NC-140 Honeycrisp Apple Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	Survival (2014, %)	Trunk cross-sectional area (2014, cm^2)	Cumulative root suckers (2010-14, no./tree)	Tree height (cm)	Canopy spread (cm)	Yield per tree (2014, kg)	Cumulative yield per tree (2011-14, kg)	Yield efficiency (2014, kg/cm^2 TCA)	Cumulative yield efficiency (2011-14, kg/cm^2 TCA)	Fruit weight (2014, g)	Average Fruit weight (2012-14, g)
B.9	95	12.6	5.1	257	135	12.1	23.6	0.9	1.8	182	180
B.10	91	24.8	1.0	317	171	14.8	27.8	0.6	1.2	223	206
B.7-3-150	100	44.9	0.7	387	198	17.2	33.6	0.5	0.9	233	204
B.7-20-21	89	6.4	1.2	187	75	1.6	3.8	0.3	0.8	127	132
B.64-194	93	48.0	4.1	404	205	13.9	27.7	0.3	0.6	230	198
B.67-5-32	100	50.7	2.8	388	194	19.8	32.4	0.4	0.6	225	203
B.70-6-8	100	48.8	0.6	401	200	17.5	35.6	0.4	0.8	221	203
B.70-20-20	98	74.0	8.4	448	231	22.1	34.1	0.3	0.5	224	201
B.71-7-22	82	7.4	2.6	204	113	6.2	11.1	0.8	1.6	192	186
G.11	97	26.6	1.3	334	192	20.2	38.8	0.8	1.6	230	219
G.41N	100	27.6	1.4	341	193	24.2	42.0	0.8	1.3	226	224
G.41TC	100	22.5	4.0	329	174	17.9	29.9	0.8	1.2	242	231
G.202N	100	34.4	5.2	355	193	16.1	36.0	0.5	1.2	229	206
G.202TC	100	24.9	5.3	311	171	15.0	32.5	0.7	1.4	211	183
G.935N	95	31.2	3.8	350	192	27.2	52.9	1.0	1.9	228	206
G.935TC	100	29.6	11.4	315	183	18.9	38.9	0.7	1.5	216	205
CG.2034	100	13.8	2.4	276	160	13.7	23.0	0.9	1.6	214	189
CG.3001	100	39.7	3.7	398	207	25.8	45.2	0.6	1.0	229	217
CG.4003	100	14.8	1.7	279	151	10.4	24.1	0.7	1.8	178	169
CG.4004	100	37.6	4.5	377	204	30.5	53.8	0.8	1.4	242	222
CG.4214	100	19.2	5.0	317	169	13.1	25.9	0.7	1.4	227	212
CG.4814	91	32.0	9.3	340	189	18.4	33.2	0.6	1.1	221	200
CG.5087	100	16.6	2.5	304	166	14.7	25.7	1.0	1.7	216	207
CG.5222	100	38.8	7.3	378	208	25.2	43.7	0.7	1.1	244	219
Supp.3	83	23.2	0.3	301	165	13.7	27.9	0.7	1.3	204	211
PiAu 9-90	100	58.8	5.0	375	208	9.2	18.4	0.2	0.4	208	186
PiAu 51-11	93	51.4	0.6	397	209	19.6	31.6	0.4	0.7	237	213
M.9 NAKBT337	78	24.4	4.9	325	176	16.4	34.2	0.8	1.6	219	205
M.9 Pajam 2	81	29.1	8.6	339	183	22.6	41.2	0.8	1.5	221	205
M.26 EMLA	85	40.8	0.6	377	198	22.1	40.4	0.6	1.0	233	214
Average HSD	22	9.7	6.9	39	23	8.3	11.7	0.3	0.4	38	25

