Journal of the American Pomological Society 70(2): 82-91 2016

Time Required for Classifying Rootstock Vigor in Multi-location Rootstock Trials

R.P. Marini[1], W.R. Autio, B. Black, J. Cline, W.P. Cowgill, Jr., R.M. Crassweller, C. Hampson, M.M. Kushad, R. Moran, M. Parker, R.L. Perry, G.L.Reighard, T. Robinson, D. Wolfe

Additional index words: tree size, NC-140, dwarf rootstocks

Abstract

Data from two multi-location NC-140 dwarf apple rootstock trials were used to determine the number of years required to detect significant differences between rootstocks based on trunk cross-sectional area (TCA) to place them in appropriate vigor classes. The 1994 trial consisted of 18 rootstocks at 19 locations and the 2003 trial consisted of 23 rootstocks at 11 locations. Data for each location were analyzed separately because a repeated measures analysis indicated a significant three-way interaction for location x rootstock x year. As part of the repeated measures analysis for each location, all rootstocks were compared to each other within each year. In general an additional year was required to detect significant differences in the 2004 trial compared to the 1994 trial, possibly due to differences in scion cultivar or the number of replications. At most locations, extremely vigorous rootstocks, such as PiAu 56-83, and low-vigor rootstocks, such as M.27, were statistically different from the standard rootstocks (M.26 and M.9 NAKBT337) four years after planting. Detecting statistical differences between rootstocks within the range represented by M.9 NAKBT337 and M.26, required six or seven years at most locations. At most locations rootstocks with similar vigor, such as M.9 NAKBT337, G.935 and G.16 were not significantly different after 10 years. Most cooperators in future multi-location rootstock trials should be able to properly classify rootstock vigor after six or seven years.

Introduction

Pomologists have conducted apple rootstock evaluations for nearly a century. A number of important characteristics are typically evaluated in these trials, but tree size is one of the most important because it defines tree spacing. Mismatching rootstock with scion vigor, soil type, and tree spacing, can compromise orchard profitability. Planting trees too closely may lead to crowding, extensive within canopy shading, root competition, excessive pruning and poor fruit quality. When spaced too widely, trees slowly fill their spaces, leading to low yields. Canopy size is difficult to measure, but is linearly related to trunk cross-sectional area (TCA) which is easy and inexpensive to measure (Westwood and Roberts, 1970). The linear relationship between TCA and above-ground fresh mass was verified for several scion-rootstock combinations for mature apple trees (Barden and Marini, 2001). Therefore, TCA is commonly used to classify rootstock vigor.

Some early rootstock trials, mostly with vigorous rootstocks, were continued for 15 to 35 years (Preston, 1958; Preston, 1966). In those trials, the relative ranking of rootstocks based on trunk size changed after 10 and again after 15 years, but not thereafter. Determining real differences among rootstocks was difficult because statistical analyses or multiple comparisons were not performed. In 1976 the NC-140 regional project was established to expose rootstocks to varying biotic and abiotic conditions in uniform multi-location trials so as to evaluate those rootstocks rapidly. The NC-140 technical committee initially decided that 10 years should be adequate to evaluate rootstocks (personal communication, D.C. Ferree) and

[1] Corresponding author: Department of Plant Science, The Pennsylvania State University, University Park, PA 16802 (rpm12@psu.edu)

results from numerous trials have supported that decision. However, over the years NC-140 trials have evolved. In the first large trial, referred to as the "1980-81 Trial", nine rootstocks were tested at 27 locations and the vigor of the rootstocks ranged from very vigorous (MAC.24) to very dwarfing (M.27 EMLA) (NC-140, 1987). In recent trials the number of locations has sometimes declined to fewer than 12 (Autio et al., 2013; Marini et al., 2014) and attempts were made to include only dwarfing or semi-dwarfing rootstocks in a trial. Therefore, the pooled variance for a given trial should be less than in earlier trials, making it easier to detect differences of similar magnitude. However, since the magnitude of differences and the total degrees of freedom should also be less than in earlier trials, it may not be easier to detect statistical differences between rootstocks than in earlier trials.

Multi-location rootstock trials are expensive. In 1993 NC-140 cooperators estimated the cost of maintaining a 10-year 20-location rootstock trial with 20 rootstocks and 10 single-tree replications per rootstock, at about one million dollars (personal communication, B. Barritt). Due to the high cost associated with long-term field experiments, the desire to quickly commercialize new highly productive disease-resistant rootstocks, recent changes in NC-140 protocols, and desire to conduct future rootstock trials more efficiently, this study was undertaken to estimate the number of years required to determine the size class of a rootstock in multi-location trials.

Materials and Methods

Data from two NC-140 dwarf rootstock trials were used for this study. The cooperators who provided data for this study are listed in alphabetical order in Table 1. Because 10-year summaries of the 1994 (Marini et al., 2006) and the 2003 (Marini et al. 2014) trials were published and methods were reported in detail, methods will be reported briefly in this paper.

