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Rootstock x Site Interaction and Stability Analysis of Apple Rootstocks Across Sites in Two NC-140 Multilocation Apple Rootstock Trials

Richard P. Marini[1]

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Abstract

The NC-140 technical committee performs multisite rootstock trials to quickly expose rootstocks to a wide range of biotic and abiotic stresses. The site x rootstock interaction is almost always significant for every response variable measured in multisite rootstock trials, indicating that rootstock performance varies with site. Stable rootstocks are those that perform similar across sites. The ideal rootstock is one that has high potential and is stable over sites. Data for trunk cross-sectional area (TCA), cumulative yield (CY), cumulative yield efficiency (CYE) and root suckers per tree from the 1994 and the 2003 NC-140 apple rootstock trials were subjected to five stability analyses (Findlay-Wilkinson joint regression, Shukla's stability variance, environmental variance, AMMI variance and Kang's yield-stability statistic) to evaluate the stability of the tested rootstocks. As expected, results varied depending on the trial and the stability statistic being considered. For the 1994 trial, M.26, B.9 and B.491 had above-average stability for all response variables. For the 2003 trial, M.9 NAKBT337 and B.62396 had above average stability for TCA and CY, and G.41 and G.935 had above stability for CYE. M.26 had above average stability for root suckers in both trials because it had fewer than average root suckers at most sites. These results can be useful while making rootstock recommendations for sites not included in these trials.

Since the introduction of the vertical axis tree training system, the North American apple industry has been transitioning to intensive orchard systems that require dwarfing rootstocks. Rootstock performance varies with location, and rootstocks that perform consistently well over a range of environments are desirable. However, it is also important to identify rootstocks that are adapted to certain environments. Clonally propagated apple rootstocks have been evaluated for more than a century (Hatton, 1920), but results from various rootstock trials are difficult to compare due to differences in scion cultivar, tree management, tree spacing, rootstocks being compared, replication and experimental design, and other site-related variables. The NC-140 project was established to quickly evaluate rootstocks growing in different environments. Data from multilocation uniform rootstock trials are typically analyzed with analysis of variance (ANOVA), and total sums of squares are partitioned into three sources: rootstock main effect, environment or site main effect, and the rootstock x site interaction. Means across sites (main effect rootstock means) are adequate indicators of rootstock performance only in the absence of rootstock x site interaction. For nearly every response variable analyzed in every trial, the rootstock x site interaction was significant (Autio et al., 2011; Marini et al., 2006; Marini et al., 2014; NC-140, 1991), but there has been little effort to evaluate the nature of these interactions. One reason that the interactions are significant is because there are many degrees of freedom in the error term, so the test is very powerful and even minor interactions may be significant. When rootstocks are compared within sites, the relative rankings of rootstocks sometimes differ from one site to another; this is known

[1] Department of Plant Science, The Pennsylvania State University, University Park, PA 16802-4200. Email: rpm12@psu.edu.

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as crossover interaction, making it difficult to recommend a rootstock for a given site or geographic region.

Breeders of agronomic crops often perform stability analyses to evaluate the genotype x environment interaction (GEI) (Lin and Binns, 1988). A genotype is considered stable if its performance is relatively constant across varying environments. Several stability analyses have been developed, but no single method adequately explains genotype performance across environments because the nature of the interaction may differ. Therefore, results may depend on the method used to evaluate stability.

Stability methods are based on univariate and multivariate models. The most widely used methods are univariate stability models based on regression and variance estimates. Yates and Cochran (1938) were the first to explore techniques to better understand GEI. The yield of each of six barley genotypes was regressed on the mean yield of all genotypes for each of 12 location-year combinations, referred to as "environments", providing an indication of genotype behavior across changing environments. Plotting the slopes for the yield of each genotype against mean yield averaged over all sites provided a visual partitioning of the GEI. However, this method could be applied to only two genotypes at a time. Finlay and Wilkinson (1963) and Eberhart and Russell (1966) extended this technique, called "joint regression analysis" and stated that genotypes with regression coefficients (slopes) of about 1.0 have average stability over all environments and they perform similarly over a wide range of environments. Genotypes with regression coefficients greater than 1.0 have below- average stability and perform below average in poor environments and perform above average in favorable environments. Genotypes with regression coefficients less than 1.0 have above average stability and are insensitive to environment because they perform similar regardless of environment. Rootstocks with negative slopes would perform above average at poor sites and below average at favorable sites. This technique was used by Olien et al. (1991) to evaluate the stability of rootstocks in the NC-140 1980-81 apple rootstock trial. To my knowledge theirs was the only attempt to evaluate stability of fruit tree rootstocks.

