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Summary of the NC-140 Apple Physiology Trial: The Relationship Between 'Golden Delicious' Fruit Weight and Crop Density at 12 locations as Influenced by Three Dwarfing Rootstocks

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Abstract

An experiment designed specifically to evaluate the influence of rootstock on average fruit weight of 'Golden Delicious' apple [*Malus* x *sylvestris* (L.) var. *domestica* (Borkh.) Mansf] was established at 12 locations in North America. Trees on three dwarfing rootstocks (G.16, M.26 EMLA and M.9 NAKBT337) were allowed to fruit for the first time in the third growing season. Over a 5-year period whenever initial fruit set was adequate, trees were hand-thinned to one of five crop densities (CD) ranging from 2 to 14 fruit per cm^2 of trunk cross-sectional area (TCA). Yield and number of fruit harvested per tree were used to calculate average fruit weight. Analysis of covariance was used to evaluate the effects of rootstock on fruit weight when CD was added to the linear model as a covariate. The interaction for site, rootstock, year, and crop density was significant, so data were analyzed by site. At 8 of the 12 sites, CD interacted with year and/or rootstock, so an unequal slopes model was fitted to those data. Where the CD x rootstock interaction was significant, least squares means for fruit weight were estimated at three levels of CD for each rootstock within each year and slopes for each rootstock were compared. In general, the slopes were most negative for trees on M.26 EMLA and least negative for trees on M.9 NAKBT337, indicating that fruit weight was most affected by CD for trees on M.26 EMLA. Fruit weight, regardless of CD, was generally lowest for trees on G.16 and highest for trees on M.9 NAKBT337. These results substantiate previous reports that rootstock can influence fruit weight, independent of CD, and that trees on M.9 NAKBT337 produce relatively large fruit.

Yield, fruit size, cultivar and fruit surface color are the primary factors influencing the value of an apple crop. Given the market demands for larger fruit, one of the management factors considered by apple growers is the influence of rootstock on fruit size. A common response variable often reported for rootstock trials is average fruit weight (FW). In previous reports, the influence of rootstock on FW varied with the rootstock trial. In some trials rootstock did not influence fruit size (1, 5, 7, 20), but in other trials it did (2, 3, 11, 22, 24). There are many potential reasons for the inconsistent results, including the cultivar/rootstock combinations that were compared, climatic conditions, and the availability of irrigation.

Another factor that can influence FW is crop load. The number of flowers produced on a tree is often greater than the number of marketable fruit the tree can support, and there is a negative relationship between FW and fruit per leaf (21) and CD (fruit per cm^2 of trunk cross-sectional area) (25). Since rootstock can strongly influence CD, simply reporting FW for rootstock trials may be misleading, because highly productive rootstocks may have lower FW than less productive rootstocks due to differences in crop loads. For this reason, some researchers have attempted to adjust FW for crop load by including CD as a covariate in an analysis of covariance (ANCOVA) and reported least squares means (LSmeans) that were adjusted for the mean value of CD (2, 4, 8, 9, 10, 16). When assumptions for a typical ANCOVA are not met, it is more appropriate to compare a series of regression lines as previously explained (15).

Statistical software packages appropriate for the experiment must also be used. The randomized complete block design (RCBD) is most commonly used for rootstock experiments, and a general linear models (GLM) approach, based on ordinary least squares, until recently was often used to analyze data. SAS's GLM procedure is appropriate for fixed effects models. When GLM is used for mixed models such as the RCBD the standard errors associated with the LSmeans may not be correct, especially when the experiment is unbalanced (13). Most rootstock experiments are unbalanced due to tree mortality over the course of the trial. When the rootstock x CD interaction is significant in these mixed effects models, the analysis provided by the GLM procedure is not adequate, because it does not utilize the between-block information about the slopes (13). Marini et al. (16) were the first to use SAS's MIXED procedure to test equality of slopes for a multi-location rootstock trial by including the year x CD x rootstock interaction in the model. The data set included eight rootstocks, four locations and two years. Since there was a strong 3-way interaction, ANCOVAs were performed by year and location. For two of the eight location-year combinations, slopes were not homogeneous, so LSmeans were compared at three levels of CD as suggested by Milliken and Johnson (19) and Littell et al. (14). A significant location x year x rootstock x CD interaction was identified in another rootstock trial (18), verifying that the assumption of slope homogeneity may be violated in many rootstock trials, and if so, comparing the LSmeans estimated with a typical ANCOVA is inappropriate.