1994 dwarf rootstock trial. 'Gala' trees budded to 18 dwarfing rootstocks were planted in a randomized complete block design with 10 single-tree replications, at 19 locations. Data for only 16 locations were used in the current study to avoid locations with high tree mortality and only the 13 rootstocks that were planted at all 16 locations were in-

Table 1. Location and cooperators in the 1994 and 2003 Dwarf Rootstock Trials.

Location	Cooperator	Planting Location
British Columbia	Cheryl Hampson, Frank Kappel	Summerland, Canada
Iowa	Paul A. Domoto	Ames, IA
Illinois	Mosbah M. Kushad	Urbana, IL
Kentucky	Dwight Wolfe	Princeton, KY
Maine	Renae Moran	Monmouth, ME
MA	Wesley R. Autio	Belchertown, MA
Michigan	Ronald L. Perry	Clarksville, MI
North Carolina	Michael Parker	Fletcher, NC
New Jersey	Winfred P. Cowgill, Jr.	Pittstown, NJ
New York	Terence Robinson	Geneva, NY
Ontario	John Cline	Simcoe, Canada
Pennsylvania	Robert Crassweller	Rock Springs, PA
South Carolina	Gregory I. Reighard	Clemson, SC
Tennessee	Charles A. Mullins	Crossville, TN
Utah	Brent Black	Kaysville, UT
Virginia	John A. Barden, Richard Marini	Blacksburg, VA
Wisconsin	Matt Stasiak, Teryl Roper	Sturgeon Bay, WI

cluded. Each fall, for 10 years, the TCA was determined for each tree.

2003 dwarf rootstock trial. 'Golden Delicious' trees budded to 23 dwarfing rootstocks were planted in eight locations. The rootstocks considered for the present study were limited to a core group of 11 rootstocks that were planted at all locations. At each location trees were planted in a generalized randomized complete block design with two trees per rootstock randomized within each of four blocks. Each fall for 10 years the TCA was determined for each tree. Each winter the collaborators (Table 1) submitted data to the lead author for summarization.

Statistical analyses. Each data set containing all years and locations was initially subjected to an analysis of variance with SAS's Mixed Procedure, where block was designated as a random effect (Littell et al., 2006). The three-way interaction of location x rootstock x year was significant, so data for each location were analyzed as a repeated measures analysis. Information criteria were used to select the appropriate covariance model for each location. For all locations the rootstock x year^2 term was significant, indicating that TCA increased quadratically over time. To evaluate interaction means, the Slicediff Option in the Lsmeans statement of the Glimmix Procedure was used to request all pairwise comparisons within a given year at the 5% level of probability. To summarize these data, Tables 2 and 3 contain the number of years required for a pair of Lsmeans to differ at the 5% level. Since there are 78 possible pair-wise comparisons for the 13 rootstocks, comparisons were limited to only 10 comparisons involving M.26, M.27, B.9, M.9 Pajam1 and M.9 EMLA for

Table 2. Number of years required to detect differences (P=0.05) between various pairs of rootstocks at 16 locations for the NC-140 1994 dwarf rootstock trial.

Comparison	BC	IA	IL	MA	ME	MI	NC	NJ
M.26 vs. M.27 [z]	6	4	4	4	4	3	3	2
M.26 vs. B.9	>10	4	4	4	5	4	7	3
M.26 vs. T.337	7	4	6	4	4	4	5	3
M.26 vs. M.9	7	5	6	4	4	6	6	3
M.26 vs. Pajam1	9	4	4	5	4	6	6	4
M.9 vs. M.27	10	4	5	3	4	3	4	3
M.9 vs. B.9	>10	5	5	6	5	4	8	5
M.9 vs. T.337	>10	3	>10	>10	7	7	>10	>10
M.9 vs. Pajam1	>10	>10	>10	>10	>10	>10	8	10
T.337 vs. M.27	10	4	4	3	4	4	4	3
Comparison	**NY**	**ONT**	**PA**	**SC**	**TN**	**UT**	**VA**	**WI**
M.26 vs. M.27	2	4	3	3	5	3	3	4
M.26 vs. B.9	5	5	5	3	5	4	3	5
M.26 vs. T.337	4	4	5	4	5	9	3	5
M.26 vs. M.9	5	6	4	6	5	7	4	6
M.26 vs. Pajam1	6	6	6	9	5	8	5	6
M.9 vs. M.27	3	4	6	3	7	3	3	4
M.9 vs. B.9	7	5	5	4	>10	4	6	7
M.9 vs. T.337	7	5	>10	9	7	>10	>10	8
M.9 vs. Pajam1	>10	10	6	>10	>10	>10	>10	10
T.337 vs. M.27	3	5	5	4	7	3	4	5

[z] Rootstock abbreviations: B.9 = Budagovsky 9, M.27 = M.27 EMLA, M.26 = M.26 EMLA, Pajam1 = M.9 Pajam1, Pajam2 = M.9 Pajam2, T.337 = M.9 NAKBT337.

the 1994 trial. For the 2003 trial 18 comparisons involving M.26, M.9 NAKBT337, M.9 Pajam2, G.41, G.935, G.16, and PiAu 56-83 were evaluated. Sometimes two rootstocks differed in one year, but did not differ for the following one or two years. In those cases, the number of years required for a permanent difference was recorded.

