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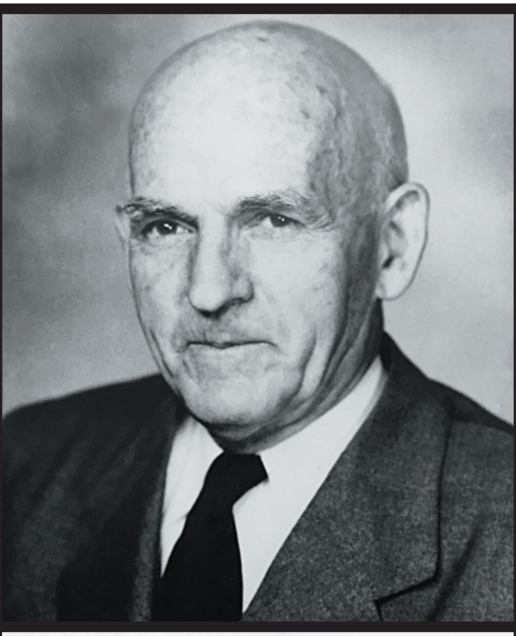


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Productivity of 'Chambourcin' Grape, Own-Rooted and Grafted to Seven Different Rootstocks

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Additional index words: French-American interspecific hybrid, yield, cane pruning weight, average cluster weight, average berry weight, soluble solids, pH, titratable acidity

Abstract

The French-American interspecific hybrid grape cultivar 'Chambourcin' (26.205 Joannés-Seyve) was planted in 2004 at Mountain Grove, Mo., on seven different rootstocks (3309C, 101-14 Mgt, 5BB, SO4, 110R, 1103P, Freedom). Own-rooted 'Chambourcin' was also grown. The site characteristics are latitude 37° 9' N, longitude 92° 16' W, elevation 442 m, USDA plant hardiness zone 6a, and a Viraton silt loam soil with 2 to 5% slope. The soil is characterized as acidic, moderately well-drained, and slowly permeable with chert and fragipan in the subsoil. This soil restricts root growth, is prone to drought, and reduces vine vigor. Rootstocks were tested in a replicated trial during the years 2009 to 2013 to improve scion productivity. 'Chambourcin' grafted to 3309C, 5BB, and 1103P had significantly higher yield per vine compared to own-rooted. The remaining rootstocks were not significantly different from own-rooted. Vines grafted to 3309C and 1103P had significantly higher pruning weight per vine compared to own-rooted in three years. The remaining rootstocks were not significantly different from own-rooted. Average cluster and berry weights were not significantly affected by rootstocks in all years, but own-rooted vines were significantly lower in some years. Juice soluble solids was significantly higher for own-rooted compared to some rootstocks in two years, a likely result of lower yields on these vines. Juice titratable acidity was not affected by rootstock, and pH was affected one year. Crop load (yield to cane pruning weight ratio) ranged from 12 to 15. Lower crop loads would likely have improved fruit composition. Productivity of 'Chambourcin', a cultivar prone to low vigor when grown on a restrictive soil, can be improved when grafted to rootstocks. The rootstocks 3309C, 5BB, and 1103P appeared best.

'Chambourcin' is a high quality wine grape that is suitable for growing in Missouri. It is one of the best red grape cultivars grown in the state that is fermented to a dry, red wine and barrel aged to a premium product (Wilker, K., personal communication, July 30, 2015). 'Chambourcin' is moderately adapted to southern Missouri (USDA Hardiness zone 6a) as phloem, cambium, and buds are cold tender when average January temperature drops below -20 ˚C (Brusky-Odneal, 1983). Using differential thermal analysis, lethal temperature for 50% primary bud mortality of 'Chambourcin' was -22.9 ˚C (Gu et al., 1997). While classified as having good resistance to downy (*Plasmopara viticola* (Berk. & M.A. Curtis) Berl. & De Toni) and powdery (*Uncinular necator* (Schwein.) Burrill) mildews (Galet, 1998), it is susceptible to these fungal diseases under the moist, humid conditions that occur in the state. A season long spray program is required to control disease and insect pests. Clusters are rated as compact, voluminous, often with shot berries (Galet, 1998). In my experience, clusters tend to be loose, so they are not susceptible to bunch rot (*Botrytis cinerea* Pers.). Additionally, fruit set is variable depending on the year, so crop regulation beyond dormant balance pruning may be needed. Fruit matures in late Sept. through early Oct. in southern Missouri. The vine is rated as extremely vigorous with a spreading growth habit and susceptible to drought (Galet, 1998); however, in my experience this depends on the site where vines are grown. The southern half

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of Missouri is in the Ozark Plateau region. Many of the soil types are of fine texture and shallow depth due to the occurrence of a fragipan. The latter is a dense subsurface horizon that restricts water drainage and root penetration, and makes soils drought prone. In my experience, 'Chambourcin' is not vigorous when grown in a soil with fragipan.

Grape rootstocks are important to overcoming the debilitating effects of phylloxera (*Daktulosphaira vitifoliae* Fitch) and nematodes (*Pratylenchus, Xiphinema, Meloidogyne spp*.) in *Vitis vinifera* L. scions (Pongrácz, 1983). They are also used to improve vine adaptation to soil problems such as high pH, salt, and drought (Howell, 1987). Rootstock influence on scion vigor is another use. Possible mechanisms for a grape rootstock to influence scion vigor are alteration of the graft union to affect phloem and xylem transport or root system growth habit to affect rooting depth (Howell, 1987, Pongracz, 1983). The purpose of this study was to determine whether 'Chambourcin' vigor and productivity could be enhanced by grafting to grape rootstocks.

Materials and Methods

'Chambourcin' was planted in 2004 at Mountain Grove, MO. The site is at latitude 37° 9' N and longitude 92° 16' W with an elevation of 442 m. It is USDA plant hardiness zone 6a. The soil is a Viraton silt loam soil with 2 to 5% slope (Web Soil Survey). The soil is characterized as a naturally acidic (pH 4.5 to 6.0), silt loam topsoil and a very cherty, silty, clay loam subsoil with a fragipan at 45 to 85 cm depth. It is rated as moderately well-drained with a low water holding capacity because of its shallow depth. The long growing season (≥190 frost-free days) of this location allows enough time for 'Chambourcin' to mature.

'Chambourcin' was grafted to seven different rootstocks: 3309C, 101-14 Mgt, 5BB, SO4, 110R, 1103P, and Freedom. Own-rooted vines were also planted. Spacing was 2.4 m within and 3.0 m between rows. Experiment design was a randomized complete block with four replications. Vines were trained to a high, bilateral cordon with eight node bearing canes and two node renewal spurs. Balance pruning was used to regulate cropping at a level of 20 plus 10 nodes retained for each pound (0.454 kg) of dormant cane prunings. The vineyard was managed with no additional crop control (cluster thinning), so the decision was made to only use balance pruning to regulate cropping for the trial period. Vineyard floor was managed using pre and post emergent herbicides along trellis rows and permanent ground cover of tall fescue (*Festuca arundinacea* Shreb.) in row middles. Nitrogen was applied annually and gradually increased to 78 kg/ha of actual N by the end of the trial. Other macronutrients were brought-up to desired soil test maintenance levels (112 kg P, 224 kg K, 2244 kg Ca, and 450 kg Mg per ha) at the beginning of the trial. Soil was amended with lime to maintain pH above 6.0 over the test years. Vine productivity measurements were recorded from 2009 through 2013 and included yield per vine; cane pruning weight per vine; average cluster and berry weights; and juice soluble solids (%), pH and titratable acidity (g/L). ANOVA was performed on the raw data and means separated by Tukey-Kramer HSD (P=0.05)

Results and Discussion

The grape rootstocks used in this trial are of varying parentage. 3309C and 101-14 Mgt are *V. riparia* x *V. rupestris* crosses. SO4 and 5BB are *V. berlandieri* x *V. riparia* crosses. 110R and 1103P are *V. berlandieri* x *V. rupestris* crosses. The rootstocks 110R and 1103P are best adapted to fine texture, shallow, droughty soil (Galet, 1998; Howell, 1987; Pongrácz, 1983; Shaffer, 2002; Shaffer et al. 2004). These are the soil conditions that occur at Mountain Grove. Because the trial vineyard was amended with lime, rootstock tolerance to acidic soil was not as important.

Rootstock enhancement of scion vigor and tolerance to drought were desirable to investigate since they were needed on our site. These attributes vary among the rootstocks with *V. berlandieri* x *V. riparia* (SO4, 5BB) rated higher in scion vigor and *V. berlandieri* x *V. rupestris* (110R, 1103P) rated higher in tolerance to drought (Howell, 1987; Shaffer, 2002; Shaffer et al. 2004). While this implies *V. riparia* x *V. rupestris* crosses (3309C, 101-14 Mgt) are intermediate, both of these have desirable effects on either scion vigor (101-14 Mgt) or tolerance to drought (3309C) (Shaffer, 2002; Shaffer et al. 2004). Freedom rootstock is a 1613C x Dog Ridge hybrid that was included in this trial (Freedom, 2015). It is nematode resistant and promotes scion vigor, but lacks phylloxera and drought resistance (Howell, 1987). The vineyard site favored the use of a rootstock that adapted vines to shallow, droughty, soil and also enhanced scion vigor. Potentially any of the rootstocks could be acceptable.

Yield per vine was not significantly different among the seven different rootstocks, but own-rooted was significantly lower than grafted vines with the specific rootstocks varying by year (Table 1). This shows an advantage of grafted over own-rooted vines. 'Chambourcin' is not prone to phylloxera infestation (Galet, 1998). No foliar form of phylloxera was noted on own-rooted vines. Of the seven different rootstocks, 3309C, 5BB, SO4 and 1103P had the highest yields although these were not significantly different from the other three rootstocks. The rootstock 5BB significantly increased yield of 'Chardonel' over own-rooted vines in Arkansas (Main et al., 2002). In that same trial, 110R and Freedom also had higher yields than own-rooted vines but the difference was not significant. The vineyard location in Fayetteville, AR has similar soil characteristics to this vineyard. In this trial, grafted vines had excessive yields in some years (Table 1). Additional crop control by cluster thinning could have prevented this, but was not done. Balance pruning to 15 to 20 nodes per pound (0.454 kg) of cane prunings and thinning to 1 to 2 clusters per shoot optimized yield of 'Chambourcin' in southern Illinois (Kurtural et al., 2006). Of the rootstocks tested, 3309C,101-14 5BB and 1103P have some tendency to overbear (Shaffer, 2002; Shaffer et al. 2004). This occurred in 2010 and 2013 in the trial (Table 1).

Pruning weight is a measure of vine growth and is positively related to yield the following season (Partridge, 1925; Kimball and Shaulis, 1958). Vines with higher pruning weights are balance pruned to leave more nodes. These nodes have buds with shoot and cluster primordia for next season's crop. Significant differences occurred in three of the five test years (2009, 2011, 2012). Vines grafted to rootstocks 3309C, 101-14 and 1103P had higher pruning weights than own-rooted vines (Table 2). The other rootstocks were not different from own-rooted; however, the latter tended toward the lowest prun-

Table 1. Yield (kg) per vine of 'Chambourcin' grape, own-rooted and grafted to seven rootstocks, at Mountain Grove, MO, 2009-2013.

Rootstock	2009		2010		2011		2012		2013	
Own	4.42	bc[z]	8.24	bc	6.11	bc	5.58	bc	5.89	bc
3309C	13.63	a	20.75	a	11.98	a	10.93	a	15.68	a
101-14	8.98	ab	16.93	ab	7.24	ab	13.27	a	10.70	ab
5BB	13.34	a	17.27	a	7.26	ab	9.79	ab	12.84	ab
SO4	12.78	ab	16.48	ab	11.90	ab	10.63	ab	14.16	ab
110R	12.82	ab	13.38	ab	9.89	ab	10.13	ab	10.73	ab
1103P	10.91	ab	18.64	a	9.13	ab	12.37	a	17.00	a
Freedom	10.88	ab	17.31	a	10.14	ab	10.31	ab	10.93	ab

[z]Means in a column not followed by a common letter are significantly different by Tukey-Kramer HSD, $P \leq 0.05$.

Table 2. Cane pruning weight (g) per vine of 'Chambourcin' grape, own-rooted and grafted to seven rootstocks, at Mountain Grove, MO, 2009-2013.

Rootstock	2009		2010		2011		2012		2013	
Own	355	bc[z]	1535		462	bc	511	bc	205	
3309C	1084	a	1560		1089	a	1150	a	686	
101-14	1008	ab	1560		706	ab	1051	ab	566	
5BB	558	ab	1285		555	bc	869	ab	621	
SO4	852	ab	1138		824	ab	795	ab	364	
110R	634	ab	1562		838	ab	911	ab	391	
1103P	935	a	1587		930	a	1152	a	674	
Freedom	724	ab	1569		597	ab	795	ab	484	

[z]Means in a column not followed by a common letter are significantly different by Tukey-Kramer HSD, $P \leq 0.05$.

ing weight. Among the rootstocks in 2009, 2011 and 2012, there were no significant differences except for 5BB being lower than 3309C and 1103P in 2011. The implication is that grafted vines were more vigorous than own-rooted vines in this trial.

A desirable crop load (yield to cane pruning weight ratio) for *V. vinifera* L. is 10 to 12 as stated by Bravdo et al. (1984, 1985), but may be lower or higher than 10 for certain training systems and vine spacings (Kliewer and Dokoozlian, 2000; Reynolds et al., 1986; Reynolds and Wardle, 1994; Reynolds et al., 1995). In the long (195 day) growing season area of southern Illinois, own-rooted 'Chambourcin' grown at wide (2.4 m) spacing could have crop loads of 10 to 14 (Dami et al., 2005). Growing season length and vine spacing used in southern Missouri are similar to southern Illinois. In contrast own-rooted 'Chambourcin' grown in a short (160 day) growing season area of northeast Ohio and at narrow (1.2 m) spacing required a crop load below 8 (Dami et al., 2005). They stated that variation in crop load between regions was due to length of growing season and vine spacing. A level of 15 to 20 nodes per pound (0.454 kg) of cane prunings was recommended for own-rooted 'Chambourcin' in a long growing season area of southern Illinois if follow-up cluster thinning of 1 to 2 per shoot was done (Kurtural et al., 2006). They stated that this balanced the vine with a yield of just under 10 kg, and provided optimum fruit composition and cane pruning weight (≥ 0.72 kg). In the present trial, an average crop load for all grafted vines varied between 12 and 15 over the first four years (data not shown). Own-rooted vines also had crop loads in this range, except in 2010 when it was 5. In 2013, crop load averaged almost 25 for all grafted vines (data not shown). Based on the work of Dami et al. (2005), vines in the first four years of the current trial were reasonably balanced, but were overcropped the last year.

Average cluster weight was influenced by rootstock in two of the five test years (2011, 2012) (Table 3). No differences occurred among the seven different rootstocks in either year. Own-rooted vines had significantly lower average cluster weight than vines on SO4 and 110R in 2011, and 101-14 Mgt and 1103P in 2012. Own-rooted vines tended to have lower average cluster weight than the other rootstocks in these years, but were not significantly different. Hybrid grapes including 'Chambourcin' have high bud fruitfulness and larger clusters compared to *V. vinifera* L. (Pool, et al., 1978; Reynolds, 1986). To obtain a crop load of 10 or less on grafted 'Chambourcin', cluster thinning to 10 per vine was needed in a short (160 day) growing season area of northeastern Ohio (Dami et al., 2006). This thinning level decreased yield and increased average cluster and berry weights. Less thinning led to higher crop load and yield, and lower

Table 3. Average cluster weight (g) of 'Chambourcin' grape, own-rooted and grafted to seven rootstocks, at Mountain Grove, MO, 2009-2013.

Rootstock	2009	2010	2011		2012		2013
Own	255	222	191	bc[z]	207	bc	152
3309C	265	305	264	ab	278	ab	214
101-14	275	306	244	ab	321	a	239
5BB	270	302	232	ab	295	ab	211
SO4	270	300	301	a	290	ab	209
110R	260	278	292	a	250	ab	186
1103P	255	292	237	ab	321	a	211
Freedom	260	292	233	ab	312	ab	211

[z]Means in a column not followed by a common letter are significantly different by Tukey-Kramer HSD, $P \leq 0.05$.

Table 4. Average berry weight (g) of 'Chambourcin' grape, own-rooted and grafted to seven rootstocks, at Mountain Grove, MO, 2009-2013.

