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

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Abstract

In 2010, an orchard trial of apple rootstocks was established at 12 locations in the United States, Canada, and Mexico using 'Honeycrisp' as the scion cultivar. Rootstocks included two named clones from the Budagovsky series (B.9, B.10), six unreleased Budagovsky clones (B.7-3-150, B.7-20-21, 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 (at initiation of the trial) 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 (Pi PiAu 51-11), and three Malling clones as controls (M.9 NAKBT337, M.9 Pajam 2, and M.26 EMLA). For trees on G.41 and G.935, there were both stool-bed-produced (N) and tissue-culture-produced (TC) liners used for trees. All trees were trained as Tall Spindles. After 8 years, the greatest mortality was for trees on CG.3001 (31%), CG.4814 (24%), CG.5222 (17%), CG.2034 (16%), and G.935N (16%). Rootstocks were partitioned into size classes from sub-dwarf to large semi-dwarf. B.7-3-150, B.7-20-21, B.64-194, B.67-5-32, and B.70-6-8 resulted in large semi-dwarf trees with comparably low cumulative yield efficiency and projected cumulative yield per hectare. CG.4004, CG.5222, and PiAu 51-11 produced moderate semi-dwarf trees. The most yield efficient trees in this group were on CG.4004. Trees on CG.3001 and CG.4013 were in the small semi-dwarf category. Projected cumulative yields were statistically similar. The large dwarf category included G.41N, G.202, G.935N, G.935TC, CG.4214, CG,4814, CG.5087, M.9 Pajam 2, and M.26 EMLA. Trees on CG.4214, G.41N, G.935N, CG.5087, and G.935TC were the most yield efficient and had the highest projected per-hectare cumulative yield for their size category. Trees on B.10, G.11, G.41TC, Supp.3, and M.9 NAKBT337 were moderate dwarfs. Trees on G.11, G.41TC, 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 B.9, CG.2034, 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 only moderately yield efficient, with a 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, with the principle goal of helping orchardists optimize their rootstock selection (Cowgill et al., 2017). NC-140 greatly enhances the evaluation process with uniform trials at diverse locations to evaluate performance across a wide variety of soils and climates.

Apple rootstocks from throughout the world, including the United States, Canada, the United Kingdom, Japan, Russia, Poland, Germany, and the Czech Republic, have been evaluated under the direction of NC-140.

Over the last 20 years a number of new rootstocks have become available from the Budagovsky, Cornell-Geneva, and Pillnitz breeding programs. Budagovsky rootstocks are from the Michurinsk State Agrarian University in Michurinsk, Tambov Region, Russia. NC-140 has evaluated numerous Budagovsky rootstocks (Autio et al., 2001a; 2001b; 2013; Marini et al., 2001a; 2001b; 2006; 2014; NC-140, 1996; Robinson et

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al., 2007). The Cornell-Geneva Apple Rootstock Breeding Program is managed jointly by Cornell University and the United States Department of Agriculture-Agricultural Research Service. Many Cornell-Geneva rootstocks have been evaluated by NC-140 (Autio et al., 2011a; 2011b, 2013; Marini et al., 2014; Robinson et al., 2007). The Pillnitz series of rootstocks (PiAu and Supporter) are from the Institut für Obstforschung Dresden-Pillnitz, Germany (Fischer, 1997). Previously, NC-140 evaluated Supporter 1, 2, 3, and 4 and PiAu 51-4, 51-11, and 56-83 (Autio et al., 2011a; 2011b; 2013; Marini et al., 2014). Members of the NC-140 project have conducted groundbreaking research on the role of the cultivar in rootstock effects on growing of the scion (Autio et al. 2001a; 2001b). As a result, the trials going forward have used different cultivars to determine rootstock suitability for different sites. This paper is reporting on the results of the rootstocks mentioned above with 'Honeycrisp' as the scion cultivar. 'Honeycrisp' is a cultivar developed by the University of Minnesota and released in the year 1991 (Luby and Bedford, 1990). Many of its characteristics have attracted growers and consumers, with a resulting increase in the planted area and production.

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 the spring of 2010, an orchard trial of 30 apple rootstocks was established at 12 sites in North America (Table 1) under the coordination of the NC-140 Multi-State Research Committee. 'Honeycrisp' 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), six unreleased Budagovsky clones (B.7-3-150, B.7-20-21, 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 (as of 2010) 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) liners used for trees on G.41 and G.935. The trial initially included three 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. PiAu 9-90 was kept in the trial to its completion, but extreme variability among trees suggested that there was a mistake in the propagation of the trees or the rootstocks. Also, the trial initially had G.202 from both stool-bed-

Table 1. Cooperators and sites in the 2010 NC-140 'Honeycrisp' Apple Rootstock Trail.

Site	Planting location	NC-140 Cooperator	Cooperator affiliation and address
British Columbia (BC)	Summerland	Hao Xu	Summerland Research & Development Centre, Agric. & Agri-Food Canada , P.O. Box 5000, Summerland, BC V0H 1Z0 Canada
Chihuahua (CH)	Cuauhtémoc	Rafael Parra Quezada	Universidad Autonoma de Chihuahua, Facultad de Ciencias Agrotecnologicas, Cuauhtémoc, Chih. 31527, Mexico
Colorado (CO)	Grand Junction	Ioannis Minas	Western Colorado Research Center, Colorado State University, 3168 B 1/2 Road, Grand Junction, CO 81503 USA
Illinois (IL)	Urbana	Mosbah Kushad	Department of Crop Sciences, 1019 Plant Sciences Laboratory, University of Illinois, Urbana, IL 61801 USA
Iowa (IA)	Ames	Diana Cochran	Department of Horticulture, 125 Horticulture Hall, Iowa State University, Ames, IA 50011 USA
Massachusetts (MA)	Belchertown	Wesley Autio	Stockbridge School of Agriculture, 205 Paige Laboratory, University of Massachusetts, Amherst, MA 01003 USA
Michigan (MI)	Sparta	Gregory Lang	Department of Horticulture, Michigan State University, East Lansing, MI 48824 USA
Minnesota (MN)	Excelsior	Emily Hoover	Department Horticultural Science, University of Minnesota, 1970 Folwell Ave, St. Paul, MN 55108 USA
New York (NY)	Geneva	Terence Robinson	Department of Horticulture, Cornell University, NYSAES, Geneva, NY 14456 USA
Nova Scotia (NS)	Kentville	Suzanne Blatt	Kentville Research & Development Centre, Agric. & Agri-Food Canada , 32 Main St, Kentville, Nova Scotia, B4N 1J5 Canada
Ohio (OH)	Carroll	Diane Miller	Department of Horticulture & Crop Science, OARDC, Ohio State University, 1680 Madison Ave., Wooster, OH 44691 USA
Wisconsin (WI)	Sturgeon Bay	Matt Stasiak	Peninsular Agricultural Research Station, University of Wisconsin, 4312 Hwy 42, Sturgeon Bay, WI 54235 USA

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.70-20-20, PiAu 9-90, and G.202 (stool-bed liners) were eliminated from the data set prior to the analyses presented here. Details of this planting were also presented in the 5-year summary of this trial (Autio et al., 2017a). This trial is very similar in design to the 2010 NC-140 'Fuji' Apple Rootstock Trial (Autio et al., 2017b), except for the cultivar, planting location, and tree spacing.