Results and Discussion

Figure 1 shows TCA increase over time at six representative locations for the 1994 trial. In general, TCA increased nearly linearly over time for the less vigorous rootstocks, but TCA increased at an increasing rate for the more vigorous rootstocks. For the less vigorous locations, such as BC, fi-

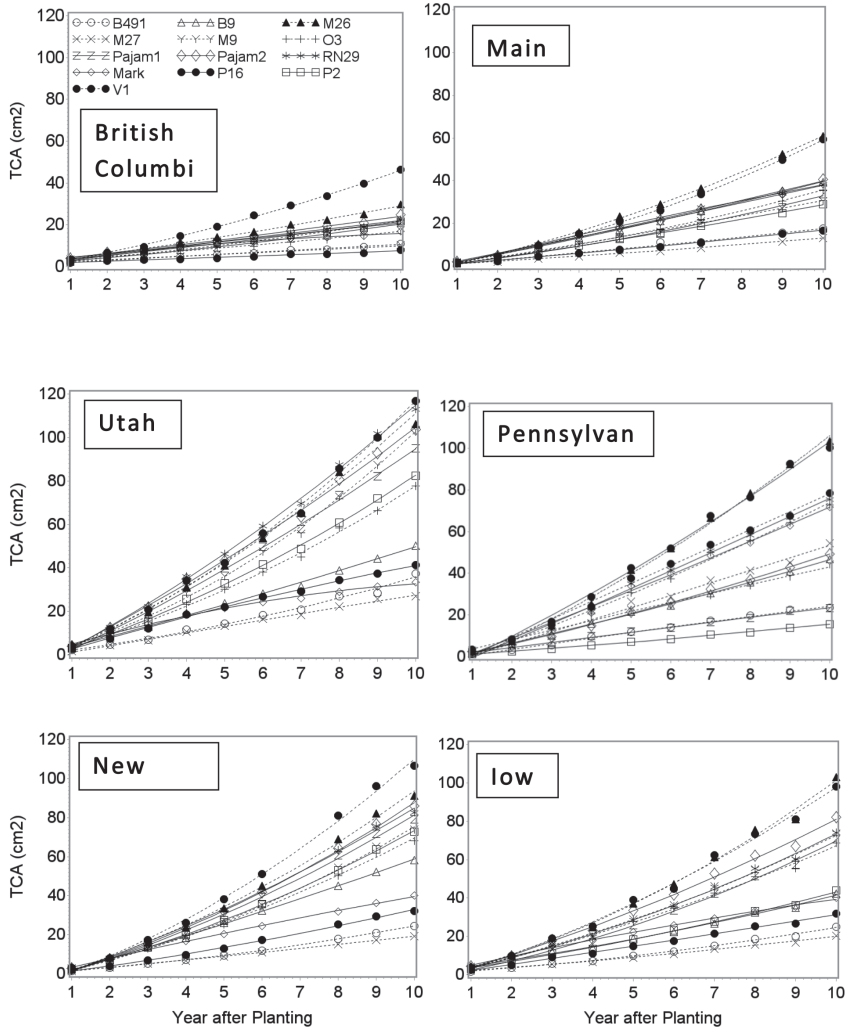


Figure 1. Trunck cross-sectional area for 13 rootstocks at six locations measured over 10 growing seasons for the NC-140 1994 dwarf rootstock trial. Rootstock abbreviations: B491 = Budagovsky 491, B9 = Budagovsky 9, M26 = Malling 26 EMLA, M27 = Malling 27 EMLA, M9 = Malling 9 EMLA, O3 = Ottowa 3, Pajam1 = Malling 9 Pajam 1, Pajam2 = Malling 9 Pajam2, RN29 = Malling 9 Nic29, P16 = Polish 16, p2 = Polish2, V1 = Vineland 1.