Unlike other rootstock trials, this study was designed specifically to evaluate the influence of rootstock on FW by evaluating the relationship between FW and CD for three rootstocks for more than one year at 12 locations. In many rootstock trials, trees on M.26 EMLA produced smaller fruit than trees on M.9 NAKBT337, so these two rootstocks were included as standards along with a new rootstock, G.16. G.16 was a promising new rootstock producing trees similar in size to M.9 Pajam2 (17) and was included in this trial to learn if it produced fruit larger than M.26 EMLA.

Material and Methods

In the spring of 2003, a rootstock trial was established at 12 locations (Table 1). At each location, 10 'Golden Delicious', Gibson strain trees on each of three rootstocks (G.16, M.26 EMLA and M.9 NAKBT337) were planted in a completely randomized design. All trees were propagated by TRECO, Inc., Woodburn, OR. Trees were planted at a spacing of 2.5 m x 4.5 m and were trained to the vertical axis system. Trees were defruited in 2004, and some cooperators allowed trees to carry a light crop in 2005. In 2006, where initial fruit set was

Table 1. Locations and cooperators participating in the 2003 NC-140 apple physiology trial.

Location	Cooperator	Planting location
(BC) British Columbia	Cheryl Hampson	Summerland, Canada
(CHIH) Chihuahua	Rafael Parra Quezada	Cuauhtémoc, Mexico
(IA) Iowa	Paul Domoto	Ames
(KY) Kentucky	Joseph Masabni	Princeton
(MA) Massachusetts	Wesley Autio	Belchertown
(ME) Maine	Renae Moran	Monmouth
(NJ) New Jersey	Winfred Cowgill, Jr.	Pittstown
(NY) New York	Terence Robinson	Geneva
(ONT) Ontario	John Cline	Simcoe, Canada
(PA) Pennsylvania	Robert Crassweller	Rock Springs
(UT) Utah	Brent Black	Kaysville
(WI) Wisconsin	Kevin Kosola	Sturgeon Bay

adequate, crop loads were adjusted by hand thinning at about 25 to 30 days after full bloom to achieve five CDs. Two trees per rootstock were thinned to CDs of 3, 5, 8, 11 or 14 fruit per cm^2 of trunk cross sectional area (TCA). The year following crop load adjustment, the trees were thinned to CDs of <3.0 fruit•cm^{-2} to ensure adequate return bloom in order to re-impose crop load treatments the following year. For various reasons, crop adjustment was not possible at every location in 2006 and again in 2008 as planned. Therefore, in years when trees bloomed adequately, the cooperators adjusted the CDs appropriately. Each year, the CD treatments were re-randomized to the 10 trees per rootstock. Graphical techniques and regression analyses verified the assumption that observations from year to year were independent and were not related to the previous year's crop load. Data recorded each year included TCA, number of fruit per tree, and yield, and these values were used to calculate CD and average fruit weight (FW).

Data analyses. Data for all combinations of location, rootstock and year were initially combined into one large data set. To ensure similar ranges of CD, when the maximum CD for any of the three rootstocks was less than 9.0, all data for that location and year were deleted from the data set. Therefore data sets that were included for analysis had CDs ranging from 14 to >8.9 fruit per cm^2 of TCA. The modified data set was subjected to an analysis of covariance (ANCOVA), using SAS's Mixed procedure (14), where FW was the response variable, CD was the covariate, and the indicator (class) variables included year, location and rootstock. All possible factorial combinations of the four effects were included in the original model statement. Since the four-way interaction of location x year x rootstock x CD was significant at the 0.0001 level, data for each location were analyzed separately.