Over the past 60 years new stability analyses have been developed to evaluate GIE. Some of the more commonly used univariate stability parameters include the Finlay and Wilkinson (1963) regression coefficient and Eberhart and Russell (1966) deviation from regression (mean square error). Variance parameters that measure stability can be estimated with Shukla's stability variance model (Shukla, 1972) and the environmental variance model (Sheffé, 1959). Since the most desirable genotypes are often those with high yield and stability, Kang (1993) proposed a rank-sum method to integrate yield and stability into a single index. Kang's yield-stability statistic (YS_i) is a nonparametric stability procedure where both the mean and Shukla's stability variance for a trait are used as selection criteria. The method gives equal weight to the mean and the variance, so genotypes with values greater than the mean YS_i are considered above average in stability. During the past 20 years, the additive main effects multiplicative interaction (AMMI) model (Piepho, 1997) has become widely used to investigate GEI. The AMMI model combines ANOVA for the genotype and environment main effects with principal components analysis (PCA) of GEI and the AMMI stability value can be used to assess genotype stability and may provide more reliable estimates of genotype performance than the mean across sites.

The objective of this study was to better understand the nature of rootstock x site interactions for two NC-140 multilocation apple rootstock trials using several stability analyses. The stability of four important rootstock characteristics [trunk cross-sectional area (TCA), cumulative yield, cumulative yield efficiency, and root suckers] was evaluated using univariate and AMMI models.

Materials and Methods

Data from two NC-140 rootstock trials were used for stability analyses and LSmeans for the interaction of site x rootstock for the four response variables (TCA, cumulative yield, cumulative yield efficiency, and root suckers) were published. The 1994 trial consisted of 'Gala' on 18 rootstocks at 25 sites (Marini et al., 2006). For the 2003 trial, 23 rootstocks were evaluated at eight sites and the scion cultivar was 'Golden Delicious' (Marini et al., 2014). At some sites some rootstocks had poor survival, so only sites and rootstocks with at least 80% tree survival were included in this study. Consequentially, there were 14 rootstocks at 17 sites for the 1994 trial and 11 rootstocks at eight sites for the 2003 trial.

Analysis of variance (ANOVA). Data for each variable were subjected to ANOVA with SAS's Proc Mixed using the model $Y_{ij} = \mu + R_i + S_j + RS_{ij} + B(S)_{ik}$; where Y_{ij} is the response variable of the i^{th} rootstock at the j^{th} site, μ is the overall mean, R is the main effect of rootstock i, S is the main effect of site j, RS is the Rootstock x Site interaction effect, and B is the k^{th} block nested in site j and was specified as a random effect. ANOVA indicated that rootstock, site and the rootstock x site interaction were all significant ($P < 0.0001$) for all response variables in both trials.

Joint-regression analysis. The main effect mean for each site is the average performance of all rootstocks within a site; it is referred to as the "site index" and is a measure of the overall potential of that site for the response variable being considered. The mean value for each response variable, averaged over all blocks within a site, was regressed against the site indexes individually for each rootstock with SAS's Proc GLM. The rootstock means, coefficients of variation (CV), slopes and deviations from regression (Dev-Reg = mean squares deviation from the regression) are presented in Table 1. According to Eberhart and Russell (1966), a regression coefficient (slope) = 1 and variance deviation (Dev-Reg) = 0 indicates average stability. Rootstocks with slopes less than 1.0 have greater than average stability, and rootstocks with slopes greater than 1.0 have less than average stability, relative to the average stability over all rootstocks in the trial.

Stability statistics. Piepho (1999) published SAS code for Proc Mixed to fit several stability models for multilocation experiments with randomized complete blocks at each location. Stability variances were estimated with Shukla's stability variance model and the environmental variance model by fitting models with different covariance structures by including RANDOM statements with different TYPE= options. A mixed model version of the AMMI model also was fit by adding an intercept term (INT) to the first RANDOM statement and the second RANDOM statement requested the first-order factor analytic [TYPE=FA(1)] covariance structure (Piepho, 1999).

Results

1994 trial, TCA. Mean TCA averaged over all sites, estimated from trees surviving to the tenth year of the study, along with the coefficients of variation (CV) are presented in Table 1. Trees on M.26 and V.1 had the largest trunks, whereas trees on M.27, B.491 and P.16 had the smallest trunks (Table 1). The CVs were not related to mean TCAs for rootstocks, but CVs were highest for M.9 NAKBT337, M.9, M.27 and B.491 and lowest for B.9, V.1, O.3 and MARK.

Linear regression models were fit for each rootstock, where the response variable was the mean TCA for a given rootstock average over all 17 sites and the regressor variable was the average TCA averaged over all 14 rootstocks at each site. Slopes, R^2-values and Dev-Reg (deviation from the regression line) are presented in Table 1. According to Finlay and Wilkinson (1963), when rootstock means are regressed on site means, the resulting regression coefficient (slope) is a stability

Table 1. Mean trunk cross-sectional area (TCA) and coefficient of variation (CV), plus five stability parameters for 'Gala' trees on 14 rootstocks averaged over 17 sites in the 1993 NC-140 rootstock trial. *Grand mean=58.6, CV=55.6, LSD=13.43.*