Rootstock	2009	2010		2011		2012	2013	
Own	2.15	2.05	bc[z]	2.16	bc	1.98	2.16	bc
3309C	2.22	2.31	a	2.48	a	2.16	2.49	a
101-14	2.28	2.32	a	2.45	a	2.29	2.55	a
5BB	2.28	2.17	ab	2.34	ab	2.13	2.42	ab
SO4	2.35	2.28	a	2.51	a	2.18	2.47	a
110R	2.29	2.30	ab	2.40	ab	2.05	2.44	ab
1103P	2.32	2.32	a	2.49	a	2.20	2.53	a
Freedom	2.27	2.38	a	2.45	ab	1.99	2.44	ab

[z]Means in a column not followed by a common letter are significantly different by Tukey-Kramer HSD, $P \leq 0.05$.

average cluster and berry weights (Dami et al., 2006).

Average berry weight was different in three of the five test years (2010, 2011, 2013) (Table 4). Much like average cluster weight, no differences occurred among the seven different rootstocks in these three years. Own-rooted vines had significantly lower average berry weight than vines on 3309C, 101-14 Mgt, 1103P and Freedom in 2010; 3309C and 1103P in 2011; and 3309C, SO4, 101-14 Mgt, and 1103P in 2013. The rootstocks 3309C and 1103P tended to have higher average berry weight in these three years. This did not result in higher average cluster weight for these rootstocks in 2011 (Table 3). Both average cluster and berry weights had significant differences only in 2011. Own-rooted vines tended to have lowest values for both average cluster and berry weights when compared to grafted vines. Cluster weight is determined by the number of berries set and berry weight. A reduction in either of these will result in lower cluster weight. It is likely that own-rooted vines also had a lower berry set, but this was not verified in this trial since number of berries per cluster was not recorded.

Juice soluble solids (SS) were significantly different in 2010 and 2013 (Table 5). An assumption is that soluble solids accumulation and yield per vine are negatively related. Cluster thinning of 'Chambourcin' increased soluble solids linearly as crop levels were reduced (Dami et al., 2005 and 2006; Kurtural et al., 2006). In this trial, own-rooted vines had significantly higher soluble solids than vines grafted to 101-14 Mgt and 5BB in 2010, and 3309C and 1103P in 2013. This was a likely result of the lower yields on own-

Table 5. Juice soluble solids (%) of 'Chambourcin' grape, own-rooted and grafted to seven rootstocks, at Mountain Grove, MO, 2009-2013.

Rootstock	2009	2010		2011	2012	2013	
Own	21.60	22.75	a[z]	23.65	23.18	22.90	a
3309C	21.23	21.70	ab	22.50	22.83	21.45	bc
101-14	21.80	20.75	bc	21.90	23.00	22.10	ab
5BB	22.15	20.58	bc	22.80	22.95	22.15	ab
SO4	21.50	21.80	ab	21.95	22.50	22.35	ab
110R	21.80	22.00	ab	23.00	22.70	22.85	ab
1103P	20.90	21.73	ab	22.03	22.55	21.48	bc
Freedom	21.85	21.75	ab	23.30	22.30	22.20	ab

[z]Means in a column not followed by a common letter are significantly different by Tukey-Kramer HSD, $P \leq 0.05$.

Table 6. Juice pH of 'Chambourcin' grape, own-rooted and grafted to seven rootstocks, at Mountain Grove, MO, 2009-2013

Rootstock	2009	2010		2011	2012	2013
Own	3.41	3.38	ab[z]	3.46	3.43	3.20
3309C	3.39	3.44	ab	3.47	3.45	3.26
101-14	3.46	3.44	ab	3.49	3.50	3.28
5BB	3.33	3.33	bc	3.42	3.40	3.21
SO4	3.41	3.39	ab	3.48	3.40	3.24
110R	3.45	3.44	ab	3.44	3.40	3.23
1103P	3.41	3.50	a	3.55	3.55	3.27
Freedom	3.43	3.46	ab	3.51	3.45	3.30

[z]Means in a column not followed by a common letter are significantly different by Tukey-Kramer HSD, $P \leq 0.05$.

rooted vines. These differences were small, about 1%, and not important from a practical winemaking standpoint. The increase in soluble solids would not offset the economic loss from lower yields on own-rooted vines.

Juice pH was significantly different only in 2010 (Table 6). Vines grafted to 1103P and 5BB had highest and lowest pH, respectively. Lower pH values could be important in winemaking but it was not consistent for 5BB across the years of the trial. For juice pH, own-rooted vines were not different from grafted even with their lower yields. In general, pH values in all years except 2013 were high for winemaking. It was a likely result of delaying fruit harvest to obtain lower titratable acidity (TA) values.

Juice titratable acidity was not influenced by rootstock (Table 7). Rootstocks rarely influenced pH and titratable acidity of 'Chardonel' own-rooted and grafted (Freedom, 5BB, 110R) vines (Main et al., 2002). Cluster thinning 'Chambourcin' vines resulted in very few pH and titratable acidity differences (Dami et al., 2005 and 2006; Kurtural et al., 2006). Based on these research reports, juice pH and titratable acidity appear to be insensitive to use of rootstock and cluster thinning. The high yields on grafted vines in some years of this trial resulted in less balanced SS, pH, and TA during fruit ripening that required delaying harvest. More balanced fruit composition and earlier ripening could be obtained by reducing crop load through greater pruning severity, cluster thinning or a combination of both.

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Dr. Keith Striegler and Ms. Susanne Howard for planting the vineyard in 2004.

Table 7. Juice titratable acidity (g/L) of 'Chambourcin' grape, own-rooted and grafted to seven rootstocks, at Mountain Grove, MO, 2009-2013.

Rootstock	2009	2010	2011	2012	2013
Own	0.92	0.75	0.70	0.67	0.86
3309C	0.91	0.75	0.79	0.71	0.97
101-14	0.85	0.74	0.80	0.67	0.92
5BB	0.88	0.82	0.80	0.72	0.93
SO4	0.94	0.78	0.75	0.67	0.83
110R	0.94	0.71	0.76	0.67	0.86
1103P	0.95	0.72	0.82	0.60	0.97
Freedom	0.85	0.73	0.74	0.69	0.93

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Performance of Geneva® Apple Rootstock Selections with 'Brookfield Gala' and 'Cripps Pink' in a Tall Spindle System

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Abstract

High density orchard systems have become standard in many apple production regions due to their earlier yield and higher cumulative yields, which results in greater return on investments. Growers in the Mid-Atlantic region have unique challenges compared to northern production regions—warm temperatures, long growing seasons, and high incidence of fire blight—which elevates the financial risk to growers that invest in the extremely high establishment cost of these systems. High density orchard systems have not been widely evaluated in replicated trials under these growing conditions, so it is unknown whether they are suitable for the region. In addition, there is little information on the performance of a suite of new rootstocks released from the Geneva breeding program designed for these high density systems in the Mid-Atlantic region. To test these high density systems and the relevant rootstocks, two scion cultivars ('Brookfield Gala' and 'Cripps Pink') were budded on stoolbed propagated G. 41, G. 202, and G. 935 as well as tissue-culture propagated G. 202.

Results support that the tall spindle system is appropriate for orchards in the Mid-Atlantic, but could be optimized with region-specific recommendations. The rootstocks tested were appropriate for tall spindle orchards in the Mid-Atlantic; however, there was a high incidence of tree death due to graft union breaks, particularly with 'Cripps Pink' on G. 41, and certain scion-rootstock combinations were too vigorous. Additionally, high amount of fire blight not controlled with standard practices indicate that care must be taken in determining a pruning and training regime for this planting system in the Mid-Atlantic. 'Cripps Pink' fruit quality was not affected by rootstock, while 'Brookfield Gala' quality was affected by choice of rootstock. Yield efficiencies for both cultivars were lower than expected. Propagation method did not appear to significantly impact production, but did have an effect on tree size.

High density orchard systems have become the industry standard for new plantings in many apple production regions due to their increased economic and production efficiency (Barritt, 1992). These systems have earlier yield and higher quality fruit which leads to earlier and greater lifetime return on investment for apple orchards (Robinson, 2008). Orchard system studies conducted since the 1970's in various regions of the world have consistently shown that marketable yields per ha increase with increasing tree density (Barritt, 1992; Jackson et al., 1987; Jackson, 1989; Marini et al., 2001; Robinson et al., 1991, 2004; Weber, 2000, 2001; Wertheim, 1980). However, there is a point of diminishing returns at which increased tree density does

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not lead to greater profits (Barritt, 1992). The most economic system and tree density for a specific scenario depends on many factors, including rootstock/scion combination, site, soil type, climate, management practice, and economic situation (Barritt, 1992; Robinson et al., 1991).

The tall spindle is one of the most economical systems for many regions (Robinson et al., 2011). In this system, tree spacing is 1 x 3 m (approximately 3' x 11') for a density of approximately 3,200 trees/ha (Robinson, 2008). In a successful system, trees begin to bear fruit in their second or third leaf, the orchard is in full production in year four or five, and investments can be recouped by year 11-12—approximately five years earlier than the central leader system (Robinson, 2008). Precocity and management during establishment are critical to the success of this system. With newer cultivars that can lead to greater wholesale prices and profits, growers have increasingly planted tall spindles to maximize early returns. These systems do require significant up-front investment in the form of establishment costs, learning new horticultural practices, training workers, and very precise management.

Rootstocks. High density orchard systems depend on fully dwarfing rootstocks to provide size control, reduced vigor, and pest resistance. Rootstock selection depends on site specific factors including regional climate, soil type and fertility, replant conditions, and pest pressures. Rootstocks should also be matched to the cultural characteristics of the orchard such as vigor of the scion and training system (Tworkoski and Fazio, 2015). Successful rootstock selection will lead to appropriate scion vigor and appropriately filled canopy space (Tworkoski and Miller, 2007).

In addition, rootstock selection influences other characteristics of the crop, such as yield and biennial bearing, which directly impact profitability (Al-Hinai and Roper, 2004; James and Middleton, 2011). Rootstock selection can also affect fruit quality, in terms of incidence of physiological disorders, fruit size, and color, thus impacting value of the crop (Webster and Wertheim, 2003). Scion compatibility and disease resistance are factors influenced by rootstocks that affect tree survival and therefore replacement costs (Webster and Wertheim, 2003). Growth habit and canopy volume, also affected by rootstock selection, influence pruning and management associated labor costs (Marini et al., 2002; Russo et al., 2007; Tworkoski and Miller, 2007). Therefore, rootstock selection is critical for the profitability of the system.

Recommended rootstocks for high density systems include B.9, M.9, G.11, G.16, G.41 or others of equivalent size (Robinson et al., 2008; Russo et al., 2007). Several selections from the joint Cornell University and US Department of Agriculture- Agricultural Research Service apple rootstock breeding program in Geneva, NY have recently become available commercially (Fazio, 2015; Fazio et al., 2015; Russo et al., 2007). These rootstocks provide size control, tolerance to replant disease, high productivity, and resistance to diseases and insects, including fire blight (caused by *Erwinia amylovora)*, wooly apple aphid, and crown rot (Fazio et al., 2015; Russo et al., 2007). Fire blight resistance in the Geneva series is notable, especially when compared to commonly planted M.9 or M.26 (Fazio et al., 2015).

Most of the research cited above has been conducted in cooler northern apple growing regions such as New York and Washington. In the Mid-Atlantic region, apple growers are challenged with warm temperatures, a long growing season, and high incidence of fire blight. Warm temperatures coupled with wet weather between bloom and the cessation of shoot growth exacerbate tree losses from fire blight. A less vigorous rootstock with fire blight resistance is desirable, although planting new cultivars on new rootstocks can lead to problems including unexpected scion vigor, fire blight damage and/or death to the scion.

'Brookfield Gala' is widely planted in the USA and its compatibility with older rootstocks is well known; however, less information is available on the performance of 'Brookfield Gala' with new Geneva rootstocks. There is little information on 'Cripps Pink' (Pink Lady™) in either this climate or with Geneva rootstocks.

The three rootstocks evaluated in this study—G.41, G.202 and G.935—have multiple benefits and are among the most widely available to growers (Robinson et al., 2011). All three are resistant to fire blight, apple replant disease, crown and root rots, and wooly apple aphids. G.41 and G.935 have shown cold hardiness while G.202 has been slightly less hardy. All produce few suckers and burr knots with productivity comparable to M.9 (Fazio, 2015). G.202 and G.935 are comparable in size control to M.26 while G.41 is more similar to M.9-T337 (Fazio, 2015).

Rootstock Propagation Method. Currently, grower rootstock selection is limited by rootstock availability from nurseries. Trees must typically be ordered two to four years ahead of planting. Even then nurseries are sometimes unable to fulfill requests. Improved propagation methods, including tissue culture propagation, have the potential to increase availability; however, tissue culture invigoration can potentially impact growth, productivity and trueness-to-type (Webster, 1995). Few studies have been conducted on propagation method, and those have reported mixed results (Autio et al., 2011). Some show that genetic fidelity of tissue culture propagation rootstocks is high (Gupta et al., 2009), while others reported genetic fidelity should remain a concern (Pathak and Dhawan, 2012). Micro-propagated rootstocks tend to have a fuller root system with 40-100% more primary roots than conventionally propagated material, which might explain the increase in vigor. While micro-propagated rootstocks have not yet played a major role in commercial orchards, several hundred thousand plants are being propagated each year to quench the demand for fire blight resistant rootstocks.

The goal of this research was to test several of the rootstock releases from the Geneva breeding program (G.202, G.41 and G.935) in a high density, tall spindle orchard system in the hot, humid, long-growing season Mid-Atlantic region with two scions ('Brookfield Gala' and 'Cripps Pink'). To gain additional insights, G.202 was propagated using both stoolbed and tissue culture liners.

Materials and Methods

Rootstocks G.41, G.202, and G.935 were propagated in traditional stool beds, and grafted with 'Cripps Pink' and 'Brookfield Gala'. G.202 was also propagated using tissue culture (TC) by Phytacell Technologies LLC (Dehli, NY), for a total of four rootstock treatments (G.41, G.202, G.202TC, and G.935). Grafted trees were grown by Willow Drive Nursery (Ephrata, WA). G.202TC trees were visibly different on arrival. TC trees had more fibrous root systems and fewer feathers when compared to stoolbed propagated trees.

Trees were planted at the Western Maryland Research and Education Center in Keedysville, MD (39°30'36.7"N and 77°43'59.9"W) in spring 2010. Trees were planted at 1.8 x 3.7 m spacing (approximately 1,481 trees/ hectare) in 7-tree panels, replicated 4 times in a Latin square design. This design was chosen due to elevation increases and concurrent soil depth decreases as the rows moved North to South, and due to strong prevailing West winds. The planting was supported by a tall spindle trellis with 4 wires. The top wire was at 2.7 m, and trellis support posts were spaced every 14.4 m. Irrigation and nitrogen (170g calcium nitrate applied around each tree) were provided at recommended rates during establishment. Standard insect, disease, and weed management program was used to control pests (Halbrendt 2012). Branch bending was practiced during the first two years, and annual pruning and tying were done per current tall spindle recommendations (Hoying, 2010). The trees had light bloom in the second leaf, and commercial cropping began in the third leaf (2012).

Fruit thinning protocol was the same for all trees of each cultivar regardless of rootstock. 'Brookfield Gala' trees received the same treatment every year: 2.7 kg/ha (4.9 pt/ha) carbaryl (Sevin™) + 4.4 kg/ha (158 oz/ha) 6-benzyladenine (Maxcel®) at 9 mm average fruit diameter. 'Cripps Pink' received 2.7 kg/ha (4.9 pt/ha) carbaryl (Sevin™) at 9 mm average fruit diameter in 2012, 2013, and 2014, and 2.7 kg/ha (4.9 pt/ha) carbaryl (Sevin™) + 4.4 kg/ha (158 oz/ha) 6-benzyladenine (Maxcel®) in 2015. Sprayer was calibrated to apply 378L/ha.

Tree height (m; 2012, 2013) from the graft union, and trunk circumference (cm) at 25 cm above the graft union (2012, 2013, 2015) were measured in select years. Neither height nor circumference were measured at the time of planting. Trunk circumference was used to calculate trunk cross-sectional-area (TCA, cm^2). Fruits were harvested at approximately 5 on the 8-point Cornell Starch-Iodine Index (Blanpied and Silsby, 1992). For each cultivar, all rootstocks were harvested on the same date. Yield (kg) was recorded per plot (2012-2015), and divided by the number of living trees. Yield efficiency (YE) was calculated by dividing the average yield per tree by the average TCSA within a plot, measured in each respective year. Approximate 2015 returns per ha were calculated, assuming 18.1 kg (40 lbs) per bushel and $8 per bushel ($0.20 per lb).