The model selection criteria suggested by Milliken and Johnson (19) and Littell et al. (14) were used to identify the appropriate model for each location. The first step involved fitting a complete factorial, where CD was included as a covariate, and year and rootstock were included as indicator variables. In all cases the CD x year x rootstock interaction was not significant, so it was deleted from the model statement and the program was rerun. When the CD x year or CD x rootstock interactions were not significant, the term with the highest P-value was deleted from the model statement and the reduced model was fitted again until only significant interaction terms remained in the model. After identifying the appropriate model, Levene's test was used to evaluate homogeneity of variances. In most cases, variances were not significantly different, but when they were, an unequal variance model was fitted with a *repeated* statement. An example of fitting a model with unequal variances for year is: *repeated / group = year.*

Significant interaction terms indicate that all slopes for each level of the indicator variable(s) are not equal. If the covariate, CD, but not an interaction term involving CD, was significant then the slopes for all levels of the indicator variable were assumed to be homogeneous, and a typical ANCOVA was performed, and LSmeans for FW were estimated at a CD of 6.0 and were compared with the DIFF option. When one or more interaction terms involving CD was significant, there was evidence that slopes for all levels of the indicator variable were not equal, so an unequal slopes model was fitted to the data by including the significant interaction term(s) in the model. Intercepts and slopes for combinations of year and rootstock were generated by including the *noint* (no intercept) and *solution* options in the model statement. Pair-wise comparisons of slopes within each year were performed with *estimate* statements and *P*-values are presented. The LSmeans statement was included to obtain LSmeans for FW at three levels of CD (3, 6, and 9) for each combination of year and rootstock. LSmeans were compared with the DIFF option and *P*-values for each pair-wise comparison are presented. A more detailed explanation of the statistical analysis, involving a slightly more complex data set, along with SAS code

Table 2. Maximum, mean and minimum values for crop density (fruit per cm² of trunk cross-sectional area) for 'Golden Delicious' trees on three dwarfing rootstocks (G.16, M.26 EMLA and M.9 NAKBT337) for five seasons at 12 locations.