The trial was planted in British Columbia (Canada), Chihuahua (Mexico), Colorado, Illinois, Iowa, Massachusetts, Michigan, Minnesota, New York, Nova Scotia (Canada), Ohio, and Wisconsin. 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 (as affected by the availability of trees from the nursery). Trees were spaced 1.2 x 3.6 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. 'Honeycrisp' leaf zonal chlorosis was assessed as the percent of the canopy affected in 2012-17.

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.

Yield efficiencies ($kg \cdot cm^{-2}$ TCA) were calculated in 2016 and 2017, and the average is presented to avoid variation due to biennial bearing. Cumulative yield efficiency was calculated using cumulative yield (2011-2017) and 2017 TCA. Yield efficiency, however, may not adequately predict relative orchard yield because of the wide variety of 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 sub-dwarf could be spaced at 0.5 x 3.0 m, small dwarfs at 0.7 x 3.2 m, moderate dwarfs at 0.9 x 3.5 m, large dwarfs at 1.1 x 3.8 m, small semi-dwarfs at 1.2 x 4.0 m, moderate semi-dwarfs at 1.4 x 4.4 m, and large semi-dwarfs at 2 x 5 m. A cubic regression relationship was built between average TCA and projected density from the spacing noted above ($Y = 8172.7 - 473.2X + 8.9973X^2 - 0.0437X^3$). Because the TCAs ranged well above the average for the most vigorous tree category, a different quadratic relationship was fit for trees with TCA greater than 35 cm^2 ($Y = 1651.7 -31.837X + 0.1816X^2$). For smaller trees, with TCA below 5 cm^2, a linear relationship was developed to prevent over estimation of tree density ($Y = 7766.5 - 333.3X$). This three-part regression relationship was applied 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 hectare.

As part of the measurement of yield in 2012-17, 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 2012 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 2017), TCA (2017), cumulative yield per tree (2011-17), BBI, cumulative yield efficiency (2011-17), and average fruit weight (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 due to the varied number of actual observations per mean, but it is very conservative in assessing differences and allows for a reasonable look at rootstock effects.

Results

Site Effects on Tree Performance. Of the 12 locations involved in this trial, ten (BC, CH, IL, MA, MI, MN, NS, NY, OH, and WI) included all rootstocks at the beginning of the trial. Data from these ten sites were used to assess location and rootstock effects on survival. Tree loss in CH and IL resulted in some rootstocks missing, so they were not included in the assessment of location and rootstock effects of tree size, yield, and fruit size.

Among the ten locations, survival was very high at all but CH, IL, NS, and OH (Table 2). In CH, 6% of the trees died due to fireblight, and 21% died from undetermined causes. In IL, 15% died due to graft-union breakage from wind, 2% were lost to fireblight, and 5% died due to undetermined causes. In OH and NS, most tree loss was due to union breakage (7% and 10%, respectively). Across all sites, 3.0% of trees were lost to graft union breakage, 0.7% to fireblight, 0.2% to other known causes, and 3.2% to undetermined causes.

Table 2. Site means for trunk cross-sectional area, projected planting density, root suckers, zonal chlorosis, yield per tree, Biennial Bearing Index, yield efficiency, projected per-hectare yield, and fruit size of 'Honeycrisp' apple trees in the 2010 NC-140 'Honeycrisp' Apple Rootstock Trial. Survival means are from all sites which began the trial with a full complement of rootstocks (BC, CH, IL, MA, MI, MN, NS, NY, OH, and WI). Tree size, yield, and fruit size means are from the same group of sites excluding CH and IL, because tree death eliminated all trees of some rootstocks. 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)	Average zonal chlorosis (2012-17, % canopy affected)	Annual yield per tree (average, 2016-17, kg)	Cumulative yield per tree (2011-17, kg)	Biennial Bearing Index (0-1)	Annual 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)
BC	99	13.8	300	160	3483	22.5	46	13.8	54.2	0.67	1.09	4.12	168	243	254
CH	67	---	---	---	---	---	---	---	---	---	---	---	---	---	---
IL	74	---	---	---	---	---	---	---	---	---	---	---	---	---	---
MA	98	20.6	316	173	2483	21.6	46	14.3	68.7	0.45	0.80	3.67	139	210	229
MI	97	20.4	282	149	2559	3.6	48	21.1	77.1	0.46	1.22	4.34	171	210	213
MN	100	21.8	285	170	2390	1.5	37	15.2	69.0	0.59	0.80	3.60	138	123	140
NS	86	18.6	268	139	2670	0.8	31	12.2	61.5	0.63	0.72	3.38	131	157	159
NY	98	24.9	337	212	1993	11.3	27	10.8	85.0	0.54	0.52	3.95	143	262	254
OH	88	25.3	271	95	2161	3.4	44	15.2	46.8	0.79	0.82	2.24	81	204	194
WI	99	20.1	320	191	2559	10.8	21	24.3	94.2	0.40	1.43	5.22	208	203	205
Estimated HSD	11	4.3	24	15	562	5.5	8	3.6	15.3	0.09	0.13	0.48	20	20	15