Fruit quality data at harvest were measured yearly from 2012-2015 using a random sample of 10 fruit per plot, harvested between 1 m and 1.5 m height along the trellis from each of the trees in the panel. Mean fruit weight (FW) was recorded for each sample. Red color was visually estimated as a percentage of surface coloration. Soluble solids concentration was measured once for each sample by collecting juice from each apple in the sample and measuring the aggregate juice with a Leica Mark II Plus Abbe Refractometer (Leica Microsystems Inc, Buffalo Grove, IL). Flesh firmness (kg) was measured on both the red and green sides of each fruit, using a vegetable peeler to remove a 18 mm diameter circle of skin, using a handheld FT 327 Fruit Penetrometer (Wagner Instruments, Greenwich, CT). Starch pattern index was recorded for each fruit (Blanpied and Silsby, 1992). Percent red color was not recorded on 'Cripps Pink' for 2012 and 2013. No fruit quality measurements were collected for 'Brookfield Gala' in 2012.

In July 2011 and August 2013, the planting experienced severe storms including high winds and hail. As a result, a considerable number of trees snapped at the graft union in 2011. Trees that were lost were not replaced. Further tree losses were experienced after data collection had ceased, in 2016 (not reported). Tree survival is reported as the percentage of trees surviving the duration of the study.

All analyses of variance were performed using the MIXED procedure of SAS 9.4 (SAS; SAS Institute Inc., Cary, NC, USA). Data were analyzed separately for 'Brookfield Gala' and 'Cripps Pink.' For fruit quality variables, analysis of variance was performed to test the fixed effects of rootstock (G.202, G.202TC, G.41, G.935). Replicate, column position, and harvest year were included as random effects. For yield and YE data, analysis of variance was performed to test the fixed effects of rootstock for each year (2012, 2013, 2014, 2015). For cumulative yield and cumulative YE, analysis of variance was performed to test the fixed effects of rootstock for the total yield (2012-2015). Replicate and column were included as random effects. Mean separations were performed using the Tukey option at the $P < 0.05$ level.

Results and Discussion

Fruit Quality. Rootstock had a significant effect on FW ($P=0.0012$) and soluble solids ($P=0.0048$) of 'Brookfield Gala' apples (Table 1). Fruit harvested from 'Brookfield Gala' on G.202 had smaller fruit than those on G.202TC or G.41; this fruit also had greater soluble solids concentrations than all other rootstocks, though likely not great

Table 1. Average fruit quality variables for 'Cripps Pink' and 'Brookfield Gala' on four rootstocks sampled from 2012 to 2015 at the Western Maryland Research and Extension Center in Keedysville, MD.

Cultivar	Root-stock	Fruit Wt. (g)	Red Color (%)	Soluble Solids (%)	Fruit Firm-ness (kg)	Starch Index	Cumul. Yield (kg/ha)[y]	Cumul. Yield (Kg/cm2)[x]
'Brookfield Gala'	G.202	126.5 b [z]	79.1	14.5 a	9.3	5.3	38.25 c	0.4 a
	G.202TC	142.4 a	64.2	13.7 b	9.0	5.3	55.52 b	0.5 a
	G.41	139.4 a	72.1	13.9 b	8.8	6.2	58.76 ab	0.8 a
	G.935	135.7 ab	65.5	13.9 b	8.9	6.1	70.55 a	0.8 a
	P-value	*0.0012*	*0.0507*	*0.0048*	*0.0942*	*0.1169*	*0.0011*	*0.03*
'Cripps Pink'	G.202	184.4	66.1	14.9	9.72	4.6 ab	74.4	0.4
	G.202TC	178.5	60.1	15.4	9.6	4.0 b	85.6	0.5
	G.41	181.6	60.1	15.3	9.4	5.0 a	87.1	0.6
	G.935	176.0	64.7	15.2	9.7	4.7 a	81.3	0.4
	P-value	*0.2467*	*0.0998*	*0.7453*	*0.124*	*0.0396*	*0.32*	*0.23*

[z] Means within columns and cultivars followed by common letters do not differ at P < 0.05 by Tukey HSD test.
[y] Cumulative yield calculated using 2012-2015 harvests.
[x] Cumulative yield efficiency calculated using cumulative yield divided by 2015

enough to be important from a consumer standpoint. 'Cripps Pink' FW and quality were not affected by rootstock.

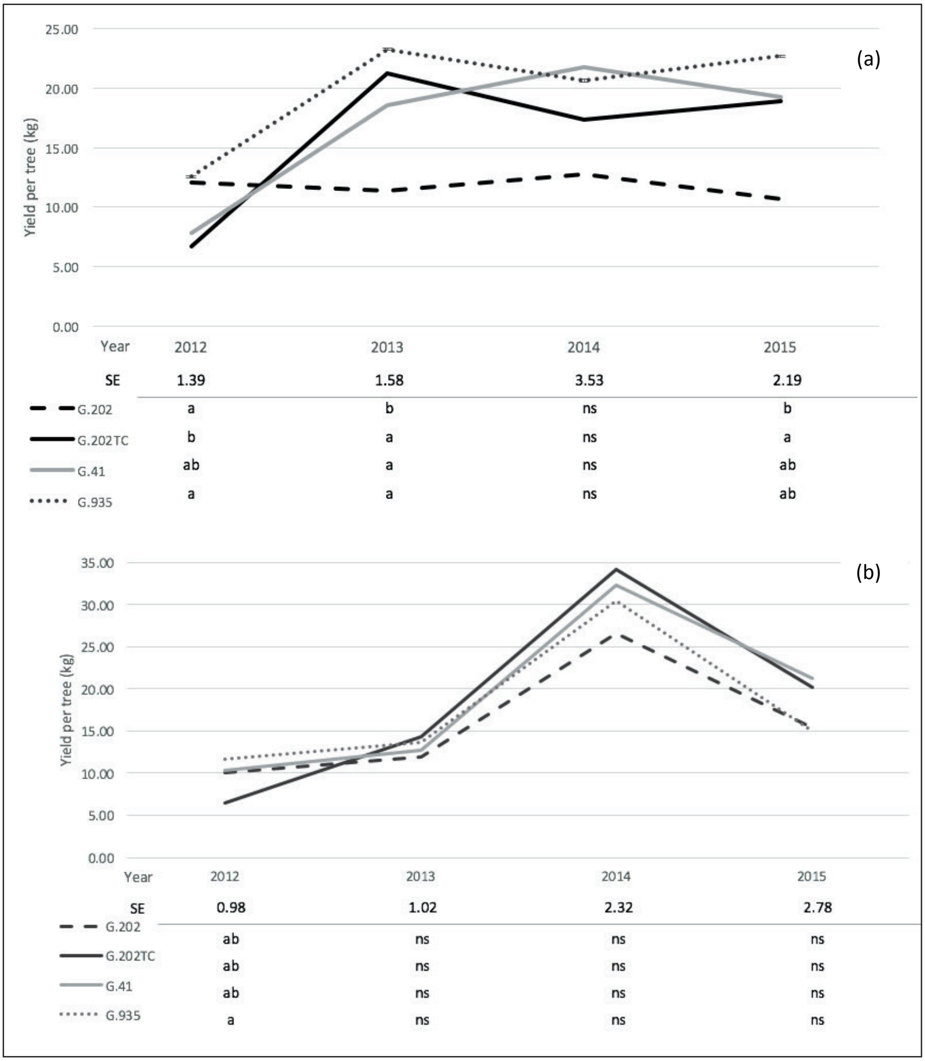
Tree size. Rootstock had a significant effect on tree height for both 'Brookfield Gala' (P=0.0011) and 'Cripps Pink' (P=0.0002), but was only measured until the 3rd leaf. For both cultivars, scions on G.202TC trees were taller than other rootstocks (Table 2). The effect of rootstock was significant for TCA (P=0.01) for 'Brookfield Gala', but not for 'Cripps Pink' in 2015. G.202TC had the largest TCA for both cultivars (Table 2). Due to an oversight, tree size was not measured at the time of planting, preventing evaluation of the influence of initial tree size. However, the findings of this work illustrate that both propagation method and rootstock selection can impact tree size.

The larger tree size observed for TC trees is consistent with other research findings, where TC-propagated trees were generally more vigorous in the nursery and the orchard (Webster, 1995). Specifically, 'Gala' trees grown on TC-propagated Ottawa-3 rootstock had larger rootstock circumference, and greater scion branching and shoot growth than stool bed cuttings, which was expected to lead to more vigorous, less precocious trees in the orchard (Hogue and Nielson, 1991). While more research examining the overall effects of micro-propagation and its interactions on specific scions and rootstock combinations is needed, in this study TC propagation increased vigor.

Yield and Productivity. For 'Brookfield Gala', rootstock significantly affected yield in 2012 (P=0.0114), 2013 (P=0.0016), and 2015 (P=0.021). In 2012, G.202 had higher yields than G.41 and G.202TC (Fig. 1). In each following year, G.202 had lower yields than other rootstocks, even in 2014 when yield differences were not significant. Yield efficiency for 'Brookfield Gala' was also significantly affected by rootstock (P=0.0318) for all three years. 'Brookfield Gala' on G.935 had the highest cumulative yield and yield efficiency.

For 'Cripps Pink', yield was affected by rootstock only in 2012 (P=0.04); G.935 had the highest yield and G.202TC had the lowest (Table 2). For 'Brookfield Gala' cumulative yield and yield efficiency were both significant (P=0.0011; 0.03); G.935 and G.41

Figure 1. The effect of four rootstocks on yield from 2012 to 2015 for cultivars (a) 'Brookfield Gala' and (b) 'Cripps Pink' planted at the Western Maryland Research Extension Center in Keedysville, MD. Yield (kg/tree) is reported as an average of trees in a plot, adjusted to account for tree death. Means in the same column followed by commonletters do not differ at $P < 0.05$, by Tukey's HSD test.



had the highest and G.202 had the lowest (Table 1).

The general trend in this work was for G.935 trees to have higher yield and YE. Russo et al. (2007) reported similar results, where G.935 had one of the highest cumulative yields and YE of the 64 rootstocks trialed.

Differences in yield per tree translate into appreciable differences in returns/ha. The following calculation is a useful illustration, albeit limited by not accounting for the influence of fruit size or color on returns. Assuming 18.1kg (40lbs) per bushel and \$8 per bushel (\$0.20/lb) with complete tree surviv-

Table 2. Tree height, TCA, average yield efficiency, tree survival, and approximate returns (with and without accounting for observed tree death) for 'Cripps Pink' and 'Brookfield Gala' on four different rootstocks planted at Western Maryland Research and Extension Center in Keedysville, MD.

Variety	Rootstock	Height (m)		TCA (cm^2)			Efficiency (kg/cm^2)[y]			Approx. Return ($/ha)[x]	Survival (%)[w]	Apprx Return ($/ha)[v]
		2012	2013	2012	2013	2015	2012	2013	2015	2015		2015
Brookfield Gala	G.202	2.6 b	2.9 b [z]	10.4 b	13.7 b	26.9 b	1.2 a	0.9 c	0.4 a	6,971	100	6,971
	G.202TC	3.5 a	4.1 a	17.3 a	22.4 a	38.9 a	0.4 b	1.0 bc	0.5 a	12,359	89	11,000
	G.41	2.9 b	3.5 b	11.2 b	14.8 b	26.0 b	0.8 ab	1.3 ab	0.8 a	12,581	100	12,581
	G.935	2.7 b	3.3 bc	13.5 ab	17.0 ab	29.5 b	0.9 ab	1.4 a	0.8 a	14,853	96	14,259
	P-value	*0.0011*	*0.0011*	*0.02*	*0.01*	*0.01*	*0.02*	*0.01*	*0.0318*	*NA*	*NA*	*NA*
Cripps Pink	G.202	2.5 b	3.0 b	13.2 ab	158.8 ab	36.6	0.8 ab	0.6	0.4	10,074	100	10,074
	G.202TC	3.0 a	3.6 a	15.8 a	22.5 a	43.4	0.4 b	0.6	0.5	13,186	96	12,659
	G.41	2.5 b	2.9 b	13.2 b	20.0 ab	35.4	0.8 ab	0.6	0.6	13,894	50	6,947
	G.935	2.4 b	2.4 b	12.2 b	18.5 b	37.4	1.0 a	0.8	0.4	9,803	68	6,666
	P-value	*0.0005*	*0.0002*	*0.02*	*0.02*	*0.13*	*0.04*	*0.29*	*0.2267*	*NA*	*NA*	*NA*

[z] Means within columns and cultivars followed by common letters do not differ at the 5% level, by Tukey's test.
[y] Yearly yield divided by the same year's trunk cross-sectional area (ie. 2012 yield /2012 truck cross-sectional area)
[x] Assuming 18.1kg (40lbs) per bushel and $8 per bushel ($0.20/lb) without any tree death
[w] Survival is presented as the percentage of trees that survived out of 28 total trees for each scion-rootstock combination.
[v] Assuming 18.1kg (40lbs) per bushel and $8 per bushel ($0.20/lb) accounting for observed tree death

al, approximate 2015 returns/ ha for 'Brookfield Gala' were highest on G.935 while approximate returns/ ha for 'Cripps Pink' were highest on G.41 (Table 2). Return/ ha for 'Brookfield Gala' on G.202 would likely be slightly less due to small fruit size (Table 1). The efficiencies measured at the end of the study were surprisingly low considering the precocious and productive scion cultivars chosen. This illustrates the difference in performance of different cultivars on the same rootstocks, and vice versa, and demonstrates the need for continued evaluation of cultivar-rootstock compatibility. Low efficiencies may also be related to growing region; in the Mid-Atlantic, vegetative growth can be more than double that experienced in regions with cooler temperatures and shorter seasons. This points to a need for continued evaluation of high density systems in various regions, and selection of appropriate scion and rootstocks for these systems in different regions.

Tree survival. The most notable difference observed between rootstocks was tree survival. Several high wind events during 2011 and 2013 led to graft union breaks that resulted in tree death. There were fewer graft union breaks in the 'Brookfield Gala' plots (Table 2); however, nine losses on G.935 and 14, or half of the total 28 trees, on G.41 were experienced for 'Cripps Pink'.

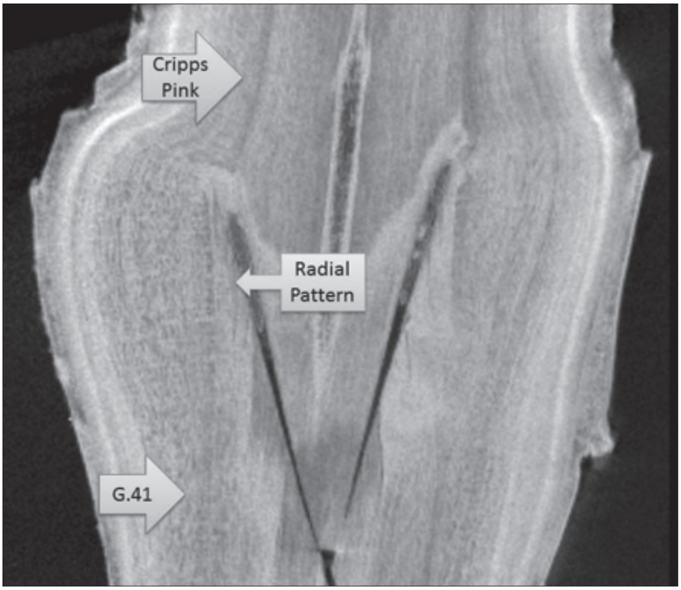
Weak graft unions have been reported by nurserymen and growers for G.41and G.935 in several growing regions, including the Mid-Atlantic. One nursery experienced approximately 60% losses on G.41 and 25% losses on G.935; losses appeared to depend on scion cultivar, with 'Stayman' having very few losses and 'Gala' with high losses (personal communication, Bill Makintosh). Weak graft unions are not uncommon, and have been reported with other rootstock/ scion combinations, including 'Honeycrisp' on M.26. Nonetheless, it is an undesirable condition, and these tree deaths have a considerable impact on returns for growers. Using the same assumptions to calculate returns as above (18.1kg (40lbs) per bushel and $8 per bushel ($0.20/lb)), but adjusting for surviving trees, approximate 2015 returns per hectare for 'Brookfield Gala' were relatively unchanged, but returns for 'Cripps Pink' on G.41 and G.935 were almost half of those on G.202 and G.202TC (Table 2).

Research has shown weak graft unions may be caused by vascular discontinuity (Warmund, 1993, Milien, 2012) and tissue composition, specifically higher parenchyma and lower fibrous tissue than stronger unions (Basedow, 2015). However, weak unions may become stronger over time. In one preliminary report of work examining rootstocks grafted to 'Honeycrisp', G.30 rootstock was among the weakest unions of 39 being investigated, requiring a force less than 70 $N \cdot cm^{-2}$ applied sideways at the union to bend the tree until it broke. After 10 years in the orchard, G.30 rootstock grafted with 'Gala' was the strongest union (requiring the most sideways force to break the union) as compared to eight other commercial rootstocks (Robinson et al., 2015).