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

TCA, tree height, and canopy spread were affected similarly by rootstock (Table 5). Trees on B.7-20-21 and those on B.71-7-22 were the smallest, and trees on B.70-20-20 were the largest. These three rootstocks produced trees that were well outside of the range of sizes produced by other rootstocks. B.7-20-21 and B.71-7-22 could be considered sub-dwarf in vigor, and B.70-20-20 could be considered semi-standard or standard in vigor. At this point in the trial, the other rootstocks can be grouped very roughly by vigor class. Small dwarfs included B.9, CG.2034, CG.4003, CG.4013, CG.4214, and CG.5087. Moderate dwarfs included B.10, G.11, G.41N, G.41TC, G.202TC, Supp.3, and M.9 NAKBT337. Large dwarfs included G.202N, G.935N, G.935TC, CG.4814, and M.9 Pajam 2. Small semi-dwarfs included B.7-3-150, CG.3001, CG.4004, CG.5222, and M.26 EMLA. Moderate semi-dwarfs included B.64-194, B.67-5-32, B.70-6-8, and PiAu 51-11. Trees on PiAu 9-90 were large semi-dwarfs. The relative rootstock effects on TCA were similar across sites (Table 7).

Root suckering was affected by rootstock (Table 5), with most resulting in very little suckering. Somewhat greater than average rootstock suckering was induced by G.935TC, CG.4814, M.9 Pajam 2, B.70-20-20, and CG.5222.

In 2014 and cumulatively (2011-14), the greatest yields were harvested from trees on CG.4004 and G.935N, and the smallest yields were from trees on B.71-7-22 and B.7-20-21 (Table 5). Within the small dwarf category, yields per tree in 2014 and cumulatively were similar. Among the moderate dwarfs, the greatest yields in 2014 and cumulatively were from trees on G.41N. The lowest yields (2014 and cumulatively) were from trees on B.10 and Supp.3. Among the large dwarfs, the greatest yields in 2014 and cumulatively were from trees on G.935N, and the lowest were from trees on CG.4814. Among the small semi-dwarfs, the largest yields in 2014 and cumulatively were from trees on CG.4004, and lowest yields in 2014 and cumulatively were from trees on B.7-3-150. Yields in 2014 and cumulatively were similar among the moderate semi-dwarfs. Site variations in rootstock effects on cumulative yield are presented in Table 8.

In 2014, the most yield efficient trees were on G.935N, CG.5087, CG.2034, and B.9, and the least efficient trees were on PiAu 9-90 (Table 5). Cumulatively (2011-14), the most yield efficient trees were on G.935N, B.9, CG.4003, and CG.5087, and the least efficient were on PiAu 9-90 and B.70-20-20 (Table 5). Between the two sub-dwarf rootstocks, trees on B.71-7-22 were more yield efficient in 2014 and cumulatively than trees on B.7-20-21. Among the small dwarfs, the most yield efficient trees in 2014 were on CG.5087, and cumulatively, they were on CG.4003 and on B.9. Among the moderate dwarfs, yield efficiency was similar in 2014, but cumulatively, the most efficient trees were on were on M.9 NAKBT337 and G.11, and the least efficient were on B.10, and G.41TC. Among the large dwarfs, the most yield efficient trees in 2014 and cumulatively were on G.935N, and the least efficient were on G.202N and CG.4814. Among the small semi-dwarfs, the most efficient trees in 2014 and cumulatively were on CG.4004, and the least efficient were on B.7-3-150. In 2014 and cumulatively, yield efficiencies were similar among trees on moderate semi-dwarf rootstocks. Site variations in rootstock effects on cumulative (2011-14) yield efficiency are presented in Table 9.

Fruit weight (2014 and averaged 2012-14) was not dramatically affected by rootstock; however, B.70-20-21 resulted in the smallest fruit in 2014 and averaged over the three fruiting years 2012-14 (Table 5). Rootstock effects on average (2012-14) fruit weight varied somewhat inconsistently from site to site (Table 10).

Discussion

After 5 years, differences in tree size allow the segregation of these rootstocks into eight vigor classes (Table 11), similar to the results