nal TCA ranged from 8 to 46 cm^2, whereas at the more vigorous locations, such as UT, TCA ranged from 20 to 115 cm^2. TCA generally separated into three or four vigor groups over time. For example, at ME M.26 and V.1 separated from the other rootstocks by year five (Table 2) and TCA increased faster than the other rootstocks for the remainder of the trial. The group of least vigorous rootstocks included M.27, P.16 and B.469 and these rootstocks started to separate from the others by the fourth year (Table 2). The other eight rootstocks were intermediate in vigor and TCA increased nearly linearly for the entire study. In UT, rootstocks also separated into three fairly distinct groups, starting in the fourth year (Table 2). The most vigorous group included M.26, V.1, M.9 RN29, M.9 Pajam1, M.9 Pajam2. M.9 EMLA; P.2 and O.3 were moderately vigorous; and the other five rootstocks were least vigorous (Fig. 1). Rootstocks in PA separated into four fairly distinct groups after four or five years (Table 2). In IA, vigor groups started to become apparent after five years (Table 2) and there were three groups of rootstocks (Fig. 1). M.9 Pajam2 was intermediate between the two most vigorous groups and there was a fairly large range of vigor among the less vigorous rootstocks. In NY, V.1 was most vigorous and started to separate from the second most vigorous rootstock, M.26, after four years (Table 1). By the tenth year a group of eight rootstocks with intermediate vigor had TCAs ranging from 41.3 to 31.0 cm^2 included M.26, Pajam2, RN29, Pajam1, P.2, M.9, and O.3, respectively, and formed a continuum of vigor that separated over time (Fig. 1). By the eighth year B.9 fell between the moderately vigorous and the less vigorous groups. After 10 years the TCA of the least vigorous group ranged from 31.0 to 9.7 cm^2 and included Mark, P.16, B.491 and M.27.

Most apple growers are interested in dwarfing rootstocks with maximum vigor similar to M.26 and minimum vigor similar to B.9 and the most commonly planted rootstock in North America, M.9 NAKBT337. M.27 is considered too dwarfing for most commercial situations. Table 2 contains the number of years required to detect significant differences between dwarfing rootstocks that are commercially available. Rootstocks tended to separate fastest in NJ, VA, and SC, whereas separation was most delayed in BC (Table 2). The difference between M.26 and M.27 was significant after just two years in NJ and NY and after six years in BC, whereas other locations were intermediate. Three to five years was required to separate M.26 and B.9 at most locations, but the difference was not significant in BC after 10 years (Table 2). Significant differences between M.26 and the three M.9 clones required three to six years at most locations. Significant differences between M.9 EMLA and M.27 or B.9 required six years at most locations, whereas the difference between M.9 EMLA and M.9 NAKBT337 was not significant after 10 years at half of the 16 locations. The difference between M.9 EMLA and M.9 Pajam1 was significant at only 19% of the locations after 10 years. The difference between M.9 NAKBT337 and M.27 was significant after three to five years at most locations.

For the 2003 trial (Fig. 2), rootstocks did not separate as well as in the 1994 trial (Fig. 1). For the 2003 trial the range of TCA was greater in UT, PA and IA than in BC, ME or NY (Fig. 2). Based on TCA, PiAu 56-83 and PiAu 51-4 separated from the other rootstocks after the third year at all locations except ME, where clear separation was evident after five years. At most locations there was no clear grouping of the other nine rootstocks. In BC, UT, NY and IA, B.9 appeared to be the least vigorous rootstock after four or five years, but the difference between B.9 and G.41 was smaller in ME and PA. In BC and ME the TCA of rootstocks with vigor between B.9 and PiAu rootstocks tended to increase at a similar rate and did not clearly separate. At the other locations, M.26, JTEH and M.9 Pajam2 tended to gradually separate from G41, G.935 and M.9 NAKBT337 was intermediate.