		2006			2007			2008			2009			2010		
Site	Stock	Max.	Mean	Min	Max.	Mean	Min	Max.	Mean	Min	Max.	Mean	Min	Max	Mean	Min
BC	G.16	13.9	7.4	1.5	2.2	1.2	0.0	10.1	5.6	1.7	3.5	1.5	0.1	10.0	5.7	1.8
	M.26	14.8	7.4	1.4	2.3	1.2	0.1	8.9	5.2	1.7	4.7	2.6	0.3	12.9	7.2	1.8
	M.9	16.7	8.0	1.5	4.5	1.8	0.4	8.4	5.3	1.7	5.3	3.3	0.9	10.4	6.2	1.7
CHIH	G.16	13.4	7.1	1.8	1.0	0.4	0.03	3.1	2.0	0.9	7.1	4.8	2.1	2.1	1.2	0.2
	M.26	12.8	6.4	1.4	1.1	0.5	0.08	2.4	1.7	1.2	6.8	4.6	2.8	3.8	1.3	0.2
	M.9	12.1	7.2	2.2	1.0	0.6	0.04	2.8	1.6	0.6	7.8	5.0	1.4	0.8	0.3	0.1
IA	G.16	12.6	7.0	2.0	3.5	2.6	2.0	4.4	3.2	1.8	4.5	3.2	2.0	8.1	4.8	1.9
	M.26	8.4	4.9	1.4	2.6	1.5	0.1	4.3	3.1	1.6	3.6	2.0	0.4	5.9	3.0	0.6
	M.9	11.4	6.0	1.0	3.1	2.1	1.2	4.0	3.2	1.7	4.3	2.8	1.0	7.8	4.5	1.9
KY	G.16	12.4	5.9	1.2	---	---	---	14.5	9.5	3.2	3.6	2.1	0.3	9.9	5.6	2.7
	M.26	8.5	4.3	1.2	---	---	---	10.6	8.1	5.4	2.7	1.6	0.5	9.6	5.4	2.4
	M.9	11.1	6.2	1.6	---	---	---	14.5	8.7	3.1	2.8	1.2	0.2	10.4	5.1	1.8
MA	G.16	4.3	2.3	1.0	13.5	7.8	2.8	3.2	1.6	1.4	16.2	11.0	5.4	3.3	1.2	0.2
	M.26	3.4	1.8	0.7	13.7	7.4	2.6	2.7	1.3	0.1	14.2	9.7	5.0	1.0	0.5	0.1
	M.9	5.0	2.8	0.5	14.6	8.6	3.2	3.5	1.9	0.1	21.9	11.8	4.6	6.0	1.3	0.0
ME	G.16	---	---	---	11.1	7.0	1.4	---	---	---	10.5	7.2	2.8	---	---	---
	M.26	---	---	---	11.0	5.6	0.9	---	---	---	9.3	5.2	2.4	---	---	---
	M.9	---	---	---	11.7	6.4	1.3	---	---	---	12.8	6.9	2.1	---	---	---
NJ	G.16	11.5	7.0	1.8	---	---	---	3.8	1.4	0.1	---	---	---	2.4	0.7	0.0
	M.26	9.4	9.4	1.9	---	---	---	2.9	2.9	0.1	---	---	---	0.7	0.4	0.1
	M.9	11.3	11.3	1.1	---	---	---	4.9	4.9	0.4	---	---	---	1.4	0.4	0.1
NY	G.16	9.2	5.0	2.3	7.6	6.4	5.5	15.9	6.4	3.1	11.7	6.5	1.0	9.7	6.3	2.3
	M.26	7.2	4.0	1.4	10.3	7.2	4.1	10.3	7.2	1.8	13.1	5.5	1.1	8.3	5.5	0.8
	M.9	6.7	3.8	1.2	10.4	6.8	5.0	10.7	6.8	2.0	10.7	5.9	1.1	9.1	6.3	1.4
ONT	G.16	8.8	5.9	1.7	4.2	2.6	0.1	4.2	2.6	0.1	4.5	2.5	1.3	4.1	2.4	1.5
	M.26	9.4	5.6	2.1	5.5	3.2	1.1	5.5	3.2	1.1	5.8	2.5	1.1	3.5	2.0	1.2
	M.9	10.4	5.5	1.0	3.9	2.2	0.1	4.1	2.2	0.1	5.2	2.8	0.7	3.6	2.4	1.7
PA	G.16	12.5	6.2	1.3	8.1	6.3	4.3	10.2	6.0	2.1	6.1	4.4	1.1	---	---	---
	M.26	11.1	5.7	1.5	7.2	4.7	3.7	8.6	5.1	1.8	4.8	2.3	0.4	---	---	---
	M.9	12.3	6.1	1.4	7.5	5.6	4.3	9.6	5.7	2.0	4.2	3.2	1.3	---	---	---
UT	G.16	12.0	6.5	1.3	3.9	2.8	1.3	9.2	5.3	1.6	2.8	2.2	1.6	7.0	4.0	1.3
	M.26	5.9	3.7	1.1	4.3	3.0	0.7	4.0	3.2	1.6	3.2	2.7	1.9	2.9	1.8	1.0
	M.9	10.6	5.6	1.4	5.1	3.4	1.3	7.5	5.4	1.9	2.4	1.7	1.2	5.4	4.2	2.4
WI	G.16	4.7	2.3	0.9	8.5	5.0	2.3	7.8	4.7	1.9	7.8	5.7	2.5	---	---	---
	M.26	4.2	1.8	0.3	5.2	3.7	2.0	5.9	3.4	1.7	4.5	3.3	1.6	---	---	---
	M.9	2.0	1.0	0.1	8.9	6.8	4.2	7.9	4.7	1.6	8.6	5.7	4.3	---	---	---

Table 3. Simplified ANCOVA model for each location, including P-values for the highest order interactions that were significant at P<0.1. This is the model that was used to generate regression models and LSmeans.

Source of Variation	BC	CHIH	IA	KY	ME	MA	NJ	NY	ONT	PA	UT	WI
Year	0.001	0.007	0.946	0.002	0.427	0.356	- - -	0.001	- - -	0.001	0.001	0.100
Stock	0.895	0.118	0.009	0.017	0.218	0.830	0.008	0.001	0.005	0.001	0.743	0.315
Year*Stock	0.092	0.082	- - -	0.076	- - -	- - -	- - -	- - -	- - -	0.046	- - -	- - -
CD	0.001	0.001	0.001	0.001	0.001	0.001	0.024	0.001	0.001	0.001	0.011	0.001
CD*Stock	0.010	- - -	- - -	- - -	- - -	0.058	- - -	- - -	0.020	- - -	- - -	- - -
CD*Year	0.021	- - -	0.019	- - -	- - -	0.031	- - -	0.011	- - -	0.048	- - -	- - -
CD*Stock*Year	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -

is presented in a companion paper (15).