Table 6. Survival (2014, %) 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	PA	UT
B.9	100	100	92	92	100	100
B.10	100	100	100	66	100	92
B.7-3-150	100	100	100	100	100	100
B.7-20-21	92	100	100	52	---	100
B.64-194	100	100	73	100	---	100
B.67-5-32	100	100	100	100	100	100
B.70-6-8	100	100	100	100	92	100
B.70-20-20	100	100	100	100	86	92
B.71-7-22	100	100	81	57	---	91
G.11	100	100	89	100	100	100
G.41N	---	100	100	100	---	100
G.41TC	100	100	100	100	---	100
G.202N	100	100	100	100	---	100
G.202TC	100	100	100	100	100	100
G.935N	100	100	100	89	88	91
G.935TC	100	100	100	100	---	100
CG.2034	---	100	100	99	---	100
CG.3001	0	100	100	100	---	100
CG.4003	100	100	100	100	---	100
CG.4004	67	100	100	100	---	100
CG.4013	---	---	100	67	---	100
CG.4214	100	100	100	100	---	100
CG.4814	36	100	100	100	---	75
CG.5087	100	100	100	100	---	100
CG.5222	100	100	100	100	100	100
Supp.3	73	100	61	65	---	100
PiAu 9-90	100	100	100	100	---	100
PiAu 51-11	100	100	91	77	75	100
M.9 NAKBT337	92	100	50	61	90	100
M.9 Pajam 2	100	100	55	65	100	100
M.26 EMLA	100	100	56	83	100	100
Average HSD	37	---	53	68	46	33

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

for 'Honeycrisp' presented in the first paper in this series (Autio et al., 2017). Specifically, B.7-20-21 and B.71-7-22 produced trees in the sub-dwarf vigor class. CG.4013, CG.4214, CG.5087, CG.4003, CG.2034, and B.9 could be considered small dwarfs. Moderate dwarf trees were on G.41N, G.11, G.202TC, B.10, M.9 NAKBT337, Supp.3, and G.41TC. Trees on G.202N, CG.4814, G.935N, G.935TC, and M.9 Pajam 2 were large dwarf trees. B.7-3-150, M.26EMLA, CG.3001, CG.5222, and CG.4004 were small semi-dwarf trees. PiAu 51-11, B.67-5-32, B.70-6-8, and B.64-194 produced moderate semi-dwarf trees. PiAu 9-90 was a large semi-dwarf, and B.70-20-20 produced

Table 7. Trunk cross-sectional area (2014, cm^2) of Fuji apple trees at individual planting locations in the 2010 NC-140 Fuji Apple Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	CH	ID	KY	NC	PA	UT
B.9	8.8	17.2	12.2	7.1	12.3	13.9
B.10	17.8	25.6	30.7	18.6	24.5	24.7
B.7-3-150	23.6	33.3	62.6	37.5	39.5	46.2
B.7-20-21	3.0	5.3	11.6	1.6	---	7.2
B.64-194	22.6	44.6	54.5	44.4	---	48.6
B.67-5-32	17.5	51.2	55.4	45.4	39.9	50.6
B.70-6-8	21.4	39.7	61.5	47.5	45.0	46.3
B.70-20-20	34.1	72.1	80.9	76.0	52.8	67.5
B.71-7-22	4.2	7.2	7.0	6.9	---	8.9
G.11	15.3	23.3	34.8	20.3	15.6	28.3
G.41N	---	41.0	18.3	23.3	---	28.3
G.41TC	15.0	26.9	24.2	16.5	---	25.6
G.202N	20.4	32.0	51.0	25.6	---	28.8
G.202TC	17.3	27.2	35.6	18.4	18.7	18.5
G.935N	12.2	28.1	42.8	21.4	24.8	32.8
G.935TC	15.3	25.8	38.7	18.3	---	37.0
CG.2034	---	13.2	11.8	11.0	---	18.8
CG.3001	---	46.2	39.2	33.6	---	40.6
CG.4003	9.1	11.6	20.5	12.2	---	15.7
CG.4004	16.6	42.9	37.6	26.6	---	43.5
CG.4013	---	---	28.2	15.5	---	21.8
CG.4214	9.0	20.6	27.5	11.4	---	16.5
CG.4814	11.2	29.9	41.0	29.4	---	26.7
CG.5087	8.1	14.5	26.4	6.0	---	21.0
CG.5222	18.0	43.5	45.6	29.3	25.3	36.8
Supp.3	16.1	18.5	32.2	19.4	---	22.9
PiAu 9-90	37.2	31.4	80.9	53.1	---	71.4
PiAu 51-11	22.2	43.9	62.5	42.1	45.7	57.5
M.9 NAKBT337	11.3	20.4	35.4	19.9	22.2	21.9
M.9 Pajam 2	10.6	29.8	36.7	19.0	22.5	31.1
M.26 EMLA	19.3	40.0	49.1	36.8	34.1	37.8
Average HSD	11.1	18.9	24.8	18.1	14.8	18.8

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

trees that were semi-standard.