Scion cultivar appeared to contribute to graft union strength in this study; there were 24 graft union breaks for 'Cripps Pink' as compared to four for 'Brookfield Gala.' These scion effects are being investigated anatomically through the use of X-Ray 3 D tomography (Fig. 2) at Cornell University where preliminary results suggest a variety specific hormonal effect on the organization of wood tissue within 1 cm of the graft union. More extensive research is necessary to determine the graft union strength of specific rootstock-scion combinations and the anatomical cause of decreased strength, as well as the differences between TC and stoolbed propagated rootstocks.

Fire blight. Fire blight control was provided each year in the form of dormant copper sprays, streptomycin following infection events in the spring for blossom blight applied according to disease forecast models, and strike removal; no summer sprays were applied due to early harvest of 'Brookfield Gala fruit' preharvest interval label restric-

Figure 2. Graph union of a bench grafted 'Cripps Pink' scion (upper portion) on G.41 rootstock (lower portion) visualized by 3D X-ray tomography[z]. The radial patterns seen in the rootstock right above where the two tissues meet is indicative of less organized wood and possibly the reason for weaker wood formation.



[z] Trees, not planted in the experiment, were imaged using a Zeiss Versa XRM-520 CT at the Cornell University Biotechnology Resource Center. Specimens were scanned at 100k V source setting at a 25-30um/pixel resolution with 1600 frames per scan.

tions (both cultivars were treated uniformly). Despite these standard control practices, the planting experienced troublesome amounts of fire blight infections. This was particularly problematic in 2015 when a shoot blight epidemic affected the Appalachian region following warm wet weather in June and July. Trees were dormant pruned in Feb. 2015, leaving Dutch stubs for renewal shoots primarily in the lower third of the trees where the heaviest wood needed to be removed to renovate the spindle. These cuts responded well with excellent shoot growth in the spring and summer of 2016. However, multiple storm events (high winds, hail, and temperatures in mid-80s) from April – July damaged foliar and stem tissues. Renewal shoots on both ‘Brookfield Gala’ and ‘Cripps Pink’ developed shoot blight infections in summer 2015 (Fig. 3). Infections were pruned out where possible in mid-summer, but no trees were removed. No tree losses were experienced at the end of the 2015 season, but cankers developed on many trees at the height of the first wire on the main trunk and significant losses are expected in the future.

Fire blight is a major concern for apple growers in the Mid-Atlantic, where optimal conditions for fire blight infections are experienced many times each year, and the pathogen is considered ubiquitous. Rootstock resistance protects the scion from tree death due to rootstock blight; however, it is not yet clear if it improves the resistance of the scion variety as some report that it does not (Norelli et al., 2003). Others indicate there is a measurable effect on expressed genes that interdict the gravity of fire blight strikes (Jensen et al. 2003 and 2012). Other strategies need to be investigated to provide recommendations for fire blight prevention, control, and replanting decisions for high

Figure 3. Dutch stub infected with fire blight (*Erwinia amylovora*) seen on 'Brookfield Gala' on G.202 in 2015 after dormant pruning cuts.

density orchards in this region, especially as these orchard systems are increasingly adopted.

Conclusion

Consistent with other research and anecdotal information, high density trellised orchard systems are effective systems for the Mid-Atlantic. However, it is evident that appropriate rootstock, scion, and management decisions should take regional characteristics into account. In particular, orchardists need to account for longer growing season and warmer temperatures, which contributed to more vegetative growth, and management of fire blight needs to be a top priority. At the conclusion of this project (sixth leaf), the trees had filled their space and the second phase of management began which is to sustainably manage the planting with the trees achieving their full size. It was at this point fire blight ravaged the 'Brookfield Gala' and damaged the 'Cripps Pink' trees to a lesser degree. Further long term study is definitely warranted.

This system has many attributes and has been easier to manage than other trials in terms of pruning, harvesting, and spraying. Less ladder work, wood to move, and need for other equipment affects the possibility of more efficient work. Future trials comparing orchard systems are necessary to quantify differences in labor and materials efficiency as well as economic impact for the Mid-Atlantic region.

Propagation method did not appear to have significant impact on production but did affect tree size. For the one rootstock that was propagated both via stoolbed and tissue culture (G.202), fruit quality was largely unaffected, with the exception of larger than average fruit weight of 'Brookfield Gala'. The tissue culture propagated stock did appear to increase the vigor of both scions which influenced management decisions for the excessively large trees; however, this increased vigor did not affect yield. There were few differences between stoolbed propagated stocks G.41, G.202 and G.935.

G.935 and G.41 had the most graft breakages, particularly with 'Cripps Pink'. Coupled with unexpectedly low yield efficiencies for both 'Brookfield Gala' and 'Cripps Pink', additional physiological understanding is needed.

Rootstock, scion, and planting system selection for commercial plantings of high density apple orchards depend on region, site, and resources available. Recommendations for using these rootstocks in high density systems in the Mid-Atlantic should take into consideration scion selection, planting system, adequate support systems, and site-specific pest pressure.

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About the Cover:

Pioneers in Pomology - from top left in clockwise direction: George M. Darrow, Wilfred Gordon Brierley, Paul Howe Shepard, and Marshal Pinckney Wilder**.** In the last two issues of the Journal we published biographical sketches of these early leaders of American pomology.

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

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Abstract

In 2010, an orchard trial of apple rootstocks was established at 13 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), 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 as Tall Spindles. After 5 years, the greatest mortality was for trees on CG.4814 (15%), with trees on all other rootstocks averaging 10% or less mortality. 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 semi-standard, and B.7-20-21 and B.64-194 were large semi-dwarfs. B.7-3-150, B.67-5-32, B.70-6-8, G.202N, CG.4004, and PiAu 9-90 were moderate semi-dwarfs. CG.3001, CG.4814, CG.5087, CG.5222, and PiAu 51-11 were small semi-dwarfs. G.202TC (TC = liners from tissue culture), G.935N (N = liners from stool beds), G.935TC, CG.4013, CG.4214, M.9 Pajam 2, and M.26 EMLA were large dwarfs. B.10, G.11, G.41N, G.41TC, Supp.3, and M.9 NAKBT337 were moderate dwarfs, and B.9, CG.2034, and CG.4003 were small dwarfs. B.71-7-22 was sub-dwarf. B.70-20-20, B.7-20-21, and B.64-194were too vigorous for a high-density system, and conversely, B.71-7-22 was not vigorous enough. Among the six moderate semi-dwarf rootstocks, CG.4004 and G.202N performed best, using cumulative (2011-14) yield efficiency as the primary determinant of performance. Among the five small semi-dwarf rootstocks, CG.5087, CG.4814, and CG.3001 performed best. Of the seven rootstocks characterized as large dwarfs, G.935, CG.4214, and G.202TC resulted in the greatest cumulative yield efficiency. Of the six rootstocks in the moderate dwarf class, G.11, M.9 NAKBT337, and G.41N performed best, and CG.4003 and B.9 resulted in the greatest cumulative yield efficiency among the three small dwarf rootstocks.

One of the most critical elements of any apple orchard is the rootstock, particularly in high-density systems where the economic risks and potential returns are the highest. 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. NC-140 greatly enhances the evaluation process with uniform trials at diverse locations including a wide variety of soils and climates.

New apple rootstocks are made available regularly from a number of sources with the potential of providing greater growth control, enhanced precocity, higher yield, improved adaptability to environmental conditions, and enhanced pest resistance. Numerous new rootstocks are available for evaluation from the Budagovsky, Cornell-Geneva, and Pillnitz breeding programs.

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Budagovsky rootstocks are from the Michurinsk State Agrarian University in Michurinsk, Tambov Region, Russia. The breeding program began with I.V. Budagovsky making crosses in 1938, with the principle goal of developing rootstocks with enhanced winter hardiness (Cummins and Aldwinckle, 1983). He released one of the best known Budagovsky Rootstocks, B.9, in 1962. NC-140 first tested Budagovsky rootstocks (B.9 and B.490) in the 1984 NC-140 Apple Rootstock Trial (NC-140, 1996) and has included Budagovsky rootstocks in numerous trials in the ensuing years (Autio et al., 2001; 2013; Marini et al., 2001a; 2001b; 2006; 2014; Robinson et al., 2007).

The Cornell-Geneva Apple Rootstock Breeding Program is managed jointly by Cornell University and the United States Department of Agriculture. Several rootstocks have been released from this program, most with a high degree of disease resistance, particularly to the fire blight bacterium (*Erwinia amylovora*). Many of these 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). The original material for this program came from discontinued breeding programs in Muncheberg and Naumburg (Cummins and Aldwinckle, 1983). These earlier programs sought better horticultural characteristics and pest resistance. NC-140 has 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).

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.

Materials and Methods

In spring, 2010, an orchard trial of 31 apple rootstocks was established at 13 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), 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 'Fuji' Apple Rootstock Trial (Autio et al., 2017), except for the cultivar, planting location, and tree spacing.

The trial was planted in British Columbia (Canada), Chihuahua (Mexico), Colorado, Iowa, Massachusetts, Michigan, Minnesota, New Jersey, Nova Scotia (Canada), New York, Ohio, Utah, 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. Trees were spaced 1.2 x 3.6 m and trained as tall spindles (Robinson and Hoying, 2011). Pest management, irrigation, and fertilization followed local recommendations at each site.

Trunk circumference, 25 cm above the

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	Cheryl Hampson	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
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 Jersey (NJ)	Pittstown	Winfred Cowgill	Rutgers Cooperative Extension, P.O. Box 2900, Flemington, NJ 08822 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 USA
Utah (UT)	Santaquin	Brent Black	Plant, Soil, and Climate Department, Utah State University, Logan, UT 84322 USA
Wisconsin (WI)	Sturgeon Bay	Matt Stasiak	Peninsular Agricultural Research Station, University of Wisconsin, 4312 Hwy 42, Sturgeon Bay, WI 54235 USA

bud union, was measured in Oct., 2014 and used to calculate trunk cross-sectional area (TCA). Also in Oct., 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. 'Honeycrisp' zonal chlorosis was assessed as the percent of the canopy affected in 2012, 2013, and 2014.

Yield was assessed in 2011 through 2014; however, very few sites harvested any fruit in 2011. Yield efficiency ($kg \cdot cm^{-2}$ 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 weight (2012-14). 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 differences and allows for a reasonable look at rootstock effects.

Results

Site and Rootstock Differences at Planting. All trees were produced by one nursery, but some variation in tree size occurred. At planting, largest trees, as assessed by trunk cross-sectional area (TCA), were in New Jersey, and the smallest were in British Columbia (Table 2). Although some variation in nursery branch development existed, cooperators removed different numbers of these branches. At planting and after the initial pruning, the largest number of branches (11.9 per tree) remained on trees in New Jersey, and the smallest number remained (1.1

Table 2. Site means for trunk cross-sectional area, number of branches after pruning, and height of the graft union at planting of Honeycrisp apple trees in the 2010 NC-140 Honeycrisp 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)
BC	1.2	1.1	109
MA	1.6	11.3	147
MI	1.4	4.7	93
MN	1.7	9.8	66
NJ	1.9	11.9	161
NS	1.6	---	82
NY	1.3	9.2	115
OH	---	10.4	63
UT	1.3	6.3	103
WI	1.3	5.6	137
Average HSD	0.6	5.3	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.

Table 3. Rootstock means for trunk cross-sectional area, number of branches, and height of the graft union at planting of Honeycrisp apple trees in the 2010 NC-140 Honeycrisp Apple Rootstock Trial. Means are based on data from BC, MA, MI, MN, NJ, NS, NY, OH, UT, and WI. 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	1.2	5.6	107
B.10	1.4	6.6	106
B.7-3-150	1.3	4.0	116
B.7-20-21	2.0	9.3	125
B.64-194	1.9	8.1	125
B.67-5-32	1.5	5.6	103
B.70-6-8	1.6	6.6	105
B.70-20-20	2.4	11.9	128
B.71-7-22	0.6	0.2	111
G.11	1.4	10.5	118
G.41N	1.3	6.4	106
G.41TC	0.9	3.4	78
G.202N	1.9	12.1	102
G.202TC	1.5	11.1	86
G.935N	1.6	11.5	103
G.935TC	1.2	7.8	85
CG.2034	1.2	6.9	88
CG.3001	1.6	12.6	97
CG.4003	1.1	6.3	111
CG.4004	1.6	15.4	108
CG.4013	1.3	9.6	89
CG.4214	1.3	13.2	108
CG.4814	1.7	13.6	107
CG.5087	1.7	14.6	114
CG.5222	1.8	10.6	87
Supp.3	1.0	4.9	105
PiAu 9-90	2.6	17.4	135
PiAu 51-11	1.9	9.2	127
M.9 NAKBT337	1.3	8.4	121
M.9 Pajam 2	1.5	8.5	119
M.26 EMLA	1.2	5.0	114
Average HSD	0.2	2.2	16

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

per tree) in British Columbia (Table 2). Likewise, planting depth varied with location, with the average graft union height greatest in New Jersey and least in Ohio (Table 2).

Rootstock also resulted in significant differences in the TCA at planting, the number of branches remaining after initial pruning, and the height of the graft union (Table 1). Likely as an expression of tree vigor, the largest trees (in TCA) and those with the great-

Table 4. Site means for survival, trunk cross-sectional area, root suckers, tree height, canopy spread, yield per tree, yield efficiency, fruit size, and zonal chlorosis of Honeycrisp 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)	Zonal chlorosis (%) 2012	2013	2014
BC	100	10.1	6.8	277	120	12.9	22.2	1.4	2.4	302	284	---	57	---
MA	98	13.5	7.4	299	188	8.9	24.8	0.8	2.0	230	222	---	54	41
MI	99	12.1	1.2	257	127	6.7	17.2	0.7	1.6	200	200	---	31	69
MN	100	13.7	0.1	292	186	8.3	17.9	0.7	1.5	174	182	14	49	43
NJ	98	18.1	3.6	335	277	9.7	23.7	0.6	1.4	322	280	---	---	16
NS	87	13.0	0.2	273	115	10.7	26.0	0.9	2.2	164	170	19	41	66
NY	99	15.3	5.5	321	170	8.0	33.0	0.6	2.5	259	239	22	20	25
OH	92	12.4	0.8	231	112	11.5	13.9	1.0	1.3	178	178	---	---	---
UT	95	11.9	1.3	208	129	13.2	15.8	1.2	1.4	---	176	---	---	---
WI	99	12.6	2.9	282	176	8.1	30.8	0.7	2.7	173	230	25	24	15
Average HSD	8	3.5	2.9	27	21	4.8	7.2	0.3	0.4	31	21	11	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.

est number of branches were on PiAu 9-90, and the smallest with the fewest branches were on B.71-7-22. Graft-union height at planting was likely affected by the distance between the graft union and lateral roots and the length of the rootstock shank, both of which were very small in a few cases. Most (77% of the rootstock treatments) trees were able to be planted at the recommended level with the graft union between 100 and 150mm above the soil. Trees on PiAu 9-90 were planted such that the average graft union height was 135 mm. Seven combinations (23%) were planted with union heights less than 100 mm, with the lowest for trees on G.41TC.

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 ten sites with a complete set of rootstocks. Colorado was missing two and Iowa was missing one rootstock treatment at the initiation of the experiment, and tree death resulted in complete loss of one rootstock treatment in Chihuahua. Data from these three sites were excluded from the analyses presented in Tables 4 and 5. Results from Chihuahua, Colorado, and Iowa, however, are included in the tree performance data presented by location in Tables 6-11.

Among the 10 sites included in Table 4, the highest mortality occurred in Nova Scotia (13%, Table 4); however, among all sites greatest mortality was in Chihuahua, with only 77% of the trees surviving for the first 5 years (Table 6). Survival was 100% in British Columbia, Minnesota (Table 4), and Colorado (Table 6).