Results were difficult to interpret because the relationship between FW and CD varied with site and year. In an attempt to summarize the results, the entire data set with 29 site/year combinations and 802 observations was used to perform a typical ANCOVA to estimate LSmeans at three CDs and LSmeans within a CD were compared with the DIFF option. Slopes for each rootstock were also compared with estimate statements.

Results

The maximum, mean and minimum values of CD for all combinations of year, site, and rootstock are presented in Table 2. In most cases, a heavy crop, as indicated by a high value for CD, was followed the next year with a low crop, indicating alternate bearing. However, in some cases there were several consecutive years with adequate CDs to include in the analysis of covariance. The terms along with the *P*-values from the simplified linear models for each location used for ANCOVA are presented in Table 3. In all cases the covariate, CD, was significant. The CD x rootstock interaction was significant in BC, ME and ONT and the CD x year interaction was significant in BC, IA, MA, NY and PA. Since slopes for the three rootstocks and different years were homogeneous in CHIH, KY, UT, and WI, a typical ANCOVA involving a common slopes model would typically be used to estimate LSmeans at the mean value of the covariate. However, to be consistent, LSmeans were estimated at a CD of 6.0 fruit per m^2 of TCA for each rootstock.

British Columbia. The planting was located on the Research Farm in Summerland at 49.34N latitude, -119.39W longitude and, 454 m above sea level. The soil was Skaha Sandy Loam, irrigation was provided and the planting was preceded by pear and apple, but soil was fumigated with Vapam the autumn before planting. There were adequate levels of CD for three years (Table 4). Intercepts were not compared because values of FW at a CD of zero are meaningless. In general, slopes were most negative in 2008. In 2006 and 2010 the slopes for G.16 were significantly more negative than for M.9 NAKBT337 indicating that FW declined most rapidly with increasing CD for trees on G.16. Because the intercept was low for G.16 in 2008, FW was lower for G.16 than for the other two rootstocks at the low value for CD. At the moderate CD of 6.0, FW was lowest for G.16 in 2008. Although not always significantly different than M.26 EMLA, trees on G.16 had the lowest FW and trees on M.9 NAKBT337 had the highest

Table 4. The relationship between fruit weight (FW) and crop density (CD) as influenced by three rootstocks in three years in British Columbia. Coefficients for intercepts and slopes along with LSmeans for FW estimated for three levels of CD are presented.

				FW(g) at CD (fruit·cm^{-2})^z		
Year	Stock	Intercept	Slope	3.0	6.0	9.0
2006	G.16	271.0	-10.1a	241	210	180b
	M.26 EMLA	254.8	-7.2ab	233	212	190ab
	M.9 NAKBT337	259.1	-6.5b	240	221	201a
2008	G.16	268.6	-11.0	236b	202b	170b
	M.26 EMLA	299.0	-12.4	262a	226a	188ab
	M.9 NAKBT337	301.8	-11.7	267a	232a	196a
2010	G.16	237.5	-12.7	199	161	123b
	M.26 EMLA	235.9	-8.7	210	184	157a
	M.9 NAKBT337	231.3	-8.4	209	184	158a

^{z} Values within column and year followed by common letters do not differ at the 5% level of significance, by contrasts.

FW at the high CD in all three years. For all years, FW was greater for M.9 NAKBT337 than for G.16.

Chihuahua. The trial was planted on a commercial farm at 28.42N latitude, -106.87W longitude and 2,020 m above sea level. The soil was sandy loam, drip irrigation was provided and the site was planted to apples before 2003. Data for 2009 are difficult to interpret because only four trees on M.9 NAKBT337 survived, so FW was estimated only at a CD value of 6.0 (Table 5). In 2006, FW was about 10% lower for trees on G.16 than for trees on M.9 NAKBT337 at a CD of 6.0. In 2009, trees on G.16 produced the largest fruit, whereas trees on M.9 NAKBT337 had the smallest fruit.