Since these results represent only 5 years, they are not expected to be the final answer regarding vigor, and it is not expected that they would align exactly with the categories determined with 'Honeycrisp'.Twenty-six of the rootstocks fell into either the same or a neighboring category for both 'Fuji' and 'Honeycrisp'. Five rootstocks, however, deviated significantly between the two cultivars. B.7-20-21 produced a large semi-dwarf 'Honeycrisp' and a sub-dwarf 'Fuji'. CG.4013, CG.4214, and CG.5087 all produced 'Honeycrisp' trees larger and 'Fuji' trees smaller than comparable trees on M.9 NAKBT337. There are no

Table 8. Cumulative yield per tree (2011-14, kg) of Fuji apple trees at individual planting locations in the 2010 NC-140 Fuji Apple Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	ID	KY	NC	PA	UT
B.9	53.6	5.0	13.4	16.1	22.5
B.10	52.7	12.0	14.2	18.8	33.2
B.7-3-150	66.4	14.5	15.2	23.4	38.4
B.7-20-21	4.6	1.6	4.1	---	5.3
B.64-194	54.0	9.0	18.8	---	29.5
B.67-5-32	63.2	10.8	17.3	23.3	38.5
B.70-6-8	72.5	12.5	19.6	26.4	38.0
B.70-20-20	70.0	9.5	16.6	16.6	41.2
B.71-7-22	18.9	1.8	9.8	---	13.5
G.11	68.4	18.5	24.2	32.2	44.5
G.41N	108.5	9.2	22.1	---	28.6
G.41TC	57.1	8.7	16.6	---	40.4
G.202N	67.7	20.0	24.8	---	31.8
G.202TC	61.4	14.7	22.5	32.6	31.3
G.935N	93.9	21.7	34.7	33.5	62.0
G.935TC	61.7	10.7	31.2	---	52.6
CG.2034	43.5	6.5	12.8	---	28.2
CG.3001	95.4	12.7	17.5	---	55.6
CG.4003	31.2	12.8	22.8	---	29.5
CG.4004	116.3	18.9	36.3	---	43.5
CG.4013	---	5.5	20.0	---	20.6
CG.4214	54.5	8.5	15.0	---	24.1
CG.4814	59.9	18.0	17.0	---	36.5
CG.5087	51.3	16.6	11.4	---	23.7
CG.5222	78.6	26.6	30.8	24.6	39.0
Supp.3	39.0	18.5	22.1	---	33.1
PiAu 9-90	31.0	8.1	11.8	---	22.6
PiAu 51-11	61.5	11.1	16.8	20.3	37.4
M.9 NAKBT337	62.7	16.4	25.7	28.4	31.8
M.9 Pajam 2	72.5	12.5	36.3	29.4	43.4
M.26 EMLA	81.3	14.0	26.0	28.0	40.8
Average HSD	33.6	12.0	20.6	18.6	23.6

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

previously published results on B.7-20-21, so it is uncertain as to the reason for this deviation. Autio et al. (2011a) noted that 10-year-old trees on CG.4013 were larger than those on M.26 EMLA with both 'Fuji' and 'McIntosh' as scion cultivars. Robinson et al. (2011) reported that 7-year-old 'Golden Delicious' trees on CG.4214 and CG.5087 were statistically similar in size to and numerically between those on M.26 and M.7. It appears, based on these published results, that the 'Honeycrisp' trees are responding as expected, and 'Fuji' trees are smaller than expected. Incompatibility may explain this difference, but at this point, we are unsure of the reason. G.202N also