[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, projected planting density, root suckers, zonal chlorosis, yield per tree, Biennial Bearing Index, yield efficiency, projected per-hectare yield, and fruit size of 'Honeycrisp' apple trees in the 2010 NC-140 'Honeycrisp' Apple Rootstock Trial. Means are based on data from BC, MA, MI, MN, NS, NY, OH, and WI. Survival means additionally include CH and IL. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	Survival (2010-17, %)	Trunk cross-sectional area (2017, cm²)	Tree height (2017, cm)	Canopy width (2017, cm)	Projected tree density (no./ha)	Cumulative root suckers (2010-17, no./tree)	Average zonal chlorosis (2012-17, % canopy affected)	Annual yield per tree (average, 2016-17, kg)	Cumulative yield per tree (2011-17, kg)	Biennial Bearing Index (0-1)	Annual yield efficiency (average, 2016-17, kg/cm² TCA)	Cumulative yield efficiency (2011-17, kg/cm² TCA)	Projected cumulative yield (2011-17, MT/ha)	Fruit weight (2016-17, g)	Average Fruit weight (2012-17, g)
B.9	99	10.2	237	121	4285	9.8	29	9.8	44.0	0.55	1.04	4.37	182	204	204
B.10	95	15.6	275	147	2907	2.4	27	15.1	69.0	0.54	1.08	4.57	196	202	208
B.7-3-150	100	37.0	365	197	1017	2.9	24	21.8	83.7	0.57	0.70	2.45	74	217	224
B.7-20-21	98	36.1	344	189	1007	4.3	29	19.4	81.3	0.60	0.62	2.42	72	210	217
B.64-194	91	41.4	368	198	808	0.8	25	23.5	90.6	0.59	0.66	2.28	64	233	232
B.67-5-32	97	37.3	363	194	985	2.6	25	19.2	73.4	0.61	0.59	2.14	63	213	220
B.70-6-8	98	35.6	354	189	1049	1.2	26	18.1	75.9	0.63	0.61	2.26	68	210	217
B.71-7-22	90	3.6	153	59	6556	5.8	44	2.6	12.3	0.59	0.78	3.60	82	177	180
G.11	89	13.6	277	149	3347	5.1	35	15.8	69.9	0.56	1.24	5.08	221	199	208
G.41N	88	17.1	291	162	2580	1.8	30	17.0	75.5	0.55	1.12	4.51	189	211	216
G.41TC	90	14.6	292	159	3136	5.0	39	16.3	69.3	0.52	1.15	4.85	205	201	208
G.202	89	17.5	300	162	2627	13.9	38	14.5	66.3	0.57	0.93	3.88	160	209	199
G.935N	84	18.7	298	166	2277	16.7	44	17.4	82.5	0.58	1.03	4.47	179	205	204
G.935TC	91	17.0	283	164	2690	21.5	45	16.3	71.3	0.55	1.08	4.41	185	201	202
CG.2034	84	9.4	252	121	4552	3.8	46	9.1	41.0	0.59	1.00	4.33	177	189	196
CG.3001	69	22.5	318	170	1888	2.6	41	18.9	90.6	0.57	0.97	4.23	158	210	213
CG.4003	86	11.6	251	123	4110	2.1	30	10.3	50.1	0.48	1.01	4.63	196	171	180
CG.4004	98	28.9	340	198	1150	11.6	32	24.7	105.7	0.57	0.97	3.81	116	208	215
CG.4013	95	22.4	325	181	2202	19.9	46	17.1	69.6	0.59	0.97	3.57	137	204	205
CG.4214	93	17.7	313	172	2508	32.0	48	17.9	82.0	0.53	1.15	4.85	200	197	202
CG.4814	76	19.5	292	164	2148	17.4	54	16.8	79.3	0.53	0.94	4.12	164	177	185
CG.5087	91	19.3	293	169	2184	7.3	49	16.9	84.2	0.53	0.97	4.43	176	168	185
CG.5222	83	22.9	312	182	1843	23.4	41	17.9	76.6	0.55	0.90	3.60	135	209	207
Supp.3	89	14.1	283	149	3327	5.4	56	10.9	51.3	0.60	0.91	3.76	159	184	192
PiAu 51-11	97	24.9	314	178	1708	4.0	39	15.7	66.4	0.63	0.72	2.80	97	218	222
M.9 NAKBT337	95	15.1	268	148	3083	11.4	36	14.0	62.6	0.56	1.03	4.30	183	200	209
M.9 Pajam 2	92	16.7	276	147	2771	21.3	39	13.6	62.1	0.56	0.89	3.81	159	202	204
M.26 EMLA	87	18.8	285	157	2311	7.7	36	13.8	61.5	0.59	0.82	3.37	136	210	212
Estimated HSD	17	4.6	25	18	506	8.5	8	3.7	12.8	0.10	0.19	0.67	31	27	18

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

The largest trees, based on TCA, were grown in NY and OH, and the smallest were in BC (Table 2). Tallest trees were in NY, and shortest were in NS. Trees with the widest canopy were in NY, and those with the narrowest were in OH. Root suckering (Table 2) was more severe in BC and MA and very low in MN and NS. Zonal chlorosis (2012-17) affected the greatest portion of the canopy in MI, MA, BC, and OH and the least in NY and WI (Table 2).

Annual yield per tree averaged over 2016 and 2017 was greatest in WI and lowest in NY, and cumulatively (2011-17), yield per tree was greatest in WI and least in OH (Table 2). Biennial bearing (BBI) was significant at all locations, but it was most pronounced in OH and was lowest in WI, MI, and MA (Table 2). The most yield efficient trees, averaged over 2016 and 2017, were in WI, and the least were in NY. Cumulatively (2011-17), the most yield efficient trees were in WI, and the least efficient were in OH. Fruit weight in 2016-2017 and averaged over all yielding years was greatest in NY and lowest in MN (Table 2).

Rootstock Effects on Tree Performance. Survival was affected by rootstock (Tables 3 and 4). Across the 10 sites that began with a full complement of rootstocks, the greatest loss occurred for trees on CG.3001, CG.4814, and CG.5222. Graft-union breakage accounted for 58% of those losses, fireblight caused 2%, and 39% were undetermined. Comparing the breeding programs, significantly more losses occurred for trees on rootstocks from Cornell-Geneva (13.1% overall) than any of the others. Overall losses of trees on Budagovsky, Pillnitz, and Malling rootstocks were 3.7%, 7.2%, and 8.3%, respectively. The greater death of trees on Cornell-Geneva rootstocks was solely due to more graft union breakage. Although some rootstocks experienced greater overall tree death than others, there was no rootstock that resulted in tree death at more than 50% of

Table 4. Survival (2010-17, %) of 'Honeycrisp' apple trees at individual planting locations in the 2010 NC-140 'Honeycrisp' Rootstock Trial.[z]

Rootstock	BC	CH	CO	IA	IL	MA	MI	MN	NS	NY	OH	WI
B.9	100	100	100	100	92	100	100	100	100	100	100	100
B.10	100	89	100	100	100	100	100	100	88	89	89	100
B.7-3-150	100	100	100	90	100	100	100	100	100	100	100	100
B.7-20-21	100	83	100	100	100	100	100	100	100	100	100	100
B.64-194	100	29	100	100	100	100	100	100	100	100	83	100
B.67-5-32	100	70	100	100	100	100	100	100	100	100	100	100
B.70-6-8	100	92	100	100	100	92	100	100	100	100	100	100
B.71-7-22	100	100	100	100	83	100	83	100	83	100	67	83
G.11	100	50	100	100	50	100	100	100	90	100	100	100
G.41N	100	82	100	100	70	100	100	100	70	100	80	90
G.41TC	100	75	100	100	100	100	75	100	50	100	100	100
G.202	100	50	100	100	83	100	100	100	100	80	83	100
G.935N	90	100	---	100	30	100	100	100	67	100	67	89
G.935TC	100	100	100	100	50	100	100	100	100	100	67	100
CG.2034	100	20	100	100	60	100	100	100	100	100	67	100
CG.3001	100	0	100	100	0	50	100	100	50	100	100	100
CG.4003	100	40	100	100	75	100	100	100	75	100	75	100
CG.4004	100	100	100	100	100	100	100	100	100	100	75	100
CG.4013	100	50	---	100	100	100	100	100	100	100	100	100
CG.4214	100	71	100	100	71	100	100	100	100	100	88	100
CG.4814	100	57	80	100	50	100	86	100	14	100	50	100
CG.5087	100	67	100	100	33	100	100	100	100	100	100	100
CG.5222	100	80	100	---	14	100	100	100	43	100	100	100
Supp.3	100	67	100	0	80	100	80	100	100	83	80	100
PiAu 51-11	100	82	100	100	100	100	100	100	100	100	90	100
M.9 NAKBT337	100	83	100	100	75	100	100	100	100	100	92	100
M.9 Pajam 2	100	50	100	92	75	100	100	100	100	100	92	100
M.26 EMLA	100	33	100	100	63	100	100	100	88	88	100	100
Estimated HSD	18	98	13	17	81	21	34	0	64	35	74	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.

the sites (Table 4). Reasons for tree death by location are presented in Table 5.