Iowa. The planting was located on the research farm at Ames at 42.1N latitude, -93.6W longitude, and 314 m above sea level. About two-thirds of the site had Nicollett Fine Loam that was somewhat poorly drained and the remainder had Clarion Fine Loam that was well drained. Irrigation was provided, and the site was previously planted to apples for 40 years and was not fumigated. There was adequate bloom for crop adjustment in two years. Slopes were more negative and fruit was smaller in 2006 than in 2010, and slopes were homogeneous for all three rootstocks in both years (Table 6). Although not always significant, for all CDs in both years, trees on M.9 NAKBT337 had the highest FW. In 2006, trees on M.9 NAKBT337 had higher FW than trees on G.16 for only the moderate CD. In 2010, trees on M.9 NAKBT337 had significantly higher FW than trees on G.16 at only the low CD.

Kentucky. The planting was located on the University research farm in Princeton at 37.1N latitude, -87.84W longitude, and 193 m above sea level. The soil was Tilsit Silt Loam with trickle irrigation. The site was previously planted to plum trees and was fallowed for 10 years with no fumigation before planting the physiology trial. There was an adequate crop for analysis for three years and the slope for M.26 EMLA was more negative than for

Table 5. The relationship between fruit weight (FW) and crop density (CD) as influenced by three rootstocks in two years in Chihuahua. Coefficients for intercepts and slopes along with LSmeans for FW estimated at CD= 6.0 are presented.

Year	Stock	Intercept	Slope	FW (g)^z
2006	G.16	152.7	-5.4	121a
	M.26 EMLA	166.9	-6.9	125ab
	M.9 NAKBT337	198.2	-11.4	130b
2009	G.16	154.1	-6.3	116a
	M.26 EMLA	192.0	-13.4	111ab
	M.9 NAKBT337	140.1	-9.4	84b

^{z} Values within columns and year followed by common letters do not differ at the 5% level of significance, by contrasts.

Table 6. The relationship between fruit weight (FW) and crop density (CD) as influenced by three rootstocks in two years in Iowa. Coefficients for intercepts and slopes along with LSmeans for FW estimated for three levels of CD are presented.

				FW(g) at CD (fruit·cm^{-2})^{z}		
Year	Stock	Intercept	Slope	3.0	6.0	9.0
2006	G.16	178.8	-7.4	157	134b	112
	M.26 EMLA	193.8	-9.6	165	136ab	107
	M.9 NAKBT337	191.9	-7.5	169	147a	124
2010	G.16	171.1	-3.2	162b	152	142
	M.26 EMLA	192.8	-6.3	174ab	155	136
	M.9 NAKBT337	193.3	-4.8	179a	165	150

^{z} Values within column and year followed by common letters do not differ at the 5% level of significance, by contrasts.

G.16 in 2006 (Table 7). LSmeans for FW at a CD of 6.0 were not consistently affected by rootstock across years. In general, FW was not influenced by rootstock, except in 2006 when trees on G.16 had lower FW than trees on M.9 NAKBT337.

Maine. The planting in Maine was located on the Highmore Research Farm at 44N latitude and -70W longitude. The soil was a Dixfield fine sandy loam and irrigation was not provided. The site was not fumigated and was fallow for several years after apples were removed. There was an adequate crop in 2007 and 2009, but CD did not interact with rootstock or year. In 2007, trees on M.9 NAKBT337 produced the largest fruit regardless of CD (Table 8). FW was similar for trees on G.16 and M.26 EMLA for both years. In 2009 FW was higher for trees on M.9 NAKBT337 and M.26 EMLA than for trees on G.16.

Table 7. The relationship between fruit weight (FW) and crop density (CD) as influenced by three rootstocks in three years in Kentucky. Coefficients for intercepts and slopes along with LSmeans for FW estimated at CD= 6.0 are presented.

Year	Stock	Intercept	Slope	FW (g)
2006	G.16	160.4	-2.6a^{z}	145b^{z}
	M.26 EMLA	234.2	-12.3b	160ab
	M.9 NAKBT337	200.5	-3.4ab	180a
2008	G.16	185.2	-6.7	145
	M.26 EMLA	152.4	-2.9	135
	M.9 NAKBT337	197.4	-5.9	162
2009	G.16	189.0	-6.8	148
	M.26 EMLA	185.0	-9.8	126
	M.9 NAKBT337	190.3	-7.6	145

^{z} Values within columns and year followed by common letters do not differ at the 5% level of significance, by contrasts.

Table 8. The relationship between fruit weight (FW) and crop density (CD) as influenced by three rootstocks in two years in Maine. Coefficients for intercepts and slopes along with LSmeans for FW estimated at CD= 6.0 are presented.