Site-related tree characteristics are presented in Table 4. After 5 years, the largest TCA was recorded for trees in New Jersey and the smallest for trees in British Columbia. Trees were also tall-

Table 5. Rootstock means for survival, trunk cross-sectional area, root suckers, tree height, canopy spread, yield per tree, yield efficiency, fruit size, and zonal chlorosis of Honeycrisp apple trees in the 2010 NC-140 Honeycrisp Apple Rootstock Trial. Means are based on data from BC, MA, MI, MN, NJ, NS, NY, OH, UT, and WI. 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)	Zonal chlorosis (%)		
												2012	2013	2014
B.9	100	6.5	2.5	216	110	5.8	14.6	0.9	2.3	208	201	14	30	30
B.10	96	10.0	0.8	256	143	8.5	21.9	0.9	2.2	237	223	10	26	32
B.7-3-150	100	17.5	0.9	311	171	11.7	23.3	0.7	1.4	241	234	15	25	26
B.7-20-21	100	20.1	1.1	296	170	11.8	25.0	0.6	1.3	227	218	17	30	30
B.64-194	98	21.0	0.2	316	184	10.7	25.4	0.6	1.2	247	230	15	24	25
B.67-5-32	100	18.6	1.0	311	163	7.9	18.3	0.5	1.0	244	234	18	27	29
B.70-6-8	99	17.6	0.5	300	166	11.0	24.1	0.7	1.4	230	221	13	27	29
B.70-20-20	99	33.9	3.3	366	222	12.0	23.8	0.4	0.7	232	234	12	20	23
B.71-7-22	91	2.0	1.9	149	58	1.6	4.1	0.8	2.0	183	189	16	45	42
G.11	99	9.2	2.1	267	155	10.5	23.4	1.2	2.6	228	219	21	45	32
G.41N	95	10.1	0.4	265	152	10.0	24.0	1.0	2.4	238	228	18	35	32
G.41TC	95	9.4	1.4	279	157	8.5	18.4	0.9	2.0	233	224	25	38	42
G.202N	95	17.6	7.0	308	187	13.8	30.2	0.8	1.8	230	228	25	31	38
G.202TC	98	10.8	4.8	279	156	9.8	22.6	1.0	2.1	206	198	29	43	38
G.935N	90	12.2	4.2	285	175	12.9	29.2	1.1	2.4	209	207	26	51	38
G.935TC	96	10.4	4.8	266	162	10.5	24.1	1.1	2.3	213	207	29	57	47
CG.2034	93	7.0	1.3	249	123	6.2	15.1	0.9	2.2	220	214	22	57	47
CG.3001	90	14.5	0.9	288	189	11.2	30.2	0.8	2.1	239	228	25	43	44
CG.4003	98	7.5	1.0	247	128	8.7	19.3	1.2	2.6	203	199	25	41	35
CG.4004	98	17.2	3.9	321	192	15.0	35.4	0.9	2.0	243	235	18	27	36
CG.4013	97	12.5	4.5	284	169	7.9	18.6	0.7	1.6	216	210	27	48	50
CG.4214	99	11.5	8.4	299	171	10.3	26.0	1.0	2.4	221	217	30	45	48
CG.4814	85	13.5	5.9	280	182	13.0	28.6	1.0	2.2	209	211	41	56	50
CG.5087	97	13.0	3.0	292	184	12.2	29.4	0.9	2.2	211	206	30	42	50
CG.5222	94	14.4	7.1	285	171	11.0	24.9	0.8	1.8	216	213	20	40	44
Supp.3	94	8.8	1.7	249	145	8.2	18.9	1.0	2.2	218	211	20	53	55
PiAu 9-90	100	17.3	0.7	287	166	5.6	15.6	0.3	0.9	185	176	60	64	68
PiAu 51-11	100	15.2	1.6	279	162	8.7	20.0	0.6	1.4	242	231	23	39	40
M.9 NAKBT337	100	9.6	4.1	253	145	10.8	22.4	1.2	2.4	224	222	16	41	34
M.9 Pajam 2	100	10.6	8.6	260	148	9.7	21.7	0.9	2.0	212	209	19	42	43
M.26 EMLA	99	11.6	2.6	263	152	8.3	19.7	0.8	1.7	222	218	20	32	38
Average HSD	10	2.2	3.0	22	15	3.2	3.7	0.2	0.3	32	22	13	14	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.

Table 6. Survival (2014, %) of Honeycrisp apple trees at individual planting locations in the 2010 NC-140 Honeycrisp Apple Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	BC	CH	CO	IA	MA	MI	MN	NJ	NS	NY	OH	UT	WI
B.9	100	100	100	100	100	100	100	100	100	100	100	100	100
B.10	100	88	100	100	100	100	100	100	88	89	100	85	100
B.7-3-150	100	100	100	100	100	100	100	100	100	100	100	100	100
B.7-20-21	100	92	100	100	100	100	100	100	100	100	100	100	100
B.64-194	100	41	100	100	100	100	100	100	100	100	84	100	100
B.67-5-32	100	79	100	100	100	100	100	100	100	100	100	100	100
B.70-6-8	100	92	100	100	92	100	100	100	100	100	100	100	100
B.70-20-20	100	100	100	100	100	100	100	92	100	100	100	100	100
B.71-7-22	100	100	100	100	100	100	100	80	82	100	68	100	83
G.11	100	58	100	100	100	100	100	100	89	100	100	100	100
G.41N	100	81	100	100	100	100	100	100	69	100	100	91	90
G.41TC	100	100	100	100	100	100	100	100	50	100	100	100	100
G.202N	100	29	100	100	100	100	100	100	82	100	68	100	100
G.202TC	100	45	100	100	100	100	100	100	100	100	84	100	100
G.935N	100	100	---	100	100	100	100	100	66	100	67	78	89
G.935TC	100	100	100	100	100	100	100	100	100	100	100	67	100
CG.2034	100	39	100	100	100	100	100	100	100	100	66	67	100
CG.3001	100	0	100	100	50	100	100	100	45	100	100	100	100
CG.4003	100	59	100	100	100	100	100	100	75	100	100	100	100
CG.4004	100	100	100	100	100	100	100	100	100	100	75	100	100
CG.4013	100	50	---	100	100	100	100	66	100	100	100	100	100
CG.4214	100	70	100	100	100	100	100	100	100	100	100	86	100
CG.4814	100	55	100	100	100	86	100	100	14	100	50	100	100
CG.5087	100	100	100	100	100	100	100	100	100	100	100	67	100
CG.5222	100	76	100	---	100	100	100	100	42	100	100	100	100
Supp.3	100	65	100	33	100	80	100	100	100	83	80	100	100
PiAu 9-90	100	100	100	100	100	100	100	100	100	100	100	100	100
PiAu 51-11	100	100	100	100	100	100	100	100	100	100	100	100	100
M.9 NAKBT337	100	92	100	100	100	100	100	100	100	100	100	100	100
M.9 Pajam 2	100	92	100	100	100	100	100	100	100	100	100	100	100
M.26 EMLA	100	100	100	100	100	100	100	100	100	88	100	100	100
Average HSD	---	10	---	20	18	22	---	27	58	25	53	43	22

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

est with the widest canopy in New Jersey, but were shortest in Utah and with the narrowest canopy in Ohio. Root suckering was greatest in Massachusetts and least in Minnesota. The zonal chlorosis typical of 'Honeycrisp' was not consistent from site to site or year to year, with no discernable patterns.

Site-related fruiting characteristics are presented in Table 4. Yield per tree in 2014 was greatest in Utah and least in Michigan, but on a cumulative basis (2011-14), yield per tree was greatest in New York and least in Utah. Yield efficiency in 2014 was highest in British Columbia and lowest in New Jersey and New York. Cumulative yield efficiency (2011-14) was highest in Wisconsin and lowest in Ohio. Fruit weights in 2014 and on average (2012-14) were highest in New Jersey and lowest in Nova Scotia.

Rootstock Effects on Tree Performance. Survival was affected by rootstock (Tables 5 and 6). Percent survival was lowest for trees on CG.4814 (85%); however, only three out of the ten core sites (or four out of all 13 sites) experienced any loss of trees on CG.4814 (Table 6). Among the 10 core sites, trees on B.9, B.7-3-150, B.7-20-21, B.67-5-32, PiAu 9-90, PiAu 51-11, M.9 NAKBT337, and M.9 Pajam 2 experienced no tree loss in the first 5 years of this trial. Where the reason for tree loss was determined, the most common causes were graft union failure and fireblight. Graft union failure was the reason for 21 trees (B.10, B.71-7-22, G.11, G.41N, G.41TC, G.202N, G.935N, G.935TC, CG.4003, CG.4814, and CG.5222) lost in Nova Scotia, 2 trees (B.10 and M.26 EMLA) in New York, 1 tree (CG.5087) in Utah, and 3 trees (B.71-7-22, G.41N, and G.935N) in Wisconsin. Fireblight resulted in the death of 6 trees (B.64-194, B.70-6-8, CG.4003, CG.4013, and CG.4814) in Chihuahua, 1 tree (Supp.3) in New York, and 1 tree (B.10) in Utah. Winter injury caused the death of 4 out of 6 trees on Supp.3 in Iowa.

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

It is interesting to note the significant difference in tree size between G.202N and G.202TC. G.202TC resulted in trees of the expected vigor, and trees on G.202N were much larger than expected, possibly showing the result of a propagation error. 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 rootstock suckering was induced by G.202TC, G.935TC, G.935N, M.9 NAKBT337, CG.4013, CG.4004, and B.70-20-20. The greatest amount of root suckering came from M.9 Pajam 2, CG.4214, CG.5222, G.202N, and CG.4814.

In 2014 and cumulatively (2011-14), the greatest yields were harvested from trees on CG.4004, and the smallest yields were from trees on B.71-7-22 (Table 5). Within the small dwarf category, the greatest yields (2014 and cumulatively) were from trees on CG.4003, and lowest were from trees on B.9. Among the moderate dwarfs, the greatest yields in 2014 were from trees on M.9 NAKBT337 and cumulatively from trees on G.41N. The lowest yields (2014 and cumulatively)

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

Rootstock	BC	CH	CO	IA	MA	MI	MN	NJ	NS	NY	OH	UT	WI
B.9	5.4	5.6	6.9	5.5	6.3	6.9	7.3	5.5	8.1	6.3	6.2	6.5	7.0
B.10	8.1	8.7	13.8	8.9	10.4	9.8	10.1	9.9	9.7	12.2	10.1	10.1	9.5
B.7-3-150	11.5	11.7	22.4	20.6	18.0	14.7	21.2	24.8	13.6	21.5	16.9	17.4	15.9
B.7-20-21	15.1	10.8	27.3	18.7	17.3	16.2	21.5	28.9	22.1	22.4	19.4	18.0	20.0
B.64-194	11.5	12.1	31.0	17.1	21.7	21.4	22.2	26.1	23.2	22.7	20.3	17.4	23.4
B.67-5-32	14.2	10.7	27.1	20.7	19.8	21.7	20.4	23.6	16.6	18.1	18.9	16.0	17.1
B.70-6-8	11.4	11.1	22.7	19.8	19.9	13.6	19.6	23.4	14.3	23.0	18.3	16.6	15.7
B.70-20-20	26.0	16.5	49.4	21.7	34.7	28.4	38.8	46.8	30.3	35.9	31.5	34.0	32.6
B.71-7-22	1.5	3.5	3.6	3.2	1.8	2.6	3.3	2.0	1.2	2.9	2.3	0.0	2.4
G.11	6.6	7.9	12.3	10.9	8.6	9.5	9.9	13.0	7.6	10.1	7.1	10.1	9.9
G.41N	9.3	6.8	15.4	9.4	9.1	9.6	11.6	11.4	10.0	12.1	9.2	7.8	11.1
G.41TC	8.0	6.8	13.7	10.5	8.6	11.0	12.2	12.9	8.9	9.0	3.9	10.3	9.8
G.202N	14.4	9.3	13.6	19.7	20.1	14.0	18.4	23.8	17.5	18.2	16.6	14.7	18.1
G.202TC	7.7	6.8	15.3	10.9	12.4	9.6	11.8	13.2	9.7	15.8	8.9	10.2	9.0
G.935N	10.3	7.0	---	10.9	12.7	10.8	12.2	16.1	10.5	14.8	11.2	10.7	13.2
G.935TC	7.2	5.1	14.9	7.8	9.2	9.7	11.1	15.7	11.5	12.1	9.1	7.1	11.2
CG.2034	7.0	5.8	8.7	7.9	6.7	6.4	6.6	8.6	7.4	6.0	4.8	8.8	7.3
CG.3001	12.1	---	23.0	17.3	20.7	9.5	11.4	21.2	14.6	18.0	13.5	13.3	11.0
CG.4003	5.6	6.5	10.7	7.9	7.5	6.8	8.3	9.4	6.9	8.8	6.3	7.0	8.4
CG.4004	13.5	10.5	18.4	13.8	16.9	15.1	18.7	21.6	22.6	17.6	16.2	12.2	17.6
CG.4013	7.9	11.5	---	15.7	11.8	13.3	10.1	20.4	11.1	17.8	15.0	10.6	6.7
CG.4214	7.0	5.5	11.6	11.1	13.8	12.1	12.1	16.1	12.0	14.0	10.3	8.2	9.4
CG.4814	11.1	8.2	14.3	17.8	12.6	12.0	13.9	21.2	14.6	15.5	11.9	9.4	13.0
CG.5087	12.5	7.2	15.6	12.2	12.4	11.2	13.5	19.8	11.6	15.7	12.1	6.8	14.0
CG.5222	12.2	6.7	19.1	---	15.5	12.8	11.9	18.2	17.3	14.4	17.4	12.7	11.5
Supp.3	7.1	7.6	16.0	10.0	8.1	8.2	7.4	13.3	8.5	11.5	7.7	8.5	7.3
PiAu 9-90	14.5	11.3	23.4	12.0	16.4	13.1	13.2	28.5	15.7	23.3	15.2	20.1	13.2
PiAu 51-11	8.3	10.8	20.3	18.2	15.4	15.8	15.2	25.0	13.6	18.4	13.3	12.8	13.8
M.9 NAKBT337	7.2	7.2	13.3	9.7	10.0	8.8	9.8	13.0	7.8	11.8	9.6	9.0	9.1
M.9 Pajam 2	8.8	7.1	15.3	12.3	9.2	10.4	9.7	13.7	9.5	12.0	10.6	10.3	12.2
M.26 EMLA	9.7	8.0	14.1	13.1	9.7	11.2	11.2	15.7	13.3	12.4	11.1	11.0	10.4
Average HSD	5.2	3.8	11.4	10	7.3	6.2	3.8	5.6	8.2	6.9	5.5	11.0	7.4

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

were from trees on 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.4013. Among the small semi-dwarfs, the largest yields in 2014 were from trees on CG.4814 and cumulatively from trees on CG.3001.Lowest yields in 2014 and cumulatively were from trees on PiAu 51.11. Among the moderate semi-dwarfs, greatest yields (2014 and cumulatively) were from trees on CG.4004, and the lowest were from trees on PiAu 9-90. The two large semi-dwarfs (B.64-194 and B.7-20-21) yielded similar in 2014 and cumulatively. Site variations in rootstock effects on cumulative yield are presented in Table 8.

In 2014, the most yield efficient trees were on M.9 NAKBT337, G.11, and CG. 4003, and the least efficient trees were on PiAu 9-90 (Table 5). Cumulatively (2011-14), the most yield efficient trees were on G.11 and CG.4003, and the least efficient were on B.70-20-20 (Table 5). Among the small dwarfs, the most yield efficient trees (2014 and cumulatively) were on CG.4003. Among the moderate dwarfs, the most efficient trees in 2014 were on M.9 NAKBT337 and G.11, and the least efficient were on B.10, and G.41TC. Cumulatively among the moderate dwarfs, the most efficient were on G.11, and the least efficient were on B.10 and Supp.3. For the large dwarfs, the most yield efficient trees in 2014 were on G.935 (N and TC), and cumulatively, the most efficient were on G.935N and CG.4214. The least efficient (2014 and cumulatively) large dwarfs were on CG.4013. The most yield efficient (2014 and cumulatively) small semi-dwarfs were on CG.4814 and CG.5087, and the least efficient (2014 and cumulatively) were on PiAu 51-11. Among the moderate semi-dwarfs in 2014 and cumulatively, the most yield efficient were on CG.4004, and the least efficient were on PiAu 9-90. The two large semi-dwarfs (B.64-194 and B.7-20-21) were similarly yield efficient in 2014 and cumulatively. 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.71-7-22 and PiAu 9-90 resulted in the smallest fruit in 2014 and averaged over the three fruiting years 2012-14 (Table 5). Similar to the overall differences, very little effect of rootstock on average (2012-14) fruit weight was seen by site, but the relatively small size of fruit from trees on B.71-7-22 and PiAu 9-90 was reasonably consistent from site to site (Table 10).

The percent of the tree canopy expressing zonal chlorosis typical of Honeycrisp was assessed in 2012-14 (Tables 5 and 11). Year-to-year variation, site differences, and most rootstock differences were not consistent. Trees on PiAu 9-90, however, consistently had the highest percent of the canopy affected. Trees on B.70-20-20 and B.64-194 tended to be among the least affected by zonal chlorosis.

Discussion

Seven to 10 years will be required to obtain an adequate evaluation of the rootstocks included in this study; however, after 5 years, rootstocks start separating based on size and tree performance. Table 12 places the rootstocks in this study into eight vigor classes, as described above. Four of those rootstocks (all from the Russian Budagovsky program) likely are unsuitable for a modern high-density system. B.70-20-20 is semi-standard or standard in vigor producing trees much too large. Very likely, the two large semi-dwarfs, B.7-20-21 and B.64-194 are also too vigorous for a high-density system. B.71-7-22, on the other hand, is sub-dwarf and produces trees which are much too low in vigor to be useful in a commercial orchard.