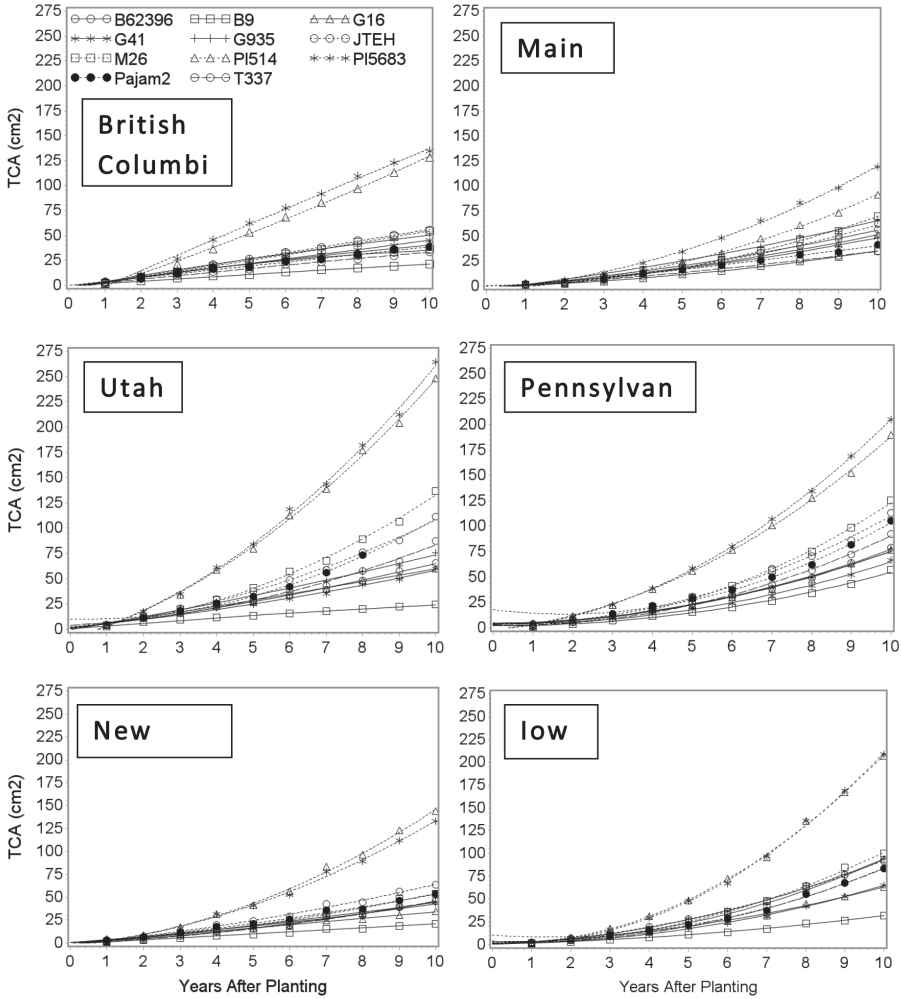


Figure 2. Trunck cross-sectional area for 11 rootstocks at six locations measured over 10 growing seasons for the NC-140 2003 dwarf rootstock trial. Rootstock abbreviations: B62396 = Budagovsky 62396, B9 = Budagovsky 9, G16 = Geneva 16, G41 =Geneva 41, G935 = Geneva 935, JTEH = J-TE-H, M26 = Malling 26 EMLA, P1514 = Polish 1514, P15683 = Polish 15683, Pajam 2 = Malling 9 Pajam2, T337 = Malling 9 NAKBT337.

For the 2003 trial significant differences occurred earliest in PA, UT and WI, whereas more than 10 years were needed to separate at least three pairs of rootstocks in BC, KY and NY (Table 3). PiAu 56-83 was the most vigorous rootstock in this trial and is likely too vigorous for most commercial situations. PiAu 56-83 differed from B.9, M.9 NAKBT337 and M.26 after four years at all locations (Table 3). At most locations significant differences between B.9 and all the other rootstocks required three to seven years. At most locations, six or more years were required for M.26 to differ significantly from the other rootstocks except the PiAu rootstocks. Seven or more years were

Table 3. Number of years required to detect differences (P=0.05) between various pairs of rootstocks at eight locations for the NC-140 2003 dwarf rootstock trial.

Comparison	BC	IA	KY	ME	NY	PA	UT	WI
B.9 vs. G.41 [z]	5	7	5	6	7	>10	5	8
B.9 vs. G.935	3	4	4	4	4	7	3	5
B.9 vs. G.16	5	6	5	6	7	7	4	7
B.9 vs. M.26	4	5	4	6	4	5	4	4
B.9 vs. M.9 Pajam 2	6	5	3	>10	4	5	4	4
B.9 vs. PiAu 56-83	3	4	2	3	3	3	3	3
B.9 vs. M.9 T337	6	6	4	>10	7	6	4	7
M.26 vs. G.41	10	6	7	8	10	5	5	5
M.26 vs. G.935	>10	>10	8	4	9	6	6	6
M.26 vs. G.16	9	7	>10	8	8	6	5	5
M.26 vs. M.9 Pajam 2	7	10	8	7	>10	8	6	7
M.26 vs. PiAu 56-83	3	4	4	4	4	4	3	4
M.26 vs. M.9 T337	6	7	10	6	>10	7	6	5
M.9 T337 vs.G.41	8	8	>10	8	>10	7	8	7
M.9 T337 vs. G.935	5	7	>10	4	>10	9	>10	>10
M.9 T337 vs. G.16	7	9	>10	7	10	10	9	9
M.9 T337 vs. M.9 Pajam 2	>10	9	7	>10	>10	10	8	6
M.9 T337 vs. PiAu 56-83	3	4	3	4	4	3	3	3

[z] Rootstock code: B.9 = Budagovsky 9, G.16 = Geneva 16, G.41 = Geneva 41, G.935 = Geneva 935, M.26 = M.26 EMLA, M.9 T337 = M.9 NAKBT337.

required for M.9 NAKBT337 to differ from most rootstocks except for PiAu 56-83. G.41 and G.935 will likely become important rootstocks due to high productivity and disease resistance, and it is important to place them into the proper size class. At most locations G.41 differed from M.26 and B.9 after five to seven years. At all locations seven or more years were required for G.41 to differ from M.9 NAKBT337 (Table 3). At two of the eight locations G.41 did not differ from M.9 NAKBT337 after 10 years. After four years G.935 was significantly larger than B.9 at six of the 8 locations. The time required to separate G.935 and M.9NAKBT337 was only four years in ME, but required more than 10 years in KY, NY, UT and WI. The time required for G.935 and M.26 to significantly differ was highly variable requiring four years in ME, six years in PA, UT and WI, eight years in KY, nine years in NY, and more than 10 years in BC and IA (Table 3).