Rootstock	TCA (cm^2)	CV (%)	Slope (b_i)	R^2	Dev-reg	Shukla's Stability variance	Pr>Z	Environment Variance model	AMMI Model	YS_i^z
M.9	66.9	37.6	1.36	0.86	86.0	230.5	0.008	557.0	21.3	2
M.26	90.7	31.7	1.58	0.83	150.5	311.7	0.006	678.8	22.9	7&
M.27	20.0	36.6	0.23	0.31	35.6	27.3	0.107	68.0	1.1	-2
M.9 Nic29	73.3	34.1	1.46	0.96	27.1	210.5	0.009	501.2	21.1	5&
M.9 Pajam 1	68.8	35.0	1.40	0.96	23.7	179.9	0.009	473.7	20.2	3
M.9 Pajam 2	74.1	31.0	1.32	0.95	28.7	171.2	0.011	417.5	19.9	10&
B.9	46.5	23.2	0.52	0.62	47.1	2.5	0.423	132.6	4.6	6&
B.491	28.3	36.6	0.50	0.68	34.6	2.4	0.498	105.6	4.8	0
O.3	65.5	29.2	1.06	0.87	49.6	86.0	0.022	353.5	14.2	5&
V.1	98.5	27.0	1.34	0.74	178.4	309.0	0.005	531.3	20.9	8&
P.2	52.9	31.2	0.85	0.75	69.3	74.2	0.025	251.2	11.2	3
P.16	27.6	35.1	0.50	0.76	22.9	2.9	0.377	103.7	5.7	-1
MARK	40.8	29.3	0.45	0.39	91.6	47.5	0.055	149.4	1.6	0
M.9 NAKBT337	61.8	39.2	1.39	0.92	45.3	221.3	0.008	543.7	21.3	0

[z] Kang's yield-stability statistic (YS_i) for TCA assumes large trunks are preferable. Values followed by & indicate these rootstocks are larger than average and are relatively stable.

parameter. Rootstocks with slopes near 1.0 (O.3) have average stability over all sites and produce large trunks at sites that tend to have large trunks and small trunks at sites that have small trunks. Rootstocks with slopes greater than 1.0 (M.26, V.1, and all five M.9 clones) had below-average stability and the vigor of those rootstocks was influenced by environmental differences. Rootstocks with slopes less than 1.0 (M.27, B.9, B.491, P.16 and MARK) had higher-than-average stability and trunk size for those rootstocks was similar at all sites. To illustrate different rootstock responses to the range of site means, rootstock means were plotted against the site means along with the associated regression lines for three rootstocks with different degrees of stability (Fig. 1). M.27 had above average stability (slope=0.23), O.3 had average stability (slope=1.06) and M.26 had below-average stability (slope=1.58).

The Dev-Reg from regression can also be used as a stability parameter (Eberhart and Russell, 1966). Rootstocks with high Dev-Reg (M.26 and V.1) are considered to have below average stability. Another stability parameter is Shukla's stability variance (Shukla, 1972) and rootstocks with low variances are considered to be stable. A Z-statistic was used to test the null hypothesis that Shukla's stability variance is equal to zero and only the low-vigor rootstocks M.27, B.9, B.491 and MARK had stability variances that did not significantly differ from zero at the 5%

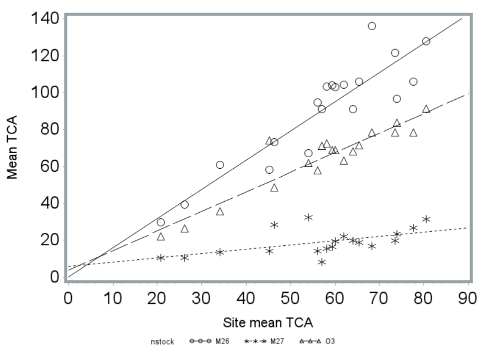

Fig. 1. The relationship between mean trunk cross-sectional area (TCA) for 'Gala' trees on three apple rootstocks at 17 sites vs. site mean TCA averaged across 14 rootstocks at 17 sites. The slope for O.3 (triangle) is 1.06 and indicates average stability; the slope for M.26 (circle) is greater than 1.0, indicating below average stability; and the slope for M.27 (star) is less than 1.0, indicating above average stability.

level (Table 1). Variance estimates produced with the environmental variance and AMMI models were low for M.27, B.9, B.491, P.16 and MARK and these rootstocks would be considered stable for TCA (Table 1). Kang's yield-stability statistic (YS_i) combines rootstock performance with stability. Rootstocks that produce large trees may or may not be considered desirable depending on scion cultivar, tree spacing, training system and site vigor. Assuming large trunks are desirable and giving equal weight to tree size and stability, the most desirable rootstocks included M.26, M.9 NIC29, M.9 Pajam 2, B.9, O.3, and V.1 (Table 1).