In the moderate semi-dwarf category (Table 12), trees on CG.4004 and G.202N performed the best as measured by cumulative yield efficiency; however, as noted earlier, G.202N may not be identified correctly. Trees on the Budagovsky rootstocks or on PiAu 9-90 were significantly less efficient.

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

Rootstock	BC	CH	CO	IA	MA	MI	MN	NJ	NS	NY	OH	UT	WI
B.9	12.6	0.6	5.5	8.7	13.4	16.2	13.2	9.0	19.7	24.3	7.4	8.3	21.6
B.10	18.3	1.1	7.6	13.8	22.8	18.1	15.6	17.7	25.7	42.9	13.4	15.4	29.0
B.7-3-150	20.0	3.5	9.8	17.9	20.4	12.3	18.3	33.2	24.7	38.6	13.8	18.3	33.4
B.7-20-21	24.4	1.0	8.8	15.7	25.7	20.1	15.5	28.2	40.3	37.1	13.4	16.8	29.0
B.64-194	18.4	2.4	8.0	14.2	22.0	17.5	13.1	33.3	36.0	35.9	10.8	27.2	40.1
B.67-5-32	23.1	1.5	4.1	15.7	18.3	15.4	9.0	20.3	19.0	26.8	12.5	15.7	23.2
B.70-6-8	19.9	2.8	5.8	15.6	25.3	12.8	21.2	30.7	27.8	39.0	12.7	18.3	33.5
B.70-20-20	24.6	2.5	4.5	4.7	23.4	21.6	9.7	25.0	38.3	21.2	19.8	20.5	33.8
B.71-7-22	4.5	0.5	0.7	5.6	2.4	3.8	5.3	4.8	3.0	6.9	2.8	0.5	6.5
G.11	19.1	3.0	8.8	15.8	28.4	22.2	23.0	20.8	22.5	32.0	9.8	19.5	36.9
G.41N	24.8	1.5	9.7	17.1	26.3	18.3	23.3	16.3	31.6	33.9	14.4	14.2	37.3
G.41TC	21.2	1.7	11.0	15.0	18.1	13.8	21.5	14.8	19.0	23.9	6.6	16.1	26.8
G.202N	29.4	3.3	4.7	12.9	50.7	20.0	22.1	28.6	38.1	37.5	18.6	22.1	34.5
G.202TC	20.5	8.0	6.4	18.4	33.6	22.2	20.8	25.3	20.5	38.6	12.9	16.1	15.6
G.935N	31.9	1.6	---	14.8	42.2	23.9	23.8	21.9	25.1	35.9	17.4	17.2	52.8
G.935TC	16.5	1.0	10.0	10.4	18.2	25.1	18.6	28.5	30.3	32.9	14.9	14.7	41.0
CG.2034	18.4	1.1	3.1	11.2	14.0	11.3	14.3	13.9	13.6	17.2	10.1	12.3	25.4
CG.3001	30.9	---	8.3	24.1	52.9	16.9	17.0	23.2	32.9	44.7	21.0	20.3	42.6
CG.4003	16.7	0.6	4.0	14.4	24.7	17.2	14.9	18.9	20.1	34.8	7.5	11.5	26.4
CG.4004	38.0	4.0	11.2	25.3	40.1	20.6	30.0	37.4	55.9	37.5	25.0	13.3	56.3
CG.4013	20.0	1.2	---	12.8	29.3	14.4	18.9	20.5	16.4	23.0	16.3	15.1	11.7
CG.4214	27.1	2.1	11.4	18.3	26.7	23.8	21.9	26.4	31.4	38.4	17.3	9.7	37.0
CG.4814	32.6	1.6	9.9	17.3	30.9	20.5	26.7	29.7	33.5	48.7	14.7	16.2	32.8
CG.5087	32.5	1.7	6.1	15.9	28.9	21.4	25.3	36.7	32.1	41.1	24.4	6.6	45.0
CG.5222	23.3	1.0	7.0	---	22.3	16.7	18.6	31.0	33.7	38.0	15.6	21.5	27.8
Supp.3	21.5	1.8	4.7	6.4	18.3	12.5	15.7	16.9	19.4	33.9	8.0	18.1	24.5
PiAu 9-90	17.5	3.6	5.2	6.5	10.0	8.9	7.4	26.1	9.2	25.6	15.3	21.6	14.3
PiAu 51-11	15.7	1.7	8.6	15.2	19.6	15.3	18.9	23.3	18.0	36.7	15.7	15.9	21.2
M.9 NAKBT337	19.2	2.1	13.2	13.1	24.3	17.4	21.5	25.5	20.0	36.3	15.3	15.9	28.3
M.9 Pajam 2	20.8	1.1	13.6	12.1	17.7	17.7	16.2	28.7	20.0	30.2	11.8	16.8	37.0
M.26 EMLA	23.4	0.5	8.0	17.7	18.3	15.8	14.8	18.5	22.0	29.0	11.8	15.3	28.1
Average HSD	11.2	3.0	10.7	8.9	16.4	12.0	12.8	15.6	13.5	18.1	8.4	11.8	17.1

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

Rootstock	BC	CH	CO	IA	MA	MI	MN	NJ	NS	NY	OH	UT	WI
B.9	2.3	0.1	0.8	1.6	2.1	2.5	1.8	1.7	2.9	3.9	1.3	1.3	3.1
B.10	2.3	0.1	0.6	1.6	2.2	1.8	1.6	1.8	2.7	3.6	1.3	1.6	3.1
B.7-3-150	1.8	0.3	0.5	1.5	1.2	0.9	0.9	1.4	1.8	1.8	0.8	1.1	2.3
B.7-20-21	1.7	0.1	0.4	0.9	1.5	1.3	0.8	1.0	1.8	1.7	0.7	0.9	1.6
B.64-194	1.7	0.2	0.3	0.9	0.9	0.8	0.6	1.3	1.6	1.6	0.6	1.6	1.7
B.67-5-32	1.7	0.1	0.2	0.8	1.0	0.7	0.5	0.9	1.2	1.5	0.7	1.0	1.4
B.70-6-8	1.8	0.3	0.3	0.8	1.3	0.9	1.1	1.3	2.0	1.7	0.7	1.1	2.3
B.70-20-20	1.0	0.1	0.1	0.3	0.7	0.8	0.3	0.5	1.3	0.6	0.6	0.6	1.1
B.71-7-22	2.6	0.2	0.3	1.8	1.6	1.2	1.7	2.3	2.4	3.1	1.3	1.2	3.0
G.11	2.8	0.4	0.7	1.6	3.3	2.3	2.3	1.6	3.0	3.1	1.4	1.9	3.8
G.41N	2.7	0.2	0.6	1.8	2.8	1.9	2.0	1.5	3.1	2.8	1.6	1.7	3.4
G.41TC	2.6	0.3	0.8	1.4	2.0	1.3	1.8	1.2	2.5	2.6	1.6	1.6	2.8
G.202N	2.1	0.4	0.3	0.9	2.5	1.4	1.3	1.2	2.2	2.6	1.2	1.4	1.9
G.202TC	2.6	1.2	0.4	1.7	2.7	2.4	1.8	1.9	2.0	2.8	1.5	1.6	1.8
G.935N	3.1	0.2	---	1.4	3.3	2.3	2.0	1.4	2.4	2.4	1.6	1.6	4.0
G.935TC	2.3	0.2	0.6	1.4	2.0	2.6	1.7	1.8	2.7	2.8	1.7	1.9	3.9
CG.2034	2.6	0.2	0.4	1.4	2.0	1.7	2.2	1.6	2.0	2.9	2.0	1.4	3.5
CG.3001	2.5	---	0.3	1.5	2.5	1.7	1.6	1.0	2.3	2.4	1.5	1.5	4.1
CG.4003	3.1	0.1	0.4	1.8	3.3	2.5	1.8	2.0	3.0	3.9	1.2	1.6	3.2
CG.4004	2.8	0.4	0.6	1.8	2.3	1.4	1.6	1.8	2.4	2.2	1.6	1.1	3.3
CG.4013	2.5	0.1	---	0.9	2.3	1.2	1.9	0.9	1.5	1.4	1.1	1.4	1.8
CG.4214	3.9	0.4	1.0	1.6	1.9	2.0	1.8	1.7	2.7	2.8	1.7	1.2	4.0
CG.4814	2.9	0.2	0.7	1.0	2.5	1.8	1.9	1.4	2.4	3.2	1.3	1.7	2.6
CG.5087	2.6	0.2	0.4	1.4	2.1	1.9	1.9	1.8	2.8	2.6	2.0	0.9	3.3
CG.5222	1.9	0.2	0.3	---	1.4	1.3	1.6	1.7	2.0	2.7	0.9	1.7	2.4
Supp.3	3.0	0.2	0.4	0.7	2.2	1.7	2.1	1.3	2.1	2.9	1.0	2.1	3.3
PiAu 9-90	1.3	0.3	0.3	0.6	0.6	0.6	0.6	0.9	0.6	1.2	1.0	1.2	1.1
PiAu 51-11	1.9	0.2	0.5	0.9	1.3	1.0	1.2	0.9	1.4	2.0	1.2	1.3	1.6
M.9 NAKBT337	2.6	0.3	1.0	1.4	2.4	2.0	2.2	2.0	2.5	3.3	1.6	1.8	3.2
M.9 Pajam 2	2.4	0.1	0.9	1.1	1.9	1.7	1.7	2.0	2.1	2.4	1.1	1.6	3.1
M.26 EMLA	2.4	0.1	0.6	1.4	1.9	1.5	1.3	1.2	1.6	2.4	1.1	1.4	2.7
Average HSD	0.9	0.3	0.6	1.2	1.0	1.0	0.9	1.1	1.1	1.5	0.8	0.7	1.2

[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 10. Average fruit size (2012-14, g) of Honeycrisp apple trees at individual planting locations in the 2010 NC-140 Honeycrisp Apple Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

Rootstock	BC	CH	CO	IA	MA	MI	MN	NJ	NS	NY	OH	UT	WI
B.9	256	162	131	162	229	180	156	258	163	222	177	155	211
B.10	297	177	186	169	215	233	178	279	173	235	191	193	240
B.7-3-150	302	164	188	212	256	209	203	304	168	266	182	199	256
B.7-20-21	274	175	185	182	224	188	181	280	183	251	183	154	264
B.64-194	279	176	197	204	229	202	228	294	195	258	192	140	282
B.67-5-32	288	177	190	201	234	246	244	273	190	232	183	180	272
B.70-6-8	281	176	187	190	232	196	198	265	177	258	181	171	254
B.70-20-20	305	163	192	210	236	202	210	280	190	263	178	211	267
B.71-7-22	214	198	141	149	179	147	159	294	151	192	187	178	191
G.11	256	164	188	186	247	217	155	282	160	242	197	186	250
G.41N	301	181	199	191	243	226	186	297	170	246	172	211	224
G.41TC	305	174	200	211	241	221	197	286	196	249	181	156	215
G.202N	322	168	217	143	245	204	204	262	158	238	201	214	227
G.202TC	231	148	178	189	203	184	170	282	134	227	191	145	217
G.935N	292	179	---	162	221	190	147	274	168	229	173	178	202
G.935TC	281	189	191	145	199	189	153	270	158	250	160	199	207
CG.2034	294	169	174	185	231	148	182	284	162	254	171	197	215
CG.3001	320	---	167	217	222	176	194	287	203	261	191	200	224
CG.4003	278	193	162	161	207	260	161	276	132	193	148	122	217
CG.4004	317	160	207	208	232	196	205	291	309	228	193	153	224
CG.4013	286	179	---	202	208	170	175	277	187	223	175	195	203
CG.4214	277	172	197	196	238	195	177	287	176	251	160	177	228
CG.4814	307	178	200	221	212	224	176	279	122	247	155	193	200
CG.5087	304	163	181	197	233	208	161	276	156	223	163	143	188
CG.5222	301	171	207	---	205	205	177	264	138	237	182	173	249
Supp.3	294	187	175	185	215	192	165	266	144	235	186	205	202
PiAu 9-90	227	158	158	137	132	162	174	248	121	219	139	155	186
PiAu 51-11	265	179	179	216	238	204	219	279	181	257	168	206	294
M.9 NAKBT337	291	174	192	193	235	216	165	307	174	253	181	164	233
M.9 Pajam 2	277	191	202	175	211	216	164	288	149	228	169	143	244
M.26 EMLA	271	172	180	197	220	185	181	306	171	241	193	161	250
Average HSD	69	52	80	47	54	99	78	59	52	50	52	102	68

[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 11. Zonal chlorosis (2014, % of canopy affected) of Honeycrisp apple trees at individual planting locations in the 2010 NC-140 Honeycrisp Apple Rootstock Trial. All values are least-squares means, adjusted for missing subclasses.[z]

	BC	IA			MA		MI		MN			NJ	NS			NY			WI		
Rootstock	2013	2012	2013	2014	2013	2014	2013	2014	2012	2013	2014	2014	2012	2013	2014	2012	2013	2014	2012	2013	2014
B.9	46	68	2	65	47	24	18	44	17	38	21	20	7	37	69	17	10	29	16	18	7
B.10	32	57	8	11	50	24	25	69	3	14	35	16	8	25	57	14	19	12	17	21	14
B.7-3-150	30	48	4	14	43	20	20	42	20	27	42	13	5	25	43	18	15	14	19	15	6
B.7-20-21	40	54	15	39	59	48	29	57	15	29	37	13	9	17	30	15	16	12	30	21	11
B.64-194	21	64	22	21	42	17	22	43	7	38	33	12	5	9	46	24	15	15	22	18	11
B.67-5-32	36	42	16	24	43	22	25	31	17	23	42	12	10	26	64	22	19	21	22	19	12
B.70-6-8	23	59	8	19	49	20	20	67	10	34	40	11	5	24	38	19	14	15	18	23	11
B.70-20-20	15	58	29	20	31	12	28	25	0	27	47	10	5	7	43	17	14	13	26	19	13
B.71-7-22	100	85	3	27	92	58	15	87	3	25	21	13	13	45	62	17	24	44	31	13	12
G.11	80	68	11	54	40	34	18	66	9	57	22	15	10	76	53	23	16	22	41	26	13
G.41N	68	60	11	29	32	15	18	57	0	49	35	18	23	42	64	21	15	24	27	20	12
G.41TC	65	54	22	32	65	34	28	81	13	44	53	27	10	17	64	28	28	24	50	23	13
G.202N	32	67	34	45	29	26	33	82	8	33	42	17	12	40	73	25	23	15	57	24	14
G.202TC	67	77	32	14	59	38	29	54	8	29	38	20	15	71	84	21	19	16	71	27	20
G.935N	68	79	60	70	43	44	59	80	22	69	33	20	10	64	56	26	23	21	46	31	13
G.935TC	95	79	73	51	71	85	39	66	24	76	65	21	5	65	39	27	19	35	59	32	18
CG.2034	96	78	27	57	79	58	15	71	20	82	42	15	5	83	74	25	28	58	40	19	14
CG.3001	55	59	10	24	64	66	56	76	24	72	52	11	27	7	61	30	24	35	19	22	8
CG.4003	70	73	8	48	42	21	25	84	20	42	20	20	46	66	76	18	29	10	18	11	11
CG.4004	18	70	26	48	33	16	35	70	5	34	42	13	9	19	78	31	16	25	29	33	10
CG.4013	73	46	13	38	58	54	46	80	13	66	53	21	21	31	88	26	23	33	47	38	22
CG.4214	83	66	48	53	54	59	28	86	22	55	39	16	35	44	78	31	21	34	32	33	22
CG.4814	72	55	45	56	66	74	39	91	13	68	44	13	87	87	81	24	22	28	41	36	20
CG.5087	57	59	53	80	55	53	39	91	25	60	66	14	31	36	79	23	17	36	40	30	10
CG.5222	58	---	---	---	68	48	30	77	3	47	51	10	28	23	72	19	30	18	28	25	29
Supp.3	92	89	85	72	54	61	38	92	12	81	82	20	20	53	74	17	18	41	31	32	16
PiAu 9-90	78	90	80	92	72	79	77	85	35	81	92	25	83	85	95	25	21	41	98	32	57
PiAu 51-11	50	52	22	19	61	46	42	74	23	60	43	13	21	18	64	20	24	23	28	21	18
M.9 NAKBT337	58	64	21	60	55	33	27	50	13	63	33	14	6	38	83	23	23	18	23	20	8
M.9 Pajam 2	53	67	36	55	53	39	28	85	17	79	50	14	8	44	76	24	17	21	30	22	13
M.26 EMLA	31	55	7	30	57	32	23	71	25	26	31	16	16	42	79	23	26	32	18	17	9
Average HSD	44	45	29	50	44	42	33	45	25	45	36	12	31	49	43	13	14	28	35	27	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.