We are unaware of other reports of the time required to detect differences among rootstocks. Preston (1958) compared 22 rootstocks over a 35 year period and reported changes in the relative order of rootstocks, with respect to trunk size, at different periods during the trial. The relative order changed from year five to year 10 and from year 10 to year 15, but there was no further change after 15 years. In another trial Preston (1966) compared 27 rootstocks over a 15 year period but presented data for only the final year of the trial. Mouat and McKenzie (1963) compared vigorous rootstocks over 18 years, but presented data for only the final year of the trial. Barden and Marini (1997 & 1999) used repeated measures ANOVA to compare TCA in two rootstock trials for 18 years and results for TCA varied over time and with the scion cultivar. After four years TCA of 'Goldspur' on M.26 was significantly greater than on M.9/MM.106 interstem trees. However, the difference was not permanent; after nine and 14 years the two rootstocks did not differ, but after 18 years trees on M.26 had significantly greater TCA than trees on

M.9/MM.106. After four years 'Smoothee' trees on M.9, M.26, M.9/MM.106 and M.9/MM.111 did not differ. TCA for trees on M.9 differed from M.9/MM111 at nine years, but not thereafter. Trees on M.9 and M.9/MM.106 did not differ for the first 14 years, but they were significantly different after 18 years (Barden and Marini, 1997). For 'Redchief Delicious' trees the relative order of TCA changed slightly from the fourth to the ninth year, but did not change thereafter and statistical differences did not change after nine years (Barden and Marini, 1999). After four years TCA for 'Red Prince Delicious'

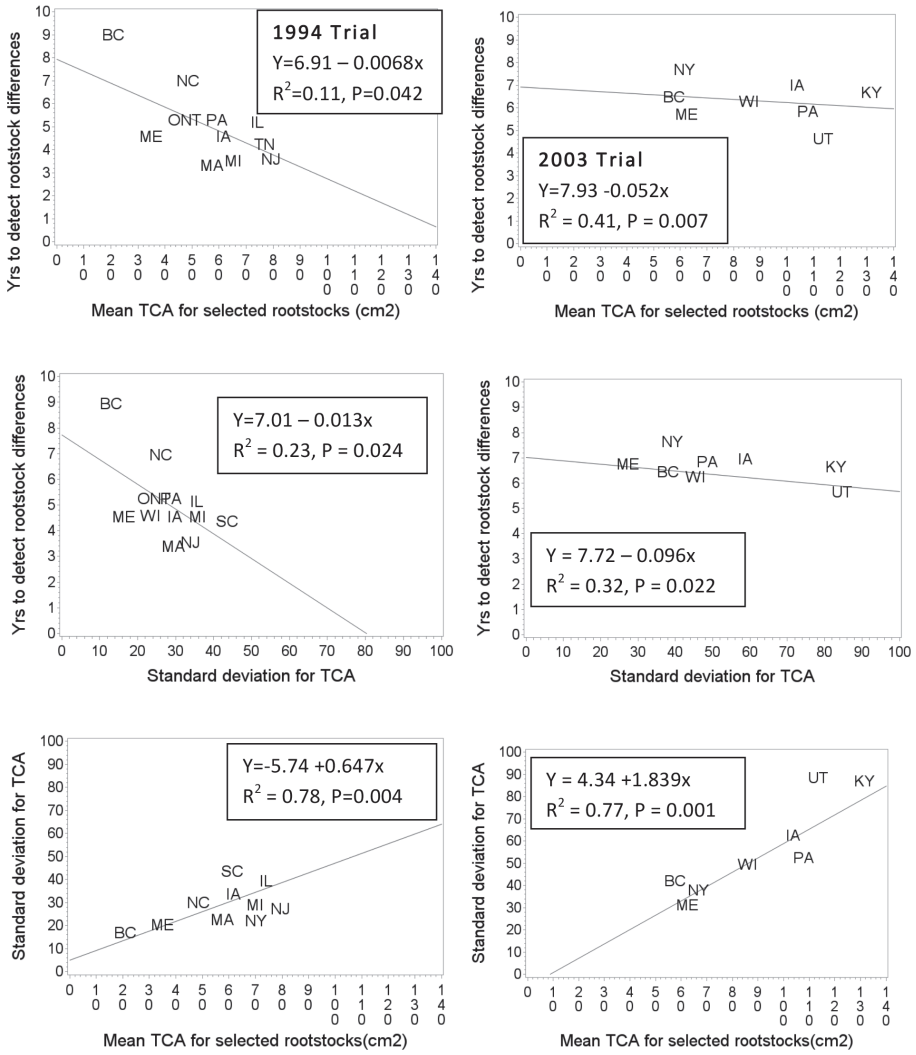


Figure 3. The relationships between mean number of years to detect differences between pairs of selected rootstocks and mean TCA and standard deviations of those rootstocks. Values are means of all pairwise comparisons of M.27, B.9, M.9 NAKBT337, M.9 EMLA, M.9 Pajam1 and M.26 for the 1994 trial (left side) and B.9, G.41, G.935, G.16, M.9 NAKBT337, M.9 Pajam2, M.26, and PiAu 56-83 for the 2003 trial (right side).