Cumulative yield, 1994 trial. In most NC-140 trials, cumulative yield was based on the trees surviving for the duration of the study. However, tree longevity is an important economic consideration. For this study, cumulative yield was based on the number of trees that were planted. Therefore, if a tree died in 1996 after producing only 2.0 kg of fruit, cumulative yield for that tree for the 10-year period was 2.0 kg, so for this study cumulative yield is also a function of tree survival. Trees on V.1, M.9 Nic 29 and M.9 Pajam 2 had the highest cumulative yield and trees on M.27 and B.491 had the lowest yield per planted tree (Table 2). P.16 had the highest CV, V.1 had the lowest CV and CVs for the other 12 rootstocks ranged from 63.4 to 49.6%. Rootstocks with slopes greater than or equal to 1.25 included M.9, M.9 Nic 29, M.9 Pajam 1, M.9 Pajam 2, and V.1 and had lower-than-average stability. The rootstock P.2 had a slope of 0.99 and would be considered to have average stability, whereas M.27, B.9, B.491, and Mark would be considered to have above-average stability. MARK had the highest Dev-Reg, whereas M.27, B.491 and M.9 NAKBT337 had the lowest Dev-Reg. Rootstocks with values for Shukla's stability variance differing significantly from zero included M.26, M.27, B.9, B.491, V.1, P.2, P.16, MARK and M.9 NAKBT3377. The variances from the environmental variance and the AMMI models were lowest for M.27, B.9, B.491, P.2, P.16 and MARK and highest for M.9, M.9 Nic 29, M.9 Pajam 2 and V.1. Considering both cumulative yield and stability, Kang's yield-stability statistic indicated that M.9, M.26, M.9 Nic 29, M.9 Pajam 1, M.9 Pajam 2, O.3 and V.1 were desirable

Table 2. Cumulative yield per planted tree and coefficients of variation (CV), plus five stability parameters for 'Gala' trees on 14 rootstocks averaged over 17 sites in the 1993 NC-140 rootstock trial. When a tree died, it had 0.0 yield for the remainder of the trial. *Grand mean = 177.2, CV = 64.55, LSD=13.8*

Stock	Mean Cum. Yld. (kg/tree)	CV	Slope	R^2	Dev-Reg	Shukla's Stability variance	Pr>Z	Env. Var. model	AMMI	YS_i[z]
M.9	202.9	62.2	1.35	0.92	855.0	692.1	0.053	10130.0	86.7	6&
M.26	218.7	51.3	1.04	0.82	1318.7	755.4	0.048	6889.1	75.6	9&
M.27	55.4	61.4	0.29	0.67	239.6	3826.8	0.009	1100.2	13.3	-9
M.9 NIC29	227.5	52.0	1.33	0.93	730.1	382.6	0.127	9748.1	91.0	14&
M.9 Pajam 1	217.8	53.7	1.30	0.95	518.2	86.8	0.351	9084.8	87.4	12&
M.9 Pajam 2	237.6	49.6	1.41	0.94	691.0	523.2	0.091	10760.0	95.8	13&
B.9	160.9	51.2	0.66	0.68	1137.9	2298.8	0.014	3576.8	33.6	3
B.491	95.1	57.8	0.53	0.84	282.1	2075.2	0.015	2059.0	28.5	-4
O.3	200.2	57.6	1.15	0.89	898.6	610.0	0.064	7712.2	72.8	7&
V.1	253.7	46.6	1.24	0.86	1357.3	781.6	0.048	9189.3	89.6	12&
P.2	158.0	56.3	0.85	0.77	1177.1	1573.6	0.021	5044.5	46.3	-1
P.16	107.4	71.4	0.82	0.81	862.3	1258.7	0.029	4524.3	44.2	-3
MARK	135.5	63.4	0.79	0.67	1713.9	2316.5	0.013	5038.4	37.0	-6
M.9 NAKBT337	190.6	55.8	1.22	0.96	323.7	3932.5	0.001	8010.5	79.9	0

[z] Kang's yield-stability statistic (YS_i), where values followed by & indicate these rootstocks have high cumulative yield and are relatively stable.

Table 3. Cumulative yield efficiency (CYE, kg·cm² TCA) per surviving tree and coefficients of variation (CV), plus five stability parameters for 'Gala' trees on 14 rootstocks averaged over 17 sites in the 1993 NC-140 rootstock trial. *Grand mean = 3.32, CV=47.5, LSD = 0.87.*

Stock	CYE (kg·cm^{-2})	CV	Slope	R^2	DevReg	Shukla's Stability variance	Pr>Z	Env. Var. model	AMMI	YS_i [z]
M.9	3.28	49.0	1.01	0.91	0.148	633.5	0.590	9809.7	84.4	5&
M.26	2.62	42.5	0.64	0.79	0.151	766.7	0.461	6861.7	75.4	1
M.27	3.08	50.4	0.91	0.79	0.319	3734.1	0.009	1083.6	13.1	-5
M.9 NIC29	3.34	43.9	1.07	0.88	0.212	352.9	0.135	9259.6	88.8	7&
M.9 Pajam 1	3.37	43.4	1.03	0.94	0.102	90.6	0.343	9053.1	87.3	9&
M.9 Pajam 2	3.34	41.1	0.01	0.93	0.114	445.1	0.108	10169.0	94.1	7&
B.9	3.63	42.9	0.93	0.75	0.398	2260.4	0.014	3577.9	32.7	8&
B.491	3.78	48.6	1.14	0.97	0.055	2013.1	0.016	2004.5	28.2	9&
O.3	3.38	45.5	1.05	0.95	0.077	455.9	0.091	7008.4	68.4	8&
V.1	2.65	38.3	0.66	0.88	0.082	748.6	0.050	8920.2	88.2	-2
P.2	3.24	39.8	0.84	0.83	0.208	1486.9	0.022	4896.6	44.5	0
P.16	4.07	54.0	1.49	0.83	0.629	1266.4	0.028	4412.6	42.1	10&
MARK	3.38	46.2	1.00	0.76	0.445	2012.5	0.016	5139.6	38.6	6&
M.9 NAKBT337	3.34	48.9	1.21	0.91	0.194	3873.3	0.001	7991.2	79.6	-1

[z] Kang's yield-stability statistic (YS_i), where values followed by & indicate these rootstocks have high cumulative yield and are relatively stable.

rootstocks. Most of these rootstocks were fairly vigorous, and since trees on vigorous rootstocks must be planted further apart, yield per unit land area would likely be less.