TCA, tree height, and canopy spread were affected similarly by rootstock (Table 3). Trees on B.71-7-22 were the smallest, and those on B.64-194, B.67-5-32, B.7-3-150, B.7-20-21, and B.70-6-8 were the largest. The relative rootstock effects on TCA were similar across sites (Table 6). Projected planting densities ranged from a low of 808 trees per hectare for B.64-194 to a high of 6556 trees per hectare for B.71-7-22 (Table 3).

Root suckering was affected by rootstock (Table 3), with CG.4214 resulting in the most root suckering over the life of this trial. Trees on B.64-194 and B.70-6-8 produced the fewest.

The percent of the tree canopy expressing leaf zonal chlorosis typical of 'Honeycrisp' was assessed in 2012-17 (Tables 3). Trees on Supp.3 had the highest percent of the canopy affected. Trees on Budagovsky rootstocks, with the exception of B.71-7-22, were the least affected by zonal chlorosis.

Cumulative (2011-17) yield per tree was greatest for those on CG.4004 and least for trees on B.71-7-22 (Table 3). Relative differences among rootstocks were reasonably consistent across locations (Table 7).

For all rootstocks, biennial bearing was relatively high, with a BBI (2012-17) generally greater than 0.5 (Table 3). Trees on PiAu 51-11 and those on B.70-6-8 expressed the highest degree of biennial bearing with BBI = 0.63. Trees on CG.4003 had the lowest degree with BBI = 0.48. Generally, trees from the Cornell-Geneva program had slightly lower BBI on average than those from either the Budagovsky or Pillnitz programs, with Malling rootstocks intermediate. Rootstock differences in BBI varied somewhat with site and were not significant for BC, CH, CO, MN, NY and WI (Table 8). In IA, BBI was highest for CG.2034 and lowest for CG.4004. In IL, BBI was highest for B.7-3-150, B.64-194, and B.70-6-8 and lowest for G.935N. In

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

Location	Rootstock	Graft union breakage (no.)	Fireblight (no.)	Winter injury (no.)	Phytophthora (no.)	Unknown cause (no.)	Trees at the beginning of the trial (no.)	Location	Rootstock	Graft union breakage (no.)	Fireblight (no.)	Winter injury (no.)	Phytophthora (no.)	Unknown cause (no.)	Trees at the beginning of the trial (no.)
BC	G.935N	1					10	IA	B.7-3-150					1	10
CH	B.10					1	9		Supp.3			4		2	6
	B.7-20-21					2	12		M.9 Pajam 2					1	12
	B.64-194		1			4	7	MA	B.70-6-8					1	12
	B.67-5-32					3	10		CG.3001					1	2
	B.70-6-8		1				12	MI	B.71-7-22					1	6
	G.11					6	12		G.41TC					1	4
	G.41N					2	11		CG.4814					1	7
	G.41TC		1				4		Supp.3					1	5
	G.202					1	2	NS	B.10	1					8
	CG.2034					4	5		B.71-7-22	1					6
	CG.3001					2	2		G.11	1					10
	CG.4003		2			1	5		G.41N	2				1	10
	CG.4013		2				4		G.41TC	2					4
	CG.4214					2	7		G.935N	3					4
	CG.4814		1			2	7		CG.3001					1	2
	CG.5087					1	3		CG.4003	1					4
	CG.5222					1	5		CG.4814	6					7
	Supp.3					2	6		CG.5222	4					7
	PiAu 51-11		1			1	11		M.26 EMLA					1	8
	M.9 NAKBT337		1			1	12	NY	B.10	1					9
	M.9 Pajam 2		2			4	12		G.202					1	5
	M.26 EMLA		1			3	6		Supp.3		1				6
CO	CG.4814					1	5		M.26 EMLA	1					8
IL	B.9					1	12	OH	B.10					1	9
	B.71-7-22	1					6		B.64-194	1					6
	G.11	5					10		B.71-7-22					2	6
	G.41N	2				1	10		G.41N	2					10
	G.202	1					6		G.202					1	6
	G.935N	7					10		G.935N	1				2	9
	G.935TC	1					2		G.935TC	1					3
	CG.2034	1				1	5		CG.2034	1					3
	CG.3001	1				1	2		CG.4003	1					4
	CG.4003	1					4		CG.4004	1					4
	CG.4214		2				7		CG.4214	1					8
	CG.4814	3				1	8		CG.4814	1				3	8
	CG.5087	1	1				3		Supp.3	1					5
	CG.5222	6					7		PiAu 51-11	1					10
	Supp.3	1					5		M.9 NAKBT337	1					12
	M.9 NAKBT337					3	12		M.9 Pajam 2	1					12
	M.9 Pajam2	1	1			1	12	WI	B.71-7-22	1					6
	M.26 EMLA		1		1	1	7		G.41N	1					10
									G.935N	1					9