CG.4004, in a New York trial with 'Honeycrisp' as the scion, performed similarly to what is noted in this NC-140 trial (Robinson et al., 2011). After 6 years, trees were similar in size to those on M.7 and were significantly more yield efficient.

In the small semi-dwarf category (Table 12), trees on CG.5087, CG.4814, and CG.3001 were the most yield efficient, and those on PiAu 51-11 were the least efficient. In a New York trial with 'Golden Delicious', 7-year-old trees on CG.5087 were between M.26 and M.7 in size but significantly more yield efficient (Robinson et al, 2011). In the 1999 NC-140 Semi-dwarf Apple Rootstock Trial, after 10 years (Autio et al., 2011b), 'McIntosh' trees on CG.4814 were similar in size to those on M.26 EMLA and smaller than those on M.7 EMLA, but trees on CG.4814 were more yield efficient than trees on either M.26 EMLA or M.7 EMLA. 'Fuji' trees on CG.4814, M.26 EMLA, and M.7 EMLA were similar in size, but those on CG.4814 were the most yield efficient.

In the large dwarf category (Table 12), trees on G.935N, CG.4214, G.935TC, and G.202TC performed the best as assessed by yield efficiency, similar in size but more efficient than trees on M.26 EMLA. After 10 years, 'Fuji' and 'McIntosh' trees in the 1999 NC-140 Dwarf Apple Rootstock Trial on G.935 and G.202 performed similarly to those on M.26 EMLA (Autio et al., 2011a). After 6 years with 'Honeycrisp' as the scion cultivar in New York, G.935 and G.202 were similar in size and yield efficiency to trees on M.7 (Robinson et al., 2011). In the 2002 NC-140 Apple Rootstock Trial after 10 years, 'Gala' trees on G.935 were similar in size to those on M.26 EMLA (Autio et al., 2013). In the 2002 trial, G.935 only occurred at two locations, and at one location (Chihuahua, Mexico), trees on G.935 were similarly yield efficient to those on M.26 EMLA, but at the other location (New York), they were significantly more yield efficient than trees on M.26 EMLA. In the 2003 NC-140 Dwarf Apple Rootstock Trial after 10 years, 'Golden Delicious' trees on G.935 were similar in size to those on M.9 NAKBT337 at four out of eight sites, and similar to trees on M.26 at the other four (Marini et al., 2014). Trees on G.935 were similarly yield efficient to trees on M.9 NAKBT337 at all sites and more efficient than those on M.26 at five of eight sites. After 7 years, 'Golden Delicious' trees on CG.4214 in New York were similar to trees on M.26 in size and yield efficiency (Robinson et al., 2011).

In the moderate dwarf category, G.41N and G.11 performed well and comparably to M.9 NAKBT337. Autio et al. (2011a) and Marini et al. (2014) found after 10 years that 'McIntosh', 'Fuji', and 'Golden Delicious' trees on G.41were similar in size and yield efficiency to those on M.9 NAKBT337. Robinson et al. (2011) found 7-year-old 'Golden Delicious' trees on G.41 to be similar in size to comparable trees on M.26 but significantly more yield efficient. 'Golden Delicious' trees on G.11 were somewhat smaller than those on M.26 and more yield efficient. Robinson et al. (2011) also reported that 6-year-old 'Honeycrisp' trees on G.11 were somewhat smaller than comparable trees on M.9 and similarly yield efficient.

In the small dwarf category, trees on CG.4003 performed well, somewhat greater but statistically similarly to trees on B.9. Among the few reports of CG.4003 performance, a 6-year study with 'Honeycrisp' as the scion cultivar reported that trees on CG.4003 were statistically similar in size and yield efficiency to trees on B.9 (Robinson et al., 2011).

As noted above, these results represent an early assessment of many of the rootstocks in this study. At this point few, if any, of the new Budagovsky rootstocks have shown promise; many are too large and lack efficiency. B.10, however, is a somewhat promising, moderate dwarf rootstock, but it is not yet showing any particularly valuable traits. None of the Pillnitz rootstocks (PiAu 9-90, PiAu 51-11, and Supp.3) have performed well, all three have the lowest yield efficiency in their respec-

Table 12. 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 Honeycrisp Apple Rootstock Trial data are from BC, MA, MI, MN, NJ, NS, NY, OH, UT, and WI. All values are least-squares means, adjusted for missing subclasses.

Vigor category	Rootstock	Trunk cross-sectional area (2014, cm^2)	Cumulative yield efficiency (2011-14, kg/cm^2 TCA)
Semi-standard	B.70-20-20	33.9	0.7
Large semi-dwarf	B.7-20-21	20.1	1.3
	B.64-194	21.0	1.2
Moderate semi-dwarf	CG.4004	17.2	2.0
	G.202N	17.6	1.8
	B.70-6-8	17.6	1.4
	B.7-3-150	17.5	1.4
	B.67-5-32	18.6	1.0
	PiAu 9-90	17.3	0.9
Small semi-dwarf	CG.5087	13.0	2.2
	CG.4814	13.5	2.2
	CG.3001	14.5	2.1
	CG.5222	14.4	1.8
	PiAu 51-11	15.2	1.4
Large dwarf	G.935N	12.2	2.4
	CG.4214	11.5	2.4
	G.935TC	10.4	2.3
	G.202TC	10.8	2.1
	M.9 Pajam 2	10.6	2.0
	M.26 EMLA	11.6	1.7
	CG.4013	12.5	1.6
Moderate dwarf	G.11	9.2	2.6
	M.9 NAKBT337	9.6	2.4
	G.41N	10.1	2.4
	B.10	10.0	2.2
	Supp.3	8.8	2.2
	G.41TC	9.4	2.0
Small dwarf	CG.4003	7.5	2.6
	B.9	6.5	2.3
	CG.2034	7.0	2.2
Sub-dwarf	B.71-7-22	2.0	2.0

tive size class, and trees on PiAu 9-90 have produced the smallest fruit in the trial. The Cornell-Geneva rootstocks (both CG and G), on the other hand, are performing very well, often among the best in their size class.

This trial will continue through the tenth growing season, after which a more thorough evaluation will be presented.

Acknowledgements

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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, cm²)	Cumulative yield efficiency (2011-14, kg/cm² 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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Adaptability of Blackberry Cultivars to a High-Elevation Arid Climate

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Additional index words: Rubus, yield reliability

Abstract

Winter-hardy, high-yielding cultivars with good consumer acceptance and few production problems are critical to the economic viability of growing blackberries for local consumption in high elevation arid climates. A replicated experiment was planted in 2006 to evaluate 19 cultivars and 2 numbered selections of blackberry for suitability to commercial production in the US Intermountain West. Factors evaluated included winter survival, yield, and fruit size. Winter bud survival varied among cultivars and over seasons. Semi-erect and erect cultivars averaged the highest winter bud survival and trailing cultivars consistently had the poorest winter bud survival. Per plant yields were higher when bud survival was greater, with trailing types producing the lowest average yields and semi-erect types the highest. Production from primocane-fruiting types was slowed by cold temperatures before full production was reached and consequently, yields were lower. The cultivar Triple Crown had the most consistently high overall yield (highest yield reliability index) and was among the cultivars with the largest berry size. 'Illini Hardy' had the highest yield reliability index among erect types. In general, semi-erect types had the highest and most consistent yields for the U.S. Intermountain West.

Historically, the high elevation valleys of the U.S. Intermountain West have not had significant blackberry production, likely due to harsh winters and frequent late spring freezes that result in significant blackberry cane damage and crop loss. However, local production would be advantageous as the delicate berries have a short shelf life that makes shipping to distant markets difficult. Small-acreage farmers are interested in blackberry as a high-value diversification opportunity, but need cultivars adapted to the regional climate and markets.

Winter cane dieback and winter bud damage are major limitations to floricane-fruiting blackberry production in the U.S. Intermountain West region. A typical low temperature limit for blackberries is -18 °C (Dana and Goulart, 1989). However, winter hardiness varies among growth type and cultivar. In a freezing survival study on 8 erect blackberry types, Warmund and George (1990) found that the T_{50} of primary buds was between -11.9 °C and -19 °C, with the exception of one cultivar, Darrow, which survived below -25 °C. Erect blackberries are generally considered to be more hardy than trailing types, and thorny blackberries more hardy than thornless (Crandall, 1995). Cane survival can also be negatively influenced by desiccating winds (Crandall, 1995) which can be a serious problem in the arid U.S. Intermountain West.

In areas with a sufficiently long freeze-free period, primocane-bearing cultivars may be a good option as the overwintering of floricanes is not necessary. However, in the Northern locations where the primocane-fruiting cultivars Prime-Jan and Prime-Jim were first evaluated, the first day that fruit ripened was 1 Sept. (Clark, 2008) leaving only a short window of production before fall freezes.

The objective of this research was to

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evaluate blackberry cultivars for suitability to field production in alkaline soils and high elevation valleys typical of the U.S. Intermountain West. Representative cultivars and advanced selections were included to represent all four blackberry growth types (trailing, semi-erect, erect and primocane-fruiting), with evaluation based on winter survival, yield, fruit size, and fruiting season.

Materials and Methods

Planting. A replicated blackberry cultivar trial was carried out at the Utah State University Agricultural Research Farm in Kaysville, Utah (41.01 N latitude, 1330 m elevation). The average freeze-free season is 165 d, with the average last spring freeze on 5 May and average first fall freeze on 9 Oct. (Moller and Gillies, 2008). The soil is a Kidman fine sandy loam with a pH of 7.5 and 1.5% organic matter. In 2006, blackberry plants of 19 cultivars and 2 numbered selections were obtained from commercial nurseries or from the breeder. Plants were established in 2 replicate plots arranged in a randomized block design with blocking by location within the field and by trellis type. Plants were spaced 1.5 m within the row, and rows were spaced 3 m apart. Each plot consisted of 2 or 3 plants. Cultivars included: six trailing cultivars and two trailing numbered selections, five semi-erect, six erect, and two primocane-fruiting types. Trailing cultivars from the Pacific Northwest included: Newberry (Finn et al., 2010), Siskiyou (Finn et al., 1999), Obsidian (Finn et al., 2005c), Black Diamond (Finn et al., 2005a), Metolius (Finn et al., 2005b), Marion (Moore, 1997), and the numbered selections ORUS 1793-1 and ORUS 1939-4 from the USDA-ARS breeding program at Corvallis, OR.Semi-erect cultivars included selections from Maryland [Hull (Galletta, 1981), Chester Thornless (Galletta et al., 1998a), and Triple Crown (Galletta et al., 1998b)],] Indiana [Doyle's Thornless (Doyle, 1977)] and Scotland [Loch Ness (Moore, 1997)]. Erect cultivars from the University of Arkansas breeding program included [Navaho (Moore and Clark, 1989), Arapaho (Moore and Clark, 1993), Kiowa (Moore and Clark, 1996), Apache (Clark and Moore, 1999), and Ouachita (Clark and Moore, 2005)] and from Illinois, Illini Hardy (Skirvin and Otterbacher, 1993). The primocane-fruiting cultivars from Arkansas included Prime-Jan and Prime-Jim (Clark et al., 2005). Plants of several of the cultivars were not available in time for the 2006 planting, and were planted one year later. Yield data for these were not collected until 2009.

Cultural practices. The space between plots within the row was covered with landscape fabric (5 oz. per yd^2, Dewitt, Sikeston, MI) to suppress weeds. Alleyways were planted in the summer of 2006 to a 1:1 mix of perennial ryegrass (*Lolium perenne* L.) and creeping red fescue (*Festuca rubra* L.) at a seeding rate of 56 $kg \cdot ha^{-1}$. In-row weed control was a combination of annual applications of a pre-emergent herbicide (1.9 to 2.8 $L \cdot ha^{-1}$ Surflan, Southern Agric. Insecticides, Palmetto, FL) and hand weeding. The alleyway grass was mowed at ~ 3-week intervals.

Plant nutrient needs were supplied with applications of 135 $kg \cdot ha^{-1}$ of 16.0N-7.0P-13.2K fertilizer in mid-April and again in early June of each year, banded in the blackberry row. Cane thinning and pruning was according to typical regional practices, where spent floricanes were removed and primocanes were positioned on the trellis according to conventions for the trellis system as described below.

The 2 blocks were each trained to a different trellis system. One block of all cultivars was placed on a stationary vertical trellis, with three wires on one side of the post, positioned 50 cm apart up to a height of approximately 1.5 m. The first five primocanes from each plant were attached to the wires using a commercial tape fastening system. Additional primocanes were removed. The second block was trained to a rotating cross arm (RCA) trellis (Takeda et al., 2013). Briefly, the first few primocanes were attached horizontally to the lowest training wire, and then tipped to force lateral branching. These laterals were then attached to the wires on the rotating arm portion of the trellis. During the winter months, the RCA trellis was lowered to the ground and covered with spun-bonded row covers (1.5 oz. per yd^2). After the first 3 years, the RCA trellises were fixed in a vertical position year-round and primocane training was as described for the vertical system.

Irrigation was provided using both drip and overhead systems. A single drip tape (RO-DRIP Lo Flo, 15 cm emitter spacing, John Deere Water Irrigation Products, Moline, IL), was installed in the center of each row at planting. The system was designed to supply 1.9 $mm \cdot h^{-1}$ of irrigation to the 90-cm wide root zone. An overhead irrigation system was also installed to maintain the grass cover crop in the alleyways. The overhead system consisted of mini sprinklers (2.38 mm orifice, mini-Wobbler®, Senninger Irrigation, Inc., Clermont, FL) set at 2.4 m height, placed in every third row at a 9.1 m in-row spacing, and designed to supply 3.38 $mm \cdot h^{-1}$. Irrigation scheduling was to supply crop needs based on evapotranspiration estimates from a nearby weather station, with approximately 25 mm per week applied through the overhead system and 17 to 25 mm per week applied by drip.

Data collection. Each spring from 2007 to 2012, each plot was visually evaluated to quantify winter injury based on percent of total bud survival. In the 2008 to 2012 growing seasons, plots were evaluated for total yield, fruit size, and timing of the production season. Ripe fruit in each plot was harvested three times per week, and total ripe fruit per plot weighed. For one harvest per week, mean fruit weight was determined for a 5-fruit subsample, and the seasonal weighted average was used to compare cultivars over the three seasons. Attempts were made to quantify consumer preference at a local farmers' market as described previously (Black et al., 2013). However, because of differences in ripening time among cultivars and due to crop loss from winter injury, the data were too incomplete for meaningful analysis and are not included.

A yield reliability index was calculated according to Kataoka (1963). Briefly, a reliability index is used to compare yields among locations or years, and provides a confidence interval based on a specified probability.For this study, we used a reliability index with a probability of 75% (RI_{75}), so that the calculated index value indicates the minimum yields one would expect to obtain 75% of the time.

A weather station located ~130 m from the plots recorded air temperature, humidity, wind speed, precipitation and solar radiation. Data were archived by the Utah Climate Center as part of their Fruit Grower data network (Utah Climate Center, 2016).

Data for winter survival, yield, fruit size and harvest season were analyzed as repeated measures using the GLM procedures in the SAS software package (SAS versions 9.1, Cary, NC). Means separations were calculated using the pdiff option in GLM with a threshold of $p=0.05$.

Results and Discussion

Winter injury. Winter survival differed among cultivars and across seasons (Table 1). Several cultivars were not planted in 2006, or else did not show adequate growth in 2006 to be included in the 2007 winter bud survival evaluation. Despite these missing values, there was significant year × cultivar interaction and so data were analyzed and means separations calculated separately for each year. The lowest average bud survival was noted in the spring of 2008 and 2011, but the lowest winter temperatures in these years did not differ from the other years of the study. The most likely cause of this higher mortality was sudden temperature drops in the fall, prior to adequate bud acclimation. For example, after a very mild fall where temperatures rarely dropped below freezing,

Table 1. Winter floricane survival of blackberry cultivars at the Utah State University Kaysville Research Farm. Evaluations are based on visual ratings of percent bud survival (% survival). Analysis was carried out on arcine transformed data. Means followed by the same letter are not significantly different (α=0.05) from other means within the same season.