Cumulative yield efficiency, 1994 trial. Cumulative YE (CYE) was calculated for only trees surviving until the end of the study (Table 3). Rootstocks with the highest CYE included B.9, B.491, and P.16, whereas trees on M.26 and V.1 had the lowest CYE. The CV was highest for M.9 and P.16 and lowest for V.1 and P.2 (Table 3). Several rootstocks had slopes near 1.0 (M.27, B.9, O.3, P.2, MARK and all five M.9 clones), indicating average stability. P.16 had lower than average stability (slopes >1.0), whereas M.9 Pajam 2 had a slope of 0.01 indicating above average stability. According to Shukla's stability variance, stable rootstocks (Z <0.05) included M.26, O.3 and four of the five M.9 clones. Variance estimated with the environmental variance and AMMI models were relatively low for M.27, B.9 and B.491 and highest for V.1 and the five M.9 clones. Kang's yield-stability statistic indicated that M.9, M.9 Nic 29, M.9 Pajam 1, M.9 Pajam 2, B.9, B.491, O.3, P.16, and MARK had relatively high CYE and were fairly stable.

Root suckers, 1994 trial. Averaged over all sites, rootstocks with more than 10 root suckers per tree included M.9 Nic 29, M.9 Pajam 1, M.9 Pajam 2, B.9, O.3, V.1, P.16, Mark, and M.9 NAKBT337 (Table 4). Rootstocks with low numbers of root suckers also tended to have the largest CVs. Nonstable rootstocks (slopes > 1.0) included P.16, M.9 Pajam1, M.9 Pajam2, M.9 Nic 29, and MARK and they also had high Dev-Reg. Shukla's stability variances were not significant and variances estimated with the environmental variance and AMMI models were low for M.9, M.26, M.27, B.491, and P.2. Kang's yield-stability statistic identified M.9, M.26, M.27, B.491 and P.2 as producing fewer than average root suckers and having relatively high stability.

TCA, 2003 trial. Trees on Pi Au 51-4 and Pi Au 56-83 had much larger trunks than all other rootstocks and trees on B.9 had the smallest trunks (Table 5). CVs were not related to TCA but were smallest for G.41 and G.935, and largest for B.9, M.9 Pajam 2, and M.9 NAKBT337. The two Pi Au rootstocks had slopes greater than 2.0 and high Dev-Reg, so they had below average stability and are

Table 4. Mean number of root suckers per surviving tree in year 9 and coefficients of variation (CV), plus five stability parameters for 'Gala' trees on 14 rootstocks averaged over 17 sites in the 1993 NC-140 rootstock trial. *Grand mean = 9.2, CV=186.0, LSD=10.08.*

Stock	Suckers Per tree	CV	Slope	R^2	DevReg	Shukla's Stability variance	Pr>Z	Env. Var. model	AMMI	YS_i [z]
M.9	3.4	191.5	0.40	0.74	5.58	1.9	0.810	31.5	3.8	11%
M.26	0.4	372.4	0.03	0.24	0.37	0.1	0.900	11.5	0.3	14%
M.27	2.7	207.7	0.24	0.38	8.72	0.2	0.880	22.6	2.1	12%
M.9 NIC29	11.9	163.8	1.47	0.93	17.05	118.6	0.013	229.3	13.8	1
M.9 Pajam 1	13.3	161.0	1.57	0.92	19.31	144.4	0.011	239.4	14.9	0
M.9 Pajam 2	16.5	150.0	1.78	0.85	53.68	231.0	0.009	344.1	17.2	-6
B.9	10.4	138.7	1.03	0.87	14.98	42.4	0.034	120.7	9.4	4
B.491	4.3	156.7	0.28	0.45	9.26	0.3	0.780	24.6	2.5	19%
O.3	11.6	133.1	1.33	0.92	13.92	87.8	0.018	164.6	12.6	2
V.1	10.0	176.8	1.19	0.84	25.94	72.9	0.019	159.6	10.8	9
P.2	1.1	243.1	0.11	0.67	0.60	0.1	0.880	12.7	1.0	13%
P.16	18.7	135.5	1.99	0.81	87.83	318.3	0.008	411.1	19.3	-7
MARK	13.5	156.8	1.46	0.69	91.68	176.8	0.010	266.3	13.2	-5
M.9 NAKBT337	10.6	137.2	1.11	0.88	15.45	55.3	0.025	138.2	10.3	3