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

Rootstock	BC	CH	CO	IA	IL	MA	MI	MN	NS	NY	OH	WI
B.9	7.7	7.3	8.8	8.0	12.4	9.6	10.1	11.4	10.8	9.4	11.1	11.6
B.10	11.6	12.6	18.9	13.4	26.0	15.7	13.7	15.6	15.9	17.6	19.0	15.5
B.7-3-150	20.7	19.1	43.1	46.1	112.6	38.7	36.0	46.7	23.9	44.9	50.7	34.4
B.7-20-21	22.7	14.2	46.8	38.7	92.2	31.2	31.6	36.0	37.5	41.0	49.3	39.9
B.64-194	21.7	18.4	59.6	38.4	104.4	40.3	46.4	43.5	38.0	48.4	48.1	45.1
B.67-5-32	21.9	16.7	51.2	38.0	84.5	37.9	48.6	43.7	28.7	36.4	46.7	34.3
B.70-6-8	19.5	18.0	44.9	48.5	112.3	39.2	30.1	40.7	27.0	45.5	48.2	34.7
B.71-7-22	2.2	3.9	5.1	4.3	4.1	2.5	4.0	6.6	2.3	4.1	3.4	3.7
G.11	9.5	12.0	19.7	14.1	27.9	13.0	14.2	14.5	12.3	15.0	14.5	15.5
G.41N	14.1	10.5	25.3	14.4	25.2	15.3	15.3	17.8	15.4	20.8	19.9	18.6
G.41TC	11.7	8.6	24.6	18.2	26.8	14.2	18.8	16.2	14.4	16.0	10.0	15.7
G.202	10.8	9.5	20.3	20.7	45.0	19.8	14.4	19.4	14.0	26.2	19.1	16.5
G.935N	13.4	9.4	---	18.9	34.0	19.5	18.1	19.0	16.8	22.8	20.5	19.9
G.935TC	11.4	8.1	23.6	13.6	41.8	14.0	15.2	16.5	17.3	20.3	23.6	17.4
CG.2034	9.6	13.2	14.8	11.4	15.5	10.2	9.4	9.6	9.5	8.1	7.9	10.6
CG.3001	18.7	---	30.4	28.5	---	31.4	14.1	21.3	20.8	30.6	27.0	16.1
CG.4003	8.0	8.9	16.3	10.6	14.8	10.3	9.1	11.8	9.5	21.3	10.0	12.3
CG.4004	21.1	15.0	29.4	21.9	48.0	28.1	25.2	36.3	29.0	27.7	34.4	29.2
CG.4013	11.7	13.3	---	39.5	54.9	22.1	24.9	15.4	18.7	33.0	41.2	12.3
CG.4214	10.6	7.5	17.9	16.7	37.9	21.5	18.5	18.2	17.9	21.8	18.4	14.7
CG.4814	15.0	12.1	23.9	30.5	31.0	19.9	18.0	19.4	19.3	24.6	19.8	20.0
CG.5087	16.5	9.8	22.3	17.7	34.2	18.5	16.8	19.1	16.1	24.5	21.7	21.2
CG.5222	16.4	9.6	29.1	---	32.0	23.3	20.0	19.4	23.7	24.7	36.8	18.7
Supp.3	10.3	10.7	25.2	---	14.6	12.7	15.3	14.5	12.7	19.2	16.2	11.7
PiAu 51-11	11.7	13.8	31.8	35.8	94.6	24.3	32.3	25.2	21.2	31.6	28.6	24.6
M.9 NAKBT337	10.0	9.0	20.9	13.0	30.3	14.6	14.2	15.6	12.8	19.6	20.5	13.7
M.9 Pajam 2	12.3	8.9	24.2	17.3	32.8	13.9	16.3	17.6	14.4	20.3	20.8	17.6
M.26 EMLA	14.9	15.5	24.6	21.3	44.4	14.9	21.3	19.3	19.5	20.6	21.6	18.2
Estimated HSD	8.8	5.9	22.5	21.3	31.7	11.0	13.0	15.4	11.6	14.7	15.8	16.3

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

Rootstock	BC	CH	CO	IA	IL	MA	MI	MN	NS	NY	OH	WI
B.9	32.5	6.8	12.3	26.0	22.9	41.3	56.7	37.2	38.3	54.8	31.9	59.4
B.10	52.9	12.9	17.3	34.8	46.6	70.6	74.2	57.2	60.7	93.0	49.2	94.3
B.7-3-150	61.4	17.9	24.3	48.0	39.1	78.3	90.8	107.6	58.2	103.5	46.9	123.0
B.7-20-21	61.9	9.7	24.6	44.4	37.3	76.9	86.1	80.8	94.8	94.3	52.2	103.5
B.64-194	60.1	16.0	18.1	43.8	34.4	71.3	97.3	105.7	106.2	100.1	49.3	134.7
B.67-5-32	61.1	11.6	15.7	39.7	26.5	66.8	96.8	76.6	70.1	71.3	44.1	100.4
B.70-6-8	51.6	13.9	16.5	41.2	39.5	85.7	65.7	94.6	61.1	98.2	42.0	108.6
B.71-7-22	9.8	2.5	2.0	13.5	12.8	8.4	17.4	17.2	5.7	15.1	8.4	16.5
G.11	44.8	18.5	18.2	55.6	48.6	69.9	91.1	76.5	39.3	88.6	51.9	97.4
G.41N	57.1	9.5	22.2	43.2	45.9	77.2	86.0	76.8	63.0	94.7	39.7	109.6
G.41TC	56.0	7.7	24.7	41.8	38.7	58.6	95.0	69.9	67.0	87.0	23.2	98.2
G.202	42.2	19.8	20.8	45.6	42.7	82.5	67.7	73.3	44.0	91.1	48.1	81.3
G.935N	67.5	11.3	---	39.2	71.9	101.1	87.1	65.7	56.4	92.6	57.1	132.6
G.935TC	53.2	8.7	16.2	35.9	49.7	60.5	79.4	61.7	53.9	86.7	60.2	114.5
CG.2034	39.3	7.4	6.6	28.3	26.4	41.6	44.3	44.3	25.3	35.0	30.0	68.2
CG.3001	78.3	---	13.9	70.8	---	126.2	70.7	76.2	102.6	118.1	59.5	92.9
CG.4003	41.7	17.4	12.0	32.0	25.9	54.2	47.7	46.3	39.2	70.8	22.6	78.2
CG.4004	84.2	20.3	22.9	61.1	66.9	108.0	110.5	107.0	109.6	102.4	74.9	148.9
CG.4013	47.2	9.1	---	41.3	37.0	93.5	94.6	63.1	69.3	74.5	56.7	58.3
CG.4214	63.2	10.9	25.5	37.6	49.3	70.9	91.4	86.1	86.2	97.0	63.4	97.6
CG.4814	72.4	14.0	22.8	51.6	61.6	71.0	92.7	85.6	56.9	110.0	53.1	92.9
CG.5087	81.3	12.3	17.8	43.4	29.6	70.1	76.6	80.7	82.0	98.9	69.3	114.5
CG.5222	64.1	8.9	15.9	---	68.8	65.9	82.9	62.8	85.1	88.1	61.8	101.7
Supp.3	53.2	7.2	10.5	---	14.4	43.4	46.3	42.8	34.5	84.1	32.2	74.3
PiAu 51-11	40.2	10.1	18.6	42.9	32.2	60.7	81.4	63.6	61.5	91.5	49.0	83.0
M.9 NAKBT337	46.4	11.3	25.9	39.6	58.1	67.6	79.0	61.9	39.9	87.8	47.2	71.0
M.9 Pajam 2	47.7	7.8	28.9	30.4	47.8	48.9	73.3	58.2	39.4	80.4	45.3	103.4
M.26 EMLA	50.5	3.6	20.0	50.6	67.6	52.7	74.8	52.3	69.5	71.9	40.3	80.2
Estimated HSD	26.4	8.7	13.9	20.1	34.4	35.2	40.7	35.6	46.3	37.8	27.8	45.2