Table 9. Cumulative yield efficiency (2011-14, kg/cm^2 trunk cross-sectional area) of Fuji apple trees at individual planting locations in the 2010 NC-140 Fuji Apple Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	ID	KY	NC	PA	UT
B.9	3.1	0.4	1.9	1.3	1.6
B.10	2.1	0.4	0.7	0.8	1.4
B.7-3-150	2.0	0.2	0.4	0.6	0.8
B.7-20-21	0.9	0.1	1.5	---	0.6
B.64-194	1.2	0.2	0.4	---	0.6
B.67-5-32	1.3	0.2	0.4	0.6	0.8
B.70-6-8	1.9	0.2	0.4	0.6	0.9
B.70-20-20	1.0	0.1	0.2	0.3	0.6
B.71-7-22	2.7	0.2	1.8	---	1.6
G.11	3.0	0.5	1.2	2.0	1.6
G.41N	2.6	0.5	1.0	---	1.1
G.41TC	2.1	0.4	1.0	---	1.6
G.202N	2.1	0.4	1.0	---	1.2
G.202TC	2.3	0.4	1.2	1.7	1.7
G.935N	3.3	0.5	1.7	1.4	1.9
G.935TC	2.5	0.3	1.7	---	1.5
CG.2034	3.3	0.5	1.1	---	1.5
CG.3001	2.1	0.3	0.5	---	1.3
CG.4003	2.7	0.7	1.8	---	1.9
CG.4004	2.8	0.5	1.4	---	1.0
CG.4013	---	0.2	1.5	---	0.9
CG.4214	2.6	0.3	1.2	---	1.5
CG.4814	2.0	0.4	0.5	---	1.4
CG.5087	3.5	0.6	1.4	---	1.2
CG.5222	1.9	0.6	1.0	0.9	1.1
Supp.3	2.2	0.6	1.2	---	1.4
PiAu 9-90	1.0	0.1	0.4	---	0.3
PiAu 51-11	1.4	0.2	0.5	0.4	0.7
M.9 NAKBT337	3.1	0.4	1.4	1.3	1.4
M.9 Pajam 2	2.5	0.3	1.8	1.3	1.4
M.26 EMLA	2.1	0.3	0.7	0.8	1.1
Average HSD	1.1	0.4	1.2	0.5	0.6

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

resulted in different relative tree sizes with 'Honeycrisp' and 'Fuji'. 'Honeycrisp' trees on G.202N were moderate semi-dwarfs, 61% larger than comparable trees on M.26 EMLA (Autio et al., 2017); whereas, 'Fuji' trees on G.202N were large dwarfs that were 16% smaller than comparable trees on M.26. Autio et al. (2011a) reported that 10-year-old 'Fuji' trees on G.202 were slightly, but not significantly, smaller than comparable trees on M.26 EMLA, and 'McIntosh' trees on G.202 were 30% larger than those on M.26 EMLA. Robinson et al. (2011) noted that 6-year-old 'Honeycrisp' trees on G.202 were

Table 10. Average fruit size (2011-14, g) of Fuji apple trees at individual planting locations in the 2010 NC-140 Fuji Apple Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	ID	KY	NC	PA	UT
B.9	200	173	193	182	154
B.10	232	188	205	229	202
B.7-3-150	230	158	214	211	215
B.7-20-21	110	147	140	---	134
B.64-194	250	139	192	---	212
B.67-5-32	254	151	208	217	199
B.70-6-8	239	159	204	206	209
B.70-20-20	268	149	185	197	201
B.71-7-22	184	205	170	---	188
G.11	237	184	239	205	216
G.41N	304	177	206	---	201
G.41TC	275	172	260	---	217
G.202N	249	168	213	---	192
G.202TC	207	166	190	173	168
G.935N	252	165	209	227	197
G.935TC	224	167	227	---	203
CG.2034	232	181	128	---	215
CG.3001	289	182	192	---	208
CG.4003	152	175	191	---	160
CG.4004	284	170	217	---	219
CG.4013	---	137	191	---	185
CG.4214	245	186	222	---	192
CG.4814	241	158	208	---	190
CG.5087	250	164	229	---	181
CG.5222	297	166	212	201	198
Supp.3	234	228	188	---	199
PiAu 9-90	192	154	184	---	214
PiAu 51-11	270	156	205	235	222
M.9 NAKBT337	226	177	215	228	200
M.9 Pajam 2	243	161	211	215	208
M.26 EMLA	259	173	218	227	211
Average HSD	62	62	48	36	36

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

similar in size to those on M.7. Although, rootstock x cultivar interactions are not common, as noted by Autio et al. (2001), the results presented in this study and those from the literature may show differing responses of cultivars to G.202. Also, Autio et al. (2017) noted a dramatic difference between 'Honeycrisp' on G.202 from stool-bed-produced liners versus those from liners originating in tissue culture. Some of these apparent discrepancies may be the result of identification error.