on M.26 was larger than TCA for trees on M.9, M.9/MM.106 and M.9/MM.111, but the three smaller rootstocks did not differ from each other. TCA for trees on M.9 and M.9/MM.106 did not differ after nine or 14 years, but they differed from M.26 and M.9/MM.111, which differed from each other. After 18 years all four rootstocks differed from each other. Ferree and Schmid (1997) compared the change in TCA for 'Mutsu' trees on MAC.9 and two interstems for years one to four and four to eight. The relative order of TCA increase was the same for both periods and for the final TCA after nine years. Reighard et al. (2004) suggested that peach rootstock trials longer than six years may not be necessary to classify seedling rootstocks by yield.

When testing the hypothesis that TCA of two rootstocks were equal in this study, the difference required to be significant at the 5% level varied with location and rootstocks being compared (data not shown). Additionally, the magnitude of the difference required to be significant depended on the standard error and standard errors also varied with location and rootstocks being compared. In general, smallest differences occurred in BC and ME, whereas largest differences were observed in KY. In ME, the differences ranged from 12.8 cm^2 (M.26 vs. G.41) to 6.8 cm^2 (B.9 vs. M.9 Pajam2). In BC, the difference in TCA varied from 17.3 cm^2 (M.9 NAKBT337 vs. PiAu 56-83) to 9.1 cm^2 (B.9 vs. G.935). However, in KY the differences ranged from 30.5 cm^2 (B.9 vs. G.16) to 14.7 cm^2 (B.9 vs. M.9 Pajam2).

For each location, the mean TCA and standard deviation was calculated for the six rootstocks in the 1994 trial and the eight rootstocks in the 2003 trial that were used for pair-wise comparisons. To determine if the number of years to detect significant differences between pairs of rootstocks was related to the magnitude of the mean TCA and the standard deviation, linear regression was performed, where the mean number of years to detect a significant difference between a pair of rootstocks was the response variable, and either the mean TCA or the standard deviation of the TCA was the regressor variable (Fig. 3). Years to detect significant differences were linearly related in a negative manner to mean TCA and standard deviation. All coefficients of determination were significant ($P < 0.042$), they were low for both years (< 0.42). Standard deviation was positively related to mean TCA. For the 1994 trial, the mean TCA (cm^2) ranged from 20.95 in BC to 79.32 in NJ and the mean number of years to detect a difference in TCA ranged from 3.2 in NJ to 8.6 in BC. The standard deviation ranged from 13.0 in BC to 39.8 in SC (Fig. 3). For the 2003 trial mean number of years to detect a difference in TCA ranged from 5.3 in UT to 7.3 in NY, the mean TCA ranged from 57.7 cm^2 in BC to 135.6 cm^2 in KY, and the standard deviation ranged from 27.3 cm^2 in ME to 84.6 cm^2 in UT (Fig. 3). Locations with high vigor conditions had high variability, but high-vigor locations may be able to classify rootstock vigor in just three or four years, whereas eight years may be required at low-vigor locations.

The number of years required to properly place rootstocks into vigor categories depended on the location and the trial. In general, an additional year was required to detect significant differences between M.9 NAKBT337 and M.26 in the 2003 trial compared to the 1994 trial, possibly due to differences in scion cultivar, the range in vigor of the rootstocks or experimental designs. In future experiments, researchers at most locations should be able to identify rootstocks outside the desired vigor range (vigor similar to B.9 to M.26), such as PiAu 56-83 and M.27, after just four years. Detecting statistical differences between rootstocks within the desirable vigor range, such as M.9 NAKBT337 and M.26, will require six or seven years at most locations. With the number of replications typically available for multi-location trials it is probably unrealistic to detect differences between rootstocks with similar vigor such as M.9 NAKBT337,

G.935 and G.16. Therefore, cooperators in multi-location rootstock trials should be able to properly classify rootstock vigor after six or seven years.

Acknowledgements

The authors wish to acknowledge the International Fruit Tree Association for the significant support provided for the establishment and coordination of these trials. The study reported here was supported by the Multi-State project NC-140, through the following state agricultural experiment stations: Iowa Agricultural Experiment Station, Illinois Agricultural Experiment Station, Kentucky Agricultural Experiment Station, Maine Agricultural Experiment Station,

Massachusetts Agricultural Experiment Station, Michigan Agricultural Experiment Station, North Carolina Agricultural Experiment Station, New Jersey Agricultural Experiment Station, New York Agricultural experiment Station, Pennsylvania Agricultural Experiment station, South Carolina Agricultural Experiment station, Tennessee Agricultural Experiment Station, Utah Agricultural experiment station (paper 8889), Virginia Agricultural experiment station, and Wisconsin agricultural Experiment Station. Financial support was also provided by the State Horticultural Association of Pennsylvania.