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

Table 8. Biennial Bearing Index (2012-17) of 'Honeycrisp' apple trees at individual planting locations in the 2010 NC-140 'Honeycrisp' Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	BC	CH	CO	IA	IL	MA	MI	MN	NS	NY	OH	WI
B.9	0.63	0.88	0.81	0.69	0.75	0.41	0.38	0.66	0.58	0.58	0.68	0.48
B.10	0.65	0.74	0.73	0.52	0.75	0.46	0.47	0.61	0.55	0.49	0.70	0.36
B.7-3-150	0.65	0.52	0.77	0.57	1.00	0.41	0.55	0.51	0.67	0.58	0.87	0.33
B.7-20-21	0.71	0.73	0.81	0.63	0.98	0.55	0.48	0.52	0.59	0.56	0.90	0.49
B.64-194	0.65	0.58	0.82	0.62	1.00	0.53	0.59	0.54	0.51	0.50	0.90	0.48
B.67-5-32	0.68	0.60	0.81	0.71	0.96	0.52	0.58	0.68	0.49	0.64	0.82	0.47
B.70-6-8	0.71	0.63	0.76	0.65	1.00	0.53	0.58	0.58	0.73	0.53	0.93	0.45
B.71-7-22	0.56	0.80	0.80	0.48	0.80	0.48	0.48	0.55	0.78	0.70	0.77	0.42
G.11	0.70	0.63	0.83	0.73	0.81	0.40	0.42	0.65	0.67	0.53	0.66	0.42
G.41N	0.72	0.65	0.76	0.56	0.76	0.37	0.41	0.57	0.56	0.54	0.86	0.40
G.41TC	0.71	0.59	0.83	0.60	0.83	0.40	0.53	0.58	0.53	0.39	0.69	0.33
G.202	0.68	0.58	0.78	0.59	0.88	0.46	0.36	0.65	0.68	0.53	0.78	0.42
G.935N	0.64	0.72	---	0.73	0.65	0.40	0.43	0.60	0.80	0.58	0.76	0.40
G.935TC	0.71	0.82	0.73	0.72	0.82	0.48	0.28	0.67	0.67	0.49	0.74	0.35
CG.2034	0.71	0.53	0.85	0.76	0.83	0.33	0.50	0.76	0.83	0.51	0.72	0.38
CG.3001	0.75	---	0.95	0.54	---	0.50	0.37	0.67	0.45	0.62	0.84	0.40
CG.4003	0.63	0.82	0.65	0.60	0.73	0.29	0.40	0.56	0.55	0.34	0.71	0.38
CG.4004	0.70	0.53	0.70	0.43	0.77	0.45	0.48	0.46	0.60	0.55	0.94	0.40
CG.4013	0.68	0.62	---	0.75	0.93	0.46	0.48	0.55	0.60	0.73	0.88	0.37
CG.4214	0.64	0.76	0.76	0.58	0.73	0.43	0.41	0.59	0.50	0.58	0.76	0.37
CG.4814	0.61	0.57	0.93	0.55	0.71	0.45	0.37	0.63	0.65	0.39	0.73	0.42
CG.5087	0.66	0.78	0.83	0.69	0.72	0.43	0.42	0.55	0.60	0.59	0.57	0.41
CG.5222	0.64	0.73	0.80	---	0.69	0.51	0.51	0.57	0.53	0.51	0.85	0.28
Supp.3	0.69	0.75	0.76	---	0.81	0.55	0.54	0.62	0.80	0.60	0.68	0.36
PiAu 51-11	0.70	0.63	0.70	0.63	0.95	0.56	0.56	0.57	0.68	0.53	0.92	0.48
M.9 NAKBT337	0.71	0.74	0.80	0.68	0.76	0.36	0.40	0.58	0.71	0.50	0.86	0.40
M.9 Pajam 2	0.68	0.73	0.78	0.67	0.79	0.46	0.43	0.49	0.75	0.62	0.81	0.27
M.26 EMLA	0.69	0.76	0.79	0.70	0.67	0.41	0.49	0.58	0.61	0.56	0.95	0.43
Estimated HSD	0.20	0.39	0.29	0.30	0.24	0.28	0.25	0.29	0.36	0.34	0.35	0.30

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

Rootstock	BC	CH	CO	IA	IL	MA	MI	MN	NS	NY	OH	WI
B.9	4.10	0.96	1.34	3.30	2.14	4.33	5.71	3.28	3.66	5.81	2.92	5.13
B.10	4.69	1.01	0.92	2.66	1.89	4.59	5.47	3.84	3.83	5.35	2.64	6.12
B.7-3-150	3.02	0.96	0.63	1.54	0.33	2.05	2.62	2.34	2.48	2.35	0.93	3.79
B.7-20-21	2.74	0.71	0.63	1.23	0.44	2.57	2.93	2.31	2.62	2.36	1.06	2.77
B.64-194	2.75	0.80	0.32	1.15	0.29	1.75	2.14	2.63	2.79	2.12	1.03	3.03
B.67-5-32	2.83	0.75	0.32	1.10	0.31	1.90	1.99	1.82	2.47	2.07	1.06	3.00
B.70-6-8	2.70	0.79	0.43	0.91	0.37	2.24	2.21	2.38	2.29	2.21	0.90	3.18
B.71-7-22	4.47	0.63	0.71	3.23	2.70	3.31	4.25	3.37	2.42	3.89	2.63	4.48
G.11	4.51	1.53	0.98	4.05	2.04	5.30	6.44	5.21	3.14	5.93	3.73	6.35
G.41N	4.04	0.90	0.89	3.10	1.98	4.95	5.87	4.35	4.08	4.63	2.02	6.11
G.41TC	4.64	0.91	1.08	2.24	1.56	4.13	5.22	5.79	4.86	5.47	2.39	6.34
G.202	3.80	2.11	1.16	2.29	0.96	4.09	4.67	3.83	3.00	4.06	2.55	5.02
G.935N	4.97	1.24	---	2.17	2.46	5.15	4.82	3.61	3.28	4.22	2.84	6.86
G.935TC	4.97	1.11	0.68	2.79	1.06	4.13	5.20	3.77	3.13	4.43	2.66	7.00
CG.2034	4.01	0.50	0.54	2.60	1.72	3.86	4.71	4.57	2.65	4.60	3.80	6.48
CG.3001	4.14	---	0.39	2.58	---	4.01	4.80	3.58	5.06	3.93	2.22	6.13
CG.4003	5.35	1.81	0.92	2.89	1.64	5.11	5.25	4.08	4.08	4.54	2.26	6.36
CG.4004	3.98	1.37	0.80	2.81	1.51	3.85	4.39	3.12	3.89	3.74	2.21	5.26
CG.4013	4.02	0.66	---	1.17	0.70	4.02	4.03	4.17	3.74	2.36	1.36	4.82
CG.4214	5.96	1.42	1.45	2.32	1.36	3.30	5.04	4.78	4.79	4.49	3.69	6.73
CG.4814	4.79	1.17	0.96	1.79	2.18	3.64	5.20	4.49	2.90	4.51	2.76	4.70
CG.5087	4.96	1.29	0.73	2.57	1.04	3.77	4.64	4.26	5.04	4.19	3.10	5.52
CG.5222	3.89	0.92	0.59	---	2.18	2.90	4.21	3.34	3.52	3.75	1.66	5.56
Supp.3	5.04	0.73	0.44	---	1.39	3.37	3.26	3.26	2.52	4.43	1.97	6.24
PiAu 51-11	3.44	0.74	0.62	1.41	0.39	2.53	2.58	2.54	2.93	2.97	1.79	3.59
M.9 NAKBT337	4.57	1.28	1.25	3.47	1.91	4.67	5.62	3.99	3.24	4.69	2.39	5.23
M.9 Pajam 2	3.81	0.88	1.20	1.77	1.55	3.53	4.57	3.44	2.77	4.07	2.30	5.99
M.26 EMLA	3.43	0.18	0.91	2.39	1.74	3.56	3.76	2.77	3.53	3.50	1.91	4.48
Estimated HSD	1.62	0.78	0.85	1.71	1.52	1.42	2.02	2.48	1.74	1.86	1.99	2.11