[z] Kang's yield-stability statistic (YS_i), where values followed by & indicate these rootstocks have low numbers of suckers and are relatively stable.

very sensitive to site differences. These were the only rootstocks with Shukla's stability variances significantly greater than zero, and high values for variances estimated with the environmental variance and AMMI models. Slopes for M.26 and M.9 NAKBT337 were near 1.0 and had average stability because TCA was similar despite large differences in site means. These two rootstocks also had relatively low values for the other three stability variances. The slope for B.9 was only 0.1 and along with a small Dev-Reg indicated it had above average stability and had similar TCA across all eight sites. M.26 and M.9 Pajam 2 had slopes slightly greater than 1.0, but the other five rootstocks had slopes between 0.45 and 0.83 with relatively small variances and would be considered slightly above average in stability. If large trunks are considered desirable, Kang's yield-stability

Table 5. Mean trunk cross-sectional area (TCA) and coefficient of variation (CV), plus five stability parameters for 'Golden Delicious' trees on 11 rootstocks averaged over 8 sites in the 2003 NC-140 rootstock trial. *Grand mean = 89.5, CV = 67.5, LSD=12.8.*

Stock	Mean TCA (cm^2)	CV	Slope	R^2	DevReg	Shukla's Stability variance	Pr>Z	Env. Var. model	AMMI	YS_i [z]
B.62396	67.4	34.5	0.64	0.69	145.1	33.5	0.276	4579.0	12.2	4
B.9	31.4	44.2	0.10	0.05	163.6	295.5	0.076	5346.8	0.8	-4
G.16	59.5	36.7	0.72	0.74	145.7	36.8	0.319	4506.9	14.2	1
G.41	59.1	28.3	0.53	0.77	68.5	49.4	0.262	5245.0	12.8	0
G.935	67.5	28.0	0.45	0.53	137.4	55.1	0.272	5340.2	8.9	5&
J-TE-H	85.5	31.3	0.83	0.90	59.7	48.8	0.266	4615.4	18.4	8&
M.26	91.1	36.8	1.14	0.83	208.3	225.0	0.120	5298.8	22.9	9&
Pi Au 51-4	176.6	32.7	2.04	0.86	520.6	1765.4	0.039	8471.5	55.9	7&
Pi Au 56-83	193.8	35.1	2.35	0.92	380.4	2244.8	0.036	10117.0	62.1	8&
M.9 Pajam2	74.7	45.0	1.23	0.96	46.6	191.5	0.108	4619.3	30.5	4
M.9 NAKBT337	66.7	44.8	0.96	0.94	45.0	45.2	0.290	4355.3	21.6	3

[z] Kang's yield-stability statistic (YS_i), where values followed by & indicate these rootstocks have high TCA and are relatively stable.

Table 6. Cumulative yield and coefficient of variation (CV), plus five stability parameters for 'Golden Delicious' trees on 11 rootstocks averaged over 8 sites in the 2003 NC-140 rootstock trial. Grand mean =187.2, CV =49.8, LSD=42.1.

Stock	Cum. Yld. (kg/tree)	CV	Slope	R^2	DevReg	Stability variance	Pr>Z	Var. model	AMMI	YS_i [z]
B.62396	183.8	8.9	1.13	0.85	627.2	1.0	0.361	19120.0	55.6	7&
B.9	103.1	14.9	0.09	0.01	1502.2	3177.2	0.057	23153.0	0.0	-3
G.16	141.9	29.1	0.31	0.21	976.9	1854.4	0.077	23245.0	5.6	-1
G.41	180.2	13.4	0.86	0.85	384.3	1.8	0.295	21157.0	38.9	5&
G.935	185.8	13.3	0.23	0.06	2316.7	3560.7	0.054	20403.0	0.0	6&
J-TE-H	202.1	9.6	1.28	0.70	1967.7	1583.7	0.084	24586.0	64.7	6&
M.26	181.3	6.6	0.91	0.59	1630.9	987.5	0.117	21115.0	29.7	7&
Pi Au 51-4	233.3	28.9	2.11	0.97	343.4	3207.7	0.058	29920.0	94.8	6&
Pi Au 56-83	250.9	5.1	1.90	0.80	2609.5	4290.8	0.049	33782.0	94.3	9&
M.9 Pajam2	177.3	13.9	1.25	0.73	1625.6	826.4	0.135	22018.0	58.9	4
M.9 NAKBT337	173.0	14.7	0.92	0.87	354.6	2.1	0.421	20752.0	39.7	3

[z] Kang's yield-stability statistic (YS_i), where values followed by & indicate these rootstocks have high cumulative yield and are relatively stable.

statistic identified G.935, J-TE-H, M.26, Pi Au 56-83 as being fairly stable with large trunks.