Cultivar	2007	2008	2009	2010	2011	2012	Mean
Semi-erect							
Chester Thornless	72.5 abc	72.5 ab	95.0 a	95.0 a	67.5 abc	95.0 ab	82.9
Triple Crown		42.5 bc	80.0 abc	95.0 a	90.0 a		76.9
Hull	55.0 bc	20.0 cd	90.0 ab	75.0 abc	50.0 cd	97.5 a	64.6
Doyle's Thornless	67.5 abc	5.00 d	72.5 a-d	65.0 a-d	57.5 bcd	90.0 abc	59.6
Loch Ness	35.5 cd	15.0 cd	85.0 abc	60.0 a-d	72.5 abc	77.5 a-d	57.5
Erect							
Illini Hardy	100 a	90.0 a	92.5 a	95.0 a	92.5 a	90.0 abc	93.3
Apache	92.5 ab	80.0 a	80.0 abc	100 a	90.0 a		88.5
Navaho	77.5 ab	65.0 ab	70.0 a-d	95.0 a	87.5 a	75.0 b-e	78.3
Arapaho		40.0 bc	72.5 a-d	97.5 a	92.5 a	72.5 cde	75.0
Ouachita	100 a	15.0 cd	70.0 a-d	90.0 a	85.0 ab	17.5 fg	62.9
Kiowa	10.0 d	0.00 d	45.0 def	25.0 de	5.00 ef	12.5 fg	16.3
Trailing							
Newberry		0.00 d	77.5 abc	47.5 b-e	82.5 ab	80.0 a-d	71.9
Siskyou		20.0 cd	57.5 c-f	87.5 ab	45.0 cd		42.0
Black Diamond		0.00 d	75.0 a-d	17.5 e	7.50 ef	60.0 de	40.0
ORUS 1793-1		0.00 d	65.0 a-e	42.5 cde	5.00 ef	22.5 f	33.8
ORUS 1939-4		0.00 d	60.0 b-f	40.0 cde	32.5 de	0.00 g	33.1
Metolius		0.00 d	30.0 f	37.5 cde	5.00 ef	55.0e	31.8
Obsidian	65.0 abc	0.00 d	60.0 b-f	35.0 cde	5.00 ef	15.0 fg	30.8
Marion	50.0bcd	15.0cd	35.0ef	7.50e	0.00f	7.50fg	19.2
Analysis of Variance							
Cultivar	0.01	0.01	0.02	<0.001	<0.001	<0.001	
Block	0.18	0.55	0.37	<0.001	0.14	0.928	

Means separation was by the pdiff option in PROC GLM, with a $p < 0.05$

temperatures dropped from 12.9 °C to -13.1 °C over a 4-day period during the week of 20 Nov. 2010 (Utah Climate Center, 2016). If unseasonal freezing temperatures occur before adequate acclimation, cane damage is very likely (Crandall, 1995).

Averaged over seasons, 'Illini Hardy', 'Apache', and 'Chester Thornless' had the highest rate of winter bud survival with 93, 89, and 83%, respectively. Overall, semi-erect and erect cultivars had much higher rates of winter bud survival than trailing types. The trailing types had relatively low bud survival, ranging from a high of 58% average for 'Newberry' to a low of 19% average survival for 'Marion'. Interestingly, the erect-type 'Kiowa' had the lowest rate of bud survival (16%) among all cultivars tested. This was different from what Moore and Clark (1996) reported where 'Kiowa' showed no visible injury following field exposure to -23 °C.

There was no significant difference in bud survival rates between the vertical trellis and the RCA trellis blocks during the first three years (block effect, Table 1). In addition, some cane damage occurring in the erect and semi-erect types as the trellis was moved to or from the horizontal position. Therefore, the RCA trellis was fixed in the vertical position after the first 3 seasons and cane positioning was the same as for the vertical trellis. Note that winter injury is not reported for 'Prime-Jim' or 'Prime-Jan' (primocane-fruiting cultivars) as canes were removed to the ground each winter.

Yield. The five semi-erect cultivars planted had the highest average yields of all the cultivars, suggesting semi-erect types are the best suited for Utah production. 'Triple Crown' was numerically the highest yielding cultivar in three of the 5 years, and had the highest overall average yield of 3.69 kg/plant (Table 2). Erect types were the next highest performing, with 'Illini Hardy' and 'Arapaho' being the highest yielding of the erect cultivars planted (average 2.09, and 1.53 kg/plant, respectively). Previous reports of Illini Hardy yields are difficult to interpret on a land area basis. However, these yields for 'Arapaho' were far less than the 7.8 kg/plant reported by Moore and Clark (1993) in Clarksville, AR. Strang et al. (2003) reported that in Kentucky, 'Arapaho' was the lowest yielding of the cultivars tested (0.62 kg/plant).

Interestingly, for some semi-erect and erect cultivars, most notably Hull and Illini Hardy, a tendency toward cyclic high and low producing years was observed. This pattern was also observed in an un-replicated demonstration planting in Logan, Utah (Wytsalucy et al., 2015).

Not surprisingly, yields were correlated with

Table 2. Total yield (kg/plant) of blackberry cultivars at the USU Kaysville Research Farm over 5 years (2008-2012). Reliability index (RI_{75}) is the predicted minimum yields that could be expected in at least 75% of the production years.

Cultivar	2008	2009	2010	2011	2012	mean	RI_{75}
Semi-erect							
Triple Crown	1.75 ab	4.37 a	3.72 a	5.21 a	3.38 bc	3.69	2.24
Doyle's Thornless	1.33 ab	4.06 ab	2.29 b	1.75 bc	5.99 a	3.09	1.76
Hull	0.47 cde	4.72 a	0.87 c-f	0.72 cde	5.21 ab	2.40	1.23
Chester Thornless	0.61 cd	2.94 a-d	1.15 cde	1.48 bcd	5.28 ab	2.29	1.15
Loch Ness	0.16 de	3.23 abc	0.55 def	1.24 cde	2.95 cd	1.63	0.66
Erect							
Illini Hardy	0.63 cd	3.46 abc	0.68 def	4.12 a	1.56 cde	2.09	1.00
Arapaho	0.31 de	1.83 c-f	1.28 cd	2.78 b	1.45 cde	1.53	0.60
Ouachita	0.03 e	2.25 b-e	1.72 bc	1.73 bc	1.15 de	1.38	0.49
Apache	0.31 de	0.85 ef	0.66 def	1.51 bcd	0.66 e	0.80	0.12
Navaho	0.95 bc	1.17 def	0.35 def	0.51 cde	0.71 e	0.74	0.09
Kiowa	0.32 de	1.95 c-f	0.43 def	0.00	0.71 e	0.68	0.06
Trailing							
Newberry		1.21 def	0.26 ef	1.26 cde	0.99 de	0.93	0.00
Siskyou	0.01 e	0.99 ef	0.32 def	0.22 de	0.00 e	0.31	0.00
Black Diamond	<0.01e	1.06 ef	0.00 f	0.01 e	0.22 e	0.26	0.00
ORUS 1793-1		0.72 ef	0.30 def	0.04 e	0.22 e	0.32	0.00
Obsidian		0.88 ef	0.28 ef	0.05 e	0.05 e	0.31	0.00
ORUS 1939-4		0.66 ef	0.06 f	0.34 de	0.02 e	0.27	0.00
Metolius	<0.01e	0.24 f	0.28 ef	0.07 e	0.31 e	0.18	0.00
Marion	0.01 e	0.39 f	0.00 f	0.01 e	0.05 e	0.09	0.00
Primocane-fruiting							
Prime-Jim	0.27 de	0.62 ef	0.48 def	0.64 cde	0.75 e	0.55	0.00
Prime-Jan	0.08 de	0.43 ef	0.30 def	0.26 de	0.67 e	0.35	0.00
Analysis of Variance							
Cultivar	<0.001	<0.001	<0.001	<0.001	<0.001		
Block	0.527	0.59	0.10	0.278	0.027		

Means separation was by the pdiff option in PROC GLM, with a $p < 0.05$

Table 3. First and last freeze dates recorded at the Utah State University Kaysville Research Farm, approx. 130 m from the blackberry plots.

	Freeze Dates		Harvest Dates	
	Last Spring	First Fall	First	Last
2008	10-May	10-Oct	30-Jul	10-Oct
2009	27-Apr	2-Oct	8-Jul	28-Sep
2010	7-May	27-Oct	19-Jul	11-Oct
2011	2-May	26-Oct	20-Jul	9-Oct
2012	28-Apr	7-Oct	6-Jul	5-Oct

winter bud survival, and the trailing types were the lowest yielding cultivars in the study due to lack of winter hardiness. Of the 8 trailing cultivars planted, Newberry was the highest yielding with an average of 0.93 kg/plant. 'Newberry' actually had a higher average yield than two erect cultivars, Navaho and Kiowa. However, it was still much lower than the 'Newberry' yield of 10.5 kg/plant observed in Willamette, OR (Finn et al., 2010).

'Prime-Jim' and 'Prime-Jan' performed similarly to the trailing types with a yield of 0.55 and 0.35 kg/plant, respectively. This is much lower than what was seen by Clark et al. (2005) in Aurora, OR where the average primocane yield over two years for 'Prime-Jim' and 'Prime-Jan' were 14.8 and 14.5 kg/plant, respectively. Clark et al. (2005) reported that primocane yield for both 'Prime-Jim' and 'Prime-Jan' varied greatly by location and in Clarksville, AR the three-year average primocane yield was 0.71 and 2.66 kg/plant, respectively. The low yields reported in this study were likely related to growing season length, as the primocane fruiting types did not reach peak yield before cool fall temperatures slowed production (Table 3).

Table 4. Harvest season as defined by first, last and peak harvests of blackberry cultivars over two years, 2009 and 2011.

	2009			**2011**		
	First	Peak	Last	First	Peak	Last
Semi-erect						
Loch Ness	14-Jul	17-Aug	18-Sep	19-Jul	23-Aug	22-Sep
Hull	23-Jul	10-Aug	23-Sep	28-Jul	23-Aug	16-Sep
Triple Crown	23-Jul	17-Aug	18-Sep	1-Aug	21-Aug	9-Oct
Doyle's Thornless	29-Jul	24-Aug	23-Sep	4-Aug	27-Aug	16-Sep
Chester Thornless	31-Jul	24-Aug	28-Sep	1-Aug	29-Aug	22-Sep
Erect						
Arapaho	8-Jul	21-Jul	1-Sep	19-Jul	1-Aug	6-Sep
Ouachita	16-Jul	5-Aug	3-Sep	26-Jul	11-Aug	13-Sep
Illini Hardy	16-Jul	3-Aug	8-Sep	28-Jul	14-Aug	13-Sep
Kiowa	21-Jul	24-Aug	14-Sep			
Navaho	23-Jul	10-Aug	18-Sep	19-Jul	20-Aug	13-Sep
Apache	25-Jul	24-Aug	18-Sep	4-Aug	21-Aug	2-Oct
Trailing						
Siskyou	8-Jul	21-Jul	7-Aug	19-Jul	24-Jul	4-Aug
Obsidian	8-Jul	16-Jul	22-Aug	19-Jul	24-Jul	1-Aug
Metolius	8-Jul	18-Jul	24-Aug	21-Jul	1-Aug	4-Aug
Black Diamond	8-Jul	21-Jul	22-Aug	21-Jul	28-Jul	28-Jul
Newberry	10-Jul	16-Jul	24-Aug	19-Jul	1-Aug	14-Aug
ORUS 1793-1	10-Jul	25-Jul	27-Aug	28-Jul	27-Aug	22-Sep
ORUS 1939-4	14-Jul	25-Jul	27-Aug	19-Jul	30-Jul	21-Aug
Marion	14-Jul	29-Jul	24-Aug	28-Jul	28-Jul	1-Aug
Primocane-fruiting						
Prime-Jim	7-Aug	14-Sep	28-Sep	24-Jul	2-Oct	9-Oct
Prime-Jan	7-Aug	21-Sep	28-Sep	21-Aug	2-Oct	9-Oct

Cane tipping was used as described by Strik et al. (2012) to synchronize fruiting, but earlier cultivars or season advancing techniques such as high tunnels or row covers would be needed in order for primocane-fruiting types to be a commercially viable option for the U.S. Intermountain West. Strik et al. (2012) found the use of row covers advanced bloom by 14 days and Thompson et al. (2009) found that the use of high tunnels for primocane-fruiting types extended the season into the fall by 3 weeks.

Comprehensive statistical analysis of the harvest season was difficult due to early freeze damage in some years. Additionally, due to winter injury, some cultivars did not fruit in specific years. Table 3 shows first and last freeze dates as well as first and last harvest for each year. Although a comprehensive statistical analysis of all years is not possible, discussion of years where winter injury was minimal and early freezing did not occur gives a general idea of harvest season. Table 4 shows the first, peak, and last harvest dates for two years: 2009 and 2011. Both years were selected for high winter survival rates (Table 1). The earliest fall freeze occurred in 2009, and the latest was in 2011 (Table 3).

Fruit Size. Fruit size varied among cultivars. The erect type 'Kiowa', known for its large fruit size, had the largest average fruit

Table 5. Blackberry fruit size (g/fruit) over 5 years (2008-2012). Values are a weighted average based on weekly measurements of average fruit size weighted for weekly production.

Cultivar	2008	2009	2010	2011	2012	Mean
Semi-erect						
Triple Crown	5.20 abc	4.29 bcd	6.21 a	6.63 a	5.56 b	5.58
Hull	3.08 d	3.49 d-g	4.13 cd	5.17 bcd	4.27 cde	4.03
Doyle's Thornless	3.52 bcd	2.76 fgh	3.02 de	3.46 fg	3.25 def	3.20
Loch Ness	2.03 d	3.22 efg	2.96 de	3.91 efg	3.50 c-f	3.12
Chester Thornless	2.41d	2.15 h	2.83 e	3.32 g	3.22 def	2.79
Erect						
Kiowa	5.27 ab	5.96 a	5.65 ab		8.79 a	6.42
Apache	4.07 a-d	4.27 bcd	5.73 ab	6.77 a	4.98 bc	5.17
Ouachita	1.57 d	4.92 b	4.49 bc	5.87 ab	4.47 bcd	4.26
Arapaho	3.18 cd	3.73 c-g	4.07 cde	5.41 bc	4.05 cde	4.07
Illini Hardy	2.48 d	2.73 gh	3.31 cde	3.72 fg	2.65 f	2.98
Navaho	2.98 d	2.9 fgh	2.77 e	3.54 fg	2.42 f	2.92
Trailing						
ORUS 1793-1		4.89 b	3.90 cde	4.40 c-g	5.12 bc	4.58
Siskyou	6.40 a	4.10 b-e	3.60 cde	3.90 efg		4.50
Newberry		4.71 bc	3.89 cde	4.07 d-g	4.38 bcd	4.26
Obsidian		4.72 bc	4.03 cde	4.80 b-f	2.80 ef	4.09
Metolius		3.74 c-g	4.17 cd	4.50 c-g	3.30 def	3.93
Black Diamond		3.82 c-f		3.70 fg	3.12 def	3.55
ORUS 1939-4		3.95 b-f	1.80 e	3.97 d-g	3.40 def	3.28
Marion	3.27 bcd	3.05 fgh		3.30 g	3.30 def	3.23
Primocane						
Prime-Jim	4.11 a-d	3.29 d-g	3.99 cde	4.95 b-e	5.08 bc	4.29
Prime-Jan	3.55 a-d	4.00 b-f	3.93 cde	4.70 c-f	4.91 bc	4.22
Analysis of Variance						
Cultivar	0.037	<0.001	<0.001	<0.001	<0.001	
Block	0.020	0.683	0.103	0.004	0.090	

Means separation was by the pdiff option in PROC GLM, with a $p < 0.05$

size (6.42 g/fruit) of all cultivars in the trial (Table 5). This fruit size is smaller than that reported in Arkansas (average 9.4 g/fruit across locations) (Moore and Clark, 1996). However, 'Kiowa' tended to have the lowest total yields of the semi-erect and erect types. 'Triple Crown' had the second largest fruit size, 5.58 g/fruit, which was less than the 7.6 g fruit size previously reported by Strang et al. (2003) and Galletta et al. (1998b). 'Illini Hardy', 'Navaho', and 'Chester Thornless' tended to have the smallest fruit of any cultivars in the study, averaging less than 3 g/ fruit.

Conclusion

Harsh winter conditions in the U.S. Intermountain West, including severe drops in temperature without adequate acclimating conditions, as well as late spring and early fall freezes, limit the blackberry cultivars that can reliably produce adequate yields. Semi-erect cultivars Triple Crown, Doyle's Thornless, and Hull had the highest average yield of the 19 cultivars and 2 numbered selections tested. The highest yielding erect cultivar Illini Hardy, had lower yields than all but one semi-erect cultivar, Loch Ness. Trailing type blackberries have particularly low winter survival and overall produced the lowest yields of the trial. None of the trailing cultivars included in the study had a reliability index > 0. The two primocane fruiting cultivars tested, Prime-Jim and Prime-Jan, did not have adequate season length to reach full production before a killing freeze occurred. Further research is needed to determine whether high tunnel protection or advancing growth in the spring with high tunnels or row covers could lengthen the growing season sufficiently to make the use of primocane-fruiting cultivars economically viable in the U.S. Intermountain West.

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