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

MA, it was highest for PiAu 51-11 and lowest for CG.4003. In MI, it was highest for B.64-194 and lowest for G.935TC. In NS, it was highest for CG.2034 and lowest for CG.3001, and in OH, it was highest for M.26 EMLA and lowest for CG.5087.

Trees on G.11, G.41TC, CG.4214, CG.4003, B.10, G.41N, G.935N, and CG.5087 were the most yield efficient (cumulatively 2011-17), in descending order (Table 3). The least efficient trees, also in descending order, were on B.7-3-150, B.7-20-21, B.64-194, B.70-6-8, and B.67-5-32. Relative differences among rootstocks were consistent among sites (Table 9). The most yield efficient rootstocks overall were also in the top statistical category for almost all sites, and the least efficient rootstocks overall were always in the lowest statistical category. It also is interesting to look at the overall differences among rootstocks from the different breeding programs. Rootstocks from the Cornell-Geneva Program were significantly more yield efficient than those from the other three programs. Malling rootstocks were the next most yield efficient, followed by Budagovsky rootstocks, while Pillnitz rootstocks were the least efficient.

The highest cumulative yield per hectare (based on projected tree density and measured yield per tree) was estimated from trees on G.11, G.41TC, CG.4214, CG.4003, and B.10 (in descending order) (Table 3). The lowest cumulative yield per hectare was projected for trees on B.71-7-22, B.7-3-150, B.7-20-21, B.70-6-8, B.64-194, and B.67-5-32 (in descending order).

Average fruit weight over the life of this trial (2012-17) was affected significantly by rootstock (Table 3). Fruit from trees on B.64-194, B.7-3-150, PiAu 51-11, B.67-5-32, B.7-20-21, B.70-6-8, G.41N, and CG.4004 were the largest (in descending order), and those from trees on CG.4814, CG.5807, CG.4003, and B.71-7-22, were the smallest (in descending order). Malling rootstocks, on average, resulted in larger fruit than Pillnitz rootstocks, and Cornell-Geneva

Table 10. Average fruit size (2012-17, g) of 'Honeycrisp' apple trees at individual planting locations in the 2010 NC-140 'Honeycrisp' Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	BC	CH	CO	IA	IL	MA	MI	MN	NS	NY	OH	WI
B.9	260	194	159	152	174	227	201	146	156	224	211	207
B.10	250	238	204	165	212	240	205	138	162	249	202	216
B.7-3-150	250	177	218	207	215	262	241	175	152	284	200	230
B.7-20-21	234	180	239	188	229	237	220	145	169	276	206	245
B.64-194	239	167	230	191	247	249	249	170	202	283	217	247
B.67-5-32	234	181	237	196	221	252	240	149	183	258	208	236
B.70-6-8	263	192	220	189	234	248	204	155	158	274	198	234
B.71-7-22	224	286	145	125	208	158	220	114	142	193	204	186
G.11	254	188	211	152	194	240	213	115	155	255	221	209
G.41N	287	195	228	168	213	244	228	144	167	269	185	200
G.41TC	249	249	225	189	233	245	214	162	172	266	175	183
G.202	212	176	192	189	197	225	209	149	140	251	194	211
G.935N	252	215	---	166	187	228	208	146	158	252	200	191
G.935TC	240	195	185	170	170	220	214	127	162	254	202	195
CG.2034	269	172	187	173	220	204	216	138	142	234	187	175
CG.3001	277	---	194	195	---	246	185	118	206	284	200	187
CG.4003	259	199	213	144	184	195	197	110	135	215	152	173
CG.4004	285	181	232	184	228	248	214	154	170	252	190	211
CG.4013	241	181	---	195	205	220	189	151	166	267	207	201
CG.4214	269	189	222	173	217	235	212	117	164	257	179	185
CG.4814	252	189	224	189	176	220	181	109	134	257	150	175
CG.5087	233	198	237	163	249	211	186	126	152	241	162	172
CG.5222	270	169	214	---	199	221	206	141	142	249	227	201
Supp.3	268	223	224	---	174	210	189	130	130	254	170	190
PiAu 51-11	245	181	196	195	264	246	234	155	180	268	199	250
M.9 NAKBT337	267	244	225	178	220	230	214	146	161	263	187	205
M.9 Pajam 2	246	223	233	168	206	218	225	144	146	247	192	216
M.26 EMLA	265	176	211	182	222	224	248	158	148	249	198	209
Estimated HSD	77	209	94	39	81	43	59	50	53	38	54	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.

and Budagovsky were intermediate. Rootstock effects on fruit weight varied with location (Table 10); however, fruit from trees on B.7-3-150 and B.64-194 were among the largest at many locations. Fruit from trees on CG.4003, and B.71-7-22 were among the smallest at most locations.

Effects of Rootstock Propagation Technique. Across all tree characteristics assessed (Tables 3-11), few differences were detected between stoolbed-sourced and tissue-culture-sourced rootstocks for G.41 and G.935.

Discussion

Trees were grouped into vigor classes based on TCA. Table 11 presents TCA and mean projected density, along with estimated in-row and across-row spacing for each rootstock grouped according to size categories. It also includes the cumulative yield efficiency and the projected cumulative yield per hectare. This discussion includes actual results and projections derived directly from those data.

B.64-194, B.67-5-32, B.7-3-150, B.7-20-21, and B.70-6-8 produced trees in the large semi-dwarf category (200+% of M.9 NAKBT337) and were estimated to be suitable for an orchard density of between 808 and 1049 trees per hectare. Cumulative projected yields per hectare ranged from 63 to 74 MT and were not statistically different among rootstocks in this largest category.

CG.4004, PiAu 51-11, and CG.5222 and produced trees in the moderate semi-dwarf category (150-200% of M.9 NAKBT337), with a projected orchard density ranging from 1150 to 1843 trees per hectare. Trees on CG.5222 could potentially yield 135 MT per hectare, significantly more than trees on PiAu 51-11. 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.