Literature Cited

Autio, A., T. Robinson, D. Archbold, W. Cowgill, C. Hampson, R.P. Quezada, and D. Wolfe. 2013. 'Gala' apple trees on Supporter 4, P.14, and different strains of B.9, M.9 and M.26 rootstocks: final 10-year report on the 2002 NC-140 apple rootstock trial. J. Amer. Pomol. Soc. 67:62-71.

Barden, J.A. and R.P. Marini. 1997. Growth and fruiting of a spur-type and a standard strain of 'Golden Delicious' on several rootstocks over eighteen years. Fruit Var. J. 51:165-175.

Barden, J.A. and R.P. Marini. 1999. Rootstock effects on growth and fruiting of a spur-type and standard strain of 'Delicious' over eighteen years. Fruit Var. J. 53:115-125.

Barden, J.A. and R.P. Marini. 2001. Comparison of methods to express growth, size, and productivity of apple trees. J. Amer. Pomol. Soc. 55:251-256.

Ferree, D.C. and J.C. Schmid. 1997. Performance of 'Mutsu' on MAC.9 and M.9 interstems over nine years. Fruit Var. J. 51:122-124.

Little, R.C., G.A. Milliken, W.W. Stoup, R.D. Wolfinger and O. Schabenberger. 2006. SAS® for mixed models, 2nd ed. Cary, NC: SAS Institute, Inc.

Marini, R.P., J.L. Anderson, W.R. Autio, B.H. Barritt, J. Cline, W.P. Cowgill, Jr., R.C. Crassweller, R.M. Garner, A. Gauss, R. Godin, G.M. Greene, C. Hampson, P. Hirst, M.M. Kushad, E. Mielke, R. Moran, C.A. Mullins, M. Parker, R.L. Perry, J.P. Privé, G.L. Reighard, T. Robinson, C.R. Rom, T. Roper, J.R. Schupp, E. Stover, and R. Unrath. 2006. Performance of 'Gala' apple trees on 18 dwarfing rootstocks: ten-year summary of the 1994 NC-140 Rootstock Trial. J. Amer. Pomol. Soc. 60: 69 – 83.

Marini, R.P., B.H. Barritt, J.A. Barden, J. Cline, R.L. Granger, M.M. Kushad, M. Parker, R.L. Perry, T. Robinson, S. Khanizadeh, and C.R. Unrath. 2001. Performance of 'Gala' apple on eight dwarf rootstocks: ten-year summary of the 1990 NC-140 rootstock trial. J. Amer. Pomol. Soc. 55:197-204.

Marini, R.P., B. Black, R.M. Crassweller, P.A. Domoto, C. Hampson, R. Moran, T. Robinson, M. Stasiak, and D. Wolfe. 2014. Performance of 'Golden Delicious' apple on 23 rootstocks at eight locations: a ten-year summary of the 2003 NC-140 dwarf rootstock trial. J. Am. Pomol. Soc. 68:54-68.

Mouat, H.M. and D.W. McKenzie. 1963. Apple rootstock trials III. Dougherty on East Malling, Merton and local rootstocks: a final report. New Zealand J. Agric. Res. 6:96-103.

NC-140. 1987. Growth and production of 'Starkspur Supreme Delicious' on 9 rootstocks in the NC-140 cooperative planting. Fruit Var. J. 41:31-39.

Preston, A.P. 1958. Apple rootstock studies: thirty-five years' results with Lane's Prince Albert on clonal rootstocks. J. Hort. Sci. 33:29-38.

Preston, A.P. 1966. Apple rootstock studies: fifteen years' results with Malling-Merton clones. J. Hort. Sci. 41:349-60.

Reighard, G., R. Andersen, J. Anderson, W. Autio, T. Beckman, T. Baker, R. Belding, G. Brown, P. Byers, W. Cowgill, D. Deyton, E. Durner, A. Erb, D. Ferree, A. Gaus, R. Godin, R. Hayden, P. Hirst, S. Kadir, M. Kaps, H. Larsen, T. Lindstrom, N. Miles, F. Morrison, S. Myers, D. Ouellette, C. Rom, W. Shane, B. Taylor, K. Taylor, C. Walsh, and M. Warmund. 2004. Growth and yield of Redhaven peach on 19 rootstocks at 20 North American locations. J. Amer. Pomol. Soc. 58(4):174-202.

Westwood, M.N. and A.N. Roberts. 1970. The relationship between trunk cross-sectional area and weight of apple trees. J. Amer. Soc. Hort. Sci. 95:28-30.