Cumulative yield, 2003 trial. The two Pi Au rootstocks and J-TE-H had the highest cumulative yield (cumulative yield >200 kg/tree) and they also had slopes greater than 1.0 (Table 6). B.9 had the lowest yield. Rootstocks with slopes less than 1.0 included B.9, G.16 and G.935, indicating that they had above average stability. Shukla's stability variances were significant for only Pi Au 56-83 and it had the highest variances estimated with the environmental variance and AMMI models. Variance estimates for the other rootstocks were similar. According the yield-stability statistic, rootstocks with relatively high yield and stability included B.62396, G.41, G.935, J-TE-H, M.26, Pi Au 51-4, and Pi Au 56-83. Although some of the stability statistics indicated that Pi Au 56-83 was not stable, the yield-stability statistic identified it as a better than average rootstock because it gives equal weight to cumulative yield and stability and it had the highest yield in the trial.

Cumulative yield efficiency, 2003 trial. Pi Au 51-4 and Pi Au 56-83 had the lowest CYE and relatively high CVs (Table 7). The two Pi Au rootstocks also had slopes less than 0.6, indicating above average stability, but the R^2 values were less than 0.8; the other stability statistics indicated low stability. Rootstocks with CYE greater than 3.0 included B.62396, B.9, G.16, G.41, G.935, M.9 Pajam 2 and M.9 NAKBT337. Of these seven rootstocks only B.9 had a slope much greater than 1.0, plus a high Dev-Reg and Shukla's stability variance was significant. Therefore, B.9 had below average stability and was adapted to high-yielding sites. The two Pi Au rootstocks were not selected by the yield-stability statistic as desirable rootstocks because the CYE was only about half that of the other rootstocks.

Root suckers, 2003 trial. Trees on G.935 and Pi Au 51-4 had the most root suckers whereas trees on G.41, M.26 and Pi Au 56-83 had less than one sucker per tree (Table 8). Most of the rootstocks with few suckers had high CVs. Slopes were very high for G.935, Pi Au 51-4 and M.9 Pajam 2, indicating they produced many suckers at sites that had high numbers of suckers. The rootstocks B.9, G.16 and M.9 NAKBT337 had slopes near 1.0, indicating they had average stability and root sucker development was similar across

Table 7. Cumulative yield efficiency (CYE) and coefficients of variation (CV), plus five stability parameters for 'Golden Delicious' trees on 11 rootstocks averaged over 8 sites in the 2003 NC-140 rootstock trial that survived 10 years. *Grand mean =2.83, CV=47.25, LSD=0.37.*

Stock	Mean CYE ($kg \cdot cm^{-2}$)	CV	Slope	R^2	DevReg	Shukla's Stability variance	Pr>Z	Env. Var. model	AMMI	YS_i [z]
B.62396	3.17	39.7	1.24	0.92	0.140	0.119	0.086	28888	57.0	7&
B.9	3.98	40.4	1.50	0.88	0.309	0.429	0.044	33843	8.6	10&
G.16	3.01	27.2	0.69	0.87	0.073	0.155	0.083	34427	47.5	4&
G.41	3.45	30.1	0.99	0.95	0.059	0.023	0.267	26561	50.9	11&
G.935	3.47	35.1	1.16	0.98	0.029	0.087	0.164	33317	40.3	12&
J-TE-H	2.49	40.1	0.91	0.83	0.173	0.199	0.061	33012	71.0	1&
M.26	2.49	46.1	1.07	0.92	0.101	0.045	0.188	33902	55.0	2&
Pi Au 51-4	1.64	40.7	0.57	0.77	0.100	0.304	0.052	41211	104.4	-3
Pi Au 56-83	1.42	44.9	0.50	0.64	0.150	0.417	0.045	42290	99.3	-6
M.9 Pajam2	3.03	44.9	1.16	0.97	0.051	0.156	0.288	26879	71.9	7&
M.9 NAKBT337	3.14	40.8	1.20	0.93	0.123	0.076	0.126	24090	59.4	8&

[z] Kang's yield-stability statistic (YS_i), where values followed by & indicate these rootstocks have high cumulative yield and are relatively stable.

Table 8. Mean number of root suckers per tree and coefficients of variation (CV), plus five stability parameters for 'Golden Delicious' trees on 11 rootstocks averaged over 8 sites in the 2003 NC-140 rootstock trial that survived 10 years. *Grand mean = 3.6, CV=265.3, LSD=4.7.*

Stock	Suckers per tree	CV	Slope	R^2	DevReg	Shukla's Stability variance	Pr>Z	Env. Var. model	AMMI	YS_i [z]
B.62396	1.0	284.7	0.19	0.49	1.202	0.08	0.368	4.74	1.24	7&
B.9	6.8	115.2	0.70	0.63	9.548	7.95	0.155	22.61	3.32	4
G.16	2.8	211.6	0.79	0.86	3.621	5.94	0.204	21.69	4.15	5
G.41	0.5	288.6	0.18	0.94	0.068	0.07	0.366	3.56	0.94	9&
G.935	9.2	207.9	3.17	0.96	14.281	255.30	0.035	285.6	17.14	0
J-TE-H	1.5	182.9	0.24	0.46	2.356	2.03	0.289	6.69	1.18	6&
M.26	0.4	305.8	-0.01	0.03	0.145	0.08	0.485	3.26	0.08	10&
Pi Au 51-4	9.2	207.5	2.32	0.87	27.324	144.60	0.038	132.3	12.39	-1
Pi Au 56-83	0.9	196.2	0.06	0.27	0.284	1.11	0.444	3.69	0.28	8&
M.9 Pajam2	4.1	164.9	2.35	0.97	5.115	74.22	0.118	12.42	11.67	6&
M.9 NAKBT337	4.1	174.2	1.02	0.96	1.393	10.81	0.178	14.39	5.74	5