CG.3001 and CG.4013 produced trees in the small semi-dwarf category (130-150% of M.9 NAKBT337). It is estimated that they should be planted at densities of 1888 and

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 semi-dwarf, and 200+% large semi-dwarf. 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 'Honeycrisp' Apple Rootstock Trial data are from BC, MA, MI, MN, NS, NY, OH, and WI. 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	37.0	1017	1.98 x 4.98	2.45	74
	B.7-20-21	36.1	1007	1.99 x 4.99	2.42	72
	B.64-194	41.4	808	2.32 x 5.32	2.28	64
	B.70-6-8	35.6	1049	1.93 x 4.93	2.26	68
	B.67-5-32	37.3	985	2.02 x 5.02	2.14	63
Moderate semi-dwarf	CG.4004	28.9	1150	1.81 x 4.81	3.81	116
	CG.5222	22.9	1843	1.27 x 4.27	3.60	135
	PiAu 51-11	24.9	1708	1.35 x 4.35	2.80	98
Small semi-dwarf	CG.3001	22.5	1888	1.31 x 4.06	4.23	158
	CG.4013	22.4	2202	1.16 x 3.91	3.57	137
Large dwarf	CG.4214	17.7	2508	1.05 x 3.80	4.85	200
	G.41N	17.1	2580	1.03 x 3.78	4.51	189
	G.935N	18.7	2277	1.13 x 3.88	4.47	179
	CG.5087	19.3	2184	1.17 x 3.92	4.43	176
	G.935TC	17.0	2690	0.99 x 3.74	4.41	185
	CG.4814	19.5	2148	1.18 x 3.93	4.12	164
	G.202	17.5	2627	1.01 x 3.76	3.88	160
	M.9 Pajam 2	16.7	2771	0.97 x 3.72	3.81	159
	M.26 EMLA	18.8	2311	1.12 x 3.87	3.37	136
Moderate dwarf	G.11	13.6	3347	0.88 x 3.38	5.08	221
	G.41TC	14.6	3136	0.93 x 3.43	4.85	205
	B.10	15.6	2907	0.99 x 3.49	4.57	196
	M.9 NAKBT337	15.1	3083	0.94 x 3.44	4.30	183
	Supp.3	14.1	3327	0.89 x 3.39	3.76	159
Small dwarf	CG.4003	11.6	4110	0.75 x 3.25	4.63	196
	B.9	10.2	4285	0.72 x 3.22	4.37	182
	CG.2034	9.4	4552	0.69 x 3.19	4.33	177
Sub-dwarf	B.71-7-22	3.6	6556	0.51 x 3.01	3.60	82
Estimated HSD		4.6	506		0.67	31

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

2202 trees per hectare, respectively. Projected cumulative yields of trees on these two rootstocks were 158 and 137 MT per hectare, respectively, and were statistically similar.

In the large dwarf category (110-130% of M.9 NAKBT337), trees on CG.4814, CG.5087, M.26 EMLA, G.935N, CG.4214, G.202, G.41N, G.935TC, and M.9 Pajam 2 and ranged in projected orchard density from 2148 to 2771 trees per hectare and cumulative yield from 136 to 200 MT per hectare. The greatest projected yields were from trees on CG.4214, G.41N, G.935TC, G.935N, and CG.5087. In a New York trial, 'Golden

Delicious' trees on CG.5087 were between M.26 and M.7 in size but were significantly more yield efficient than both (Robinson et al, 2011). In the same trial, trees on CG.4214 were similar to trees on M.26 in size and yield efficiency. In another New York trial, 'Honeycrisp' trees on CG.4814 were larger than those on M.9 NAKBT337, and trees on CG.4214 were intermediate between CG.4814 and M.9 NAKBT337 (Lordan et al., 2018). Cumulative yield efficiencies of trees on CG.4214, CG.4814, and M.9 NAKBT337 were statistically similar. Lordan et al. (2018) also found trees on G.935 to be larger than those on M.9 NAKBT337 and less yield efficient. Autio et al. (2011a) found that both 'Fuji' and 'McIntosh' trees on G.935 performed similarly to comparable trees on M.26 EMLA. Likewise, Autio et al. (2013) found that 'Gala' on G.935 were similar in size, with yield efficiency similar or greater, compared to trees on M.26 EMLA. Robinson et al. (2011) found 6-year-old 'Honeycrisp' trees on G.935 to be similar in size and yield efficiency to those on M.7. Marini et al. (2014) found that 'Golden Delicious' trees on G.935 were similar in size to comparable trees on M.9 NAKBT337 or M.26, depending on planting site, but were generally more yield efficient than those on M.26. Dallabetta et al. (2018b) found 'Golden Delicious' on G.202 to be larger than trees on M.9 NAKBT337 and less yield efficient.

B.10, M.9 NAKBT337, G.41TC, Supp.3, and G.11 were categorized as moderately dwarf (80-110% of M.9 NAKBT337). Projected orchard densities varied from 2907 to 3347 trees per hectare, with cumulative yields from 159 to 221 MT per hectare. Greatest yields were estimated for G.11, G.41TC, and B.10. Numerous studies (Autio et al., 2011a; Dallabetta et al., 2018b; Lordan et al., 2018; Marini et al., 2014; Robinson et al., 2011) have reported that trees on G.41 were similar in size and yield efficiency to comparable trees on M.9. Marini et al. (2014) found that 'Golden Delicious' trees on G.11 were smaller and more yield efficient than comparable trees on M.26, and Robinson et al. (2011) found that 'Honeycrisp' trees on G.11 were smaller and of similar yield efficiency to those on M.9. Dallabetta et al (2018a) found 'Gala' and 'Golden Delicious' trees on G.11 to be similar in size to comparable trees on M.9 NAKBT337, but 'Fuji' trees on G.11 were slightly larger than trees on M.9 NAKBT337. Trees on G.11 and M.9 NAKBT337 were similarly yield efficient. Lordan et al. (2018) showed that 'Honeycrisp' trees on G.11 were smaller and more yield efficient than comparable trees on M.9 NAKBT337 and larger and similarly efficient to trees on B.9.

Trees in the small dwarf category (40-80% of M.9 NAKBT337) (CG.4003, B.9, and CG.2034) ranged in projected orchard density from 4110 to 4552 trees per hectare with cumulative yields ranging from 177 to 196 MT per hectare. These three did not differentiate statistically. Robinson et al. (2011) reported that 'Honeycrisp' trees on CG.4003 were similar in size and yield efficiency to trees on B.9, after 6 years.

B.71-7-22 produced a sub-dwarf tree (0-40% of M.9 NAKBT337) with a projected orchard density of 6556 trees per hectare and cumulative yield of 82 MT per hectare.

While few of the new Budagovsky rootstocks show any commercial promise (too large and lack yield efficiency), B.10 is a promising, moderate dwarf rootstock. Neither of the Pillnitz rootstocks (PiAu 51-11 and Supp.3) performed well, and both had the lowest yield efficiency in their respective size class. The Cornell-Geneva rootstocks (both CG and G), on the other hand, performed very well and in all cases, were the best in their size classes.

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