With 'Fuji' as the scion cultivar, these data suggest that B.70-20-20 and PiAu 9-90 instill too much vigor for a tall spindle orchard system, and likely, trees on B.70-6-

Table 11. Rootstocks distributed among eight vigor classes based on trunk cross-sectional area. Within class, rootstocks are ordered highest to lowest based on cumulative (2011-14) yield efficiency. These 2010 NC-140 Fuji Apple Rootstock Trial data are from ID, KY, NC, and UT. All values are least-squares means, adjusted for missing subclasses.

Vigor category	Rootstock	Trunk cross-sectional sectional area (2014, cm^2)	Cumulative yield efficiency (2011-14, kg/cm^2 TCA)
Semi-standard	B.70-20-20	74.0	0.5
Large semi-dwarf	PiAu 9-90	58.8	0.4
Moderate semi-dwarf	B.70-6-8	48.8	0.8
	PiAu 51-11	51.4	0.7
	B.67-5-32	50.7	0.6
	B.64-194	48.0	0.6
Small semi-dwarf	CG.4004	37.6	1.4
	CG.5222	38.8	1.1
	CG.3001	39.7	1.0
	M.26 EMLA	40.8	1.0
	B.7-3-150	44.9	0.9
Large dwarf	G.935N	31.2	1.9
	M.9 Pajam 2	29.1	1.5
	G.935TC	29.6	1.5
	G.202N	34.4	1.2
	CG.4814	32.0	1.1
Moderate dwarf	M.9 NAKBT337	24.4	1.6
	G.11	26.6	1.6
	G.202TC	24.9	1.4
	Supp.3	23.2	1.3
	G.41N	27.6	1.3
	G.41TC	22.5	1.2
	B.10	24.8	1.2
Small Dwarf	CG.4003	14.8	1.8
	B.9	12.6	1.8
	CG.5087	16.6	1.7
	CG.2034	13.8	1.6
	CG.4214	19.2	1.4
	CG.4013[z]	20.8	1.3
Sub-dwarf	B.71-7-22	7.4	1.6
	B.7-20-21	6.4	0.8

[z]Estimated by lsmeans, but not included in overall analyses, since it is not represented in ID.

8, PiAu 51-11, B.67-5-32, and B.64-194 are also too vigorous. On the other end of the spectrum, these data also suggest that ‘Fuji’ on B.71-7-22 and B.7-20-21 are too weak for a commercial production systems like the tall spindle. Rootstocks categorized as small dwarfs, moderate dwarfs, large dwarfs, and small semi-dwarfs may be acceptable.

Within the small semi-dwarf category (Table 11), trees on CG.4004 were the most cumulatively yield efficient. Similarly high performance of trees on CG.4004 was noted by Autio et al. (2017) in the ‘Honeycrisp’ trial. Robinson et al. (2011) reported that 6-year-old ‘Honeycrisp’ trees on CG.4004 were similar in size to those on M.7 but were significantly more yield efficient.

In the large dwarf category (Table 11), trees on G.935N performed the best as assessed by yield efficiency. In other NC-140 trials, trees on G.935 have performed similarly or better than those on M.26 EMLA (Autio et al., 2011a; Autio et al., 2013; Marini et al., 2014).

In the moderate dwarf category, M.9 NAKBT337, G.11, and G.202TC were the most yield efficient (Table 11). Robinson et al. (2011) found 7-year-old 'Golden Delicious' trees on G.11 were more yield efficient than those on M.26 and that 6-year-old 'Honeycrisp' trees on G.11 were similarly yield efficient to those on M.9.

In the small dwarf category, trees on CG.4003, B.9, CG.5087, and CG.2034 were the most yield efficient (Table 11). Robinson et al. (2011) found 7-year-old 'Golden Delicious' trees on CG.5087 were more yield efficient than those on M.26. Robinson et al (2011) also reported that 6-year-old 'Honeycrisp' trees on CG.2034, CG.4003, and B.9 were similarly yield efficient but somewhat less efficient than trees on M.9.

As noted above and in the previous paper in this series (Autio et al., 2017), these results represent an early assessment of many of the rootstocks in this study. This trial will continue through the tenth growing season, after which a more thorough evaluation will be presented.

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