[z] Kang's yield-stability statistic (YS_i), where values followed by & indicate these rootstocks have low numbers of root suckers and are relatively stable.

all sites. Dev-Reg was positively related to suckers per tree. All three variance estimates were highest for trees on J-TE-H and G.935. The yield-stability statistic selected B.62396, G.41, J-TE-H, M.26, Pi Au 56-83, and M.9 Pajam2 as desirable rootstocks for lack of root suckers and stability.

Discussion

At least 23 stability statistics have been developed and they do not always agree because they measure different aspects of stability. Dia et al. (2016) found that Shukla's stability variance and deviation from regression were correlated for a watermelon cultivar trial and Changizi et al. (2014) found that the slope, deviation from regression and the environmental variance were correlated for a corn cultivar trial. Results from different NC-140 trials cannot be directly compared because the relative magnitude of variation associated with a given rootstock-site combination is a function of the rootstocks, scion cultivar and sites for that trial and the combination of these factors is unique for each NC-140 trial. Therefore, the stability of a rootstock can only be compared to the average stability of rootstocks in each trial. Olien et al. (1991) compared nine rootstocks based on values for the slopes using the Findlay-Wilkinson joint-regression method and the five rootstocks that were also evaluated in the current trials included MARK, O.3, M.9, M.26 and M.27. Compared to the other four rootstocks (MAC.24, M.7 EMLA, M.9 EMLA and OAR 1), all five rootstocks had above-average stability for TCA and cumulative yield. Only M.26 had above average stability for CYE (Olien et al., 1991).

In an attempt to summarize the somewhat conflicting statistics for each response variable (TCA, cumulative yield, cumulative YE and number of suckers per tree) in each of the current trials, the five stability statistics (regression coefficient, deviation from regression, Shukla's stability variance, environmental variance and AMMI variance) were ranked from low to high and summed. For TCA in the 1994 trial, the most stable rootstocks included B.9, P.2, P.16, B.491, M.27 and O.3, whereas the least stable rootstocks were M.9 T337, M.9 and M.26. Based on the sum of ranks for cumulative yield in the 1994 trial, the most stable rootstocks were M.26 and B.9, and the least stable were M.27, P.16, and MARK (data not shown). For CYE the most stable rootstocks were B.491, M.26, B.9, P.2, and M.27 and the least stable rootstocks included M.9 Nic 29, M.9 and M.9 Pajam1. For root suckers the most stable rootstocks were B.9, M.26 and B.491 and the least stable rootstocks included P.16, MARK, M.9 Pajam 1 and M.9 Pajam 2. An overall stability rating was estimated by summing the sum of the ranks over three response variables (cumulative yield, cumulative YE and root suckers). The most stable rootstocks were M.26, M.9, and M.9 Nic29 and the least stable rootstocks were P.16 and M.27 (data not shown).

For the 2003 trial, based on the sum of ranks for TCA, M.9 NAKBT337 and B.62396 were the most stable, and Pi Au 56-83 and Pi Au 51-4 were the least stable. The sum of ranks indicated that for cumulative yield the most stable rootstocks were M.9 NAKBT337, B.9, G.16 and B.62396 and the least stable were Pi Au 56-83 and J-TE-H. For CYE the sum of ranks indicated that the most stable rootstocks were G.41 and G.935 and the least stable were B.9 and Pi Au 56-83. For root suckers the most stable rootstocks were M.26 and G.41 and the least stable were G.935 and Pi Au 51-4. Based on the overall stability rankings, M.26 and B.62396 were most stable and Pi Au 51-4 was the least stable.

Results from the two trials are not very consistent, probably because the range of environmental conditions was much greater in the 1993 trial. The only southern site in the 2003 trial was KY, whereas AR, GA, NC, SC, TN and VA participated in the 1993 trial. Kang (1993) suggested that while evaluating stability, researchers should place more emphasis on performance of a genotype and his yield-stability statistic gives equal weight to performance and stability. When considering the yield-stability statistic for the 1993 trial, only M.9 had above average values for all response variables, whereas M.9 NAKBT337 had below average values for all response variables. For the 2003 trial, rootstocks with above average values for the yield-stability statistic for all response variables included M.9 Pajam 2, M.26, Pi Au 56-83, B.62396 and J-TE-H.

While selecting a rootstock, tree survival is a critical factor to consider. Tree survival was not considered in the study because it is a binomial response and not suited to these analyses. Tree longevity was taken into consideration for cumulative yield because trees that died during the trial had low cumulative yield. Stability is an important characteristic of a rootstock for making recommendations over a large region. Since cumulative yield is usually positively related to tree size and cumulative yield efficiency is usually negatively related to tree size, researchers can use stability analyses to select the most stable rootstocks within a given vigor category.

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