Year	Stock	Intercept	Slope	FW (g)^{z}
2007	G.16	250.7	-12.1	178b
	M.26 EMLA	232.4	-8.7	180b
	M.9 NAKBT337	261.5	-10.2	201a
2009	G.16	254.7	-11.1	188ab
	M.26 EMLA	252.8	-11.3	185b
	M.9 NAKBT337	256.4	-10.1	196a

^{z} Values within columns and year followed by common letters do not differ at the 5% level of significance, by contrasts.

Massachusetts. The planting was located on the research farm in Belchertown at 42.28N latitude and -72.4W longitude. Trees had heavy crops in 2007 and 2009 (Table 9). Slopes were not influenced by rootstock in 2007. In 2009, slopes were significantly less negative for trees on M.9 NAKBT337 than for trees on G.16 or M.26 EMLA. In 2007, at a CD of 3.0, trees on M.9 NAKBT337 had higher FW than trees on M.26 EMLA; at CDs of 6.0 and 9.0, trees on M.9 NAKBT337 had higher FW than trees on G.16 or M.26 EMLA. In 2009, differences were not significant for low and moderate CDs, but at a CD of 9.0, trees on M.9 NAKBT337 and M.26 EMLA had higher FW than trees on G.16.

New Jersey. The planting was located at the Snyder Research and Extension Center

Table 9. The relationship between fruit weight (FW) and crop density (CD) as influenced by three rootstocks in two years in Massachusetts. Coefficients for intercepts and slopes along with LSmeans for FW estimated for three levels of CD are presented.

				FW(g) at CD (fruit·cm^{-2})^z		
Year	Stock	Intercept	Slope	3.0	6.0	9.0
2007	G.16	241.6	-8.4	216ab	191b	166b
	M.26 EMLA	232.5	-7.1	211b	190b	168b
	M.9 NAKBT337	252.4	-7.1	231a	210a	188a
2009	G.16	247.9	-10.4b	217	186	155b
	M.26 EMLA	258.6	-10.5b	227	196	164a
	M.9 NAKBT337	248.0	-7.8a	225	201	178a

^{z} Values within column and year followed by common letters do not differ at the 5% level of significance, by contrasts.

in Pittstown at 40.6N latitude and -74.9W longitude, and at 171m above sea level. Trees had an adequate crop load for analysis only in 2006 (Table 10). Slopes were less negative for trees on M.9 NAKBT337 than those on G.16 and M.26 EMLA. In fact, the slope was positive for M.9 NAKBT337. Although a positive relationship between CD and FW was unexpected and no explanation is offered, a plot of the data indicated that the relationship was actually positive and not attributed to a single influential observation (data not shown). LSmeans for FW were greatly influenced by CD x rootstock interaction. At a CD of 3.0, trees on M.9 NAKBT337 had significantly lower FW than trees on M.26 EMLA and FW for trees on G.16 was intermediate. At a CD of 6.0, FW for trees on M.26 EMLA was higher than for trees on G.16 and FW for trees on M.9 NAKBT337 was intermediate. At a CD of 9.0, FW for trees on M.9 NAKBT337 was higher than for trees on G.16, and trees on M.26 EMLA were intermediate.

New York. Trees were planted at the Geneva Research Station at 42.87N latitude and -77.017W longitude, and at 189 m above sea level. The soil type was Lima Silt Loam, and irrigation was provided. The site had been in apples for 10 years, then left fallow for two years, and was fumigated before planting. There was an adequate crop load for five consecutive years (Table 11). In 2006 the slopes were not significantly different from zero, because about 25% of the trees with CD <5.0 produced fruit with relatively low FW. The effect of rootstock on the slope was not very consistent from year to year. In 2010 the slope for M.26 EMLA was more negative than for G.16. FW was not affected by rootstock in 2006 and 2007. In both 2008 and 2009 trees on G.16 produced fruit with the lowest FW regardless of CD. In 2010 FW was lowest for trees on G.16. At the lowest CD, FW was highest for trees on M.26 EMLA. Because the slope was most negative for M.26 EMLA, at the highest CD, FW was significantly highest for trees on M.9 NAKBT337.

Ontario. The Ontario planting was located on the Vineland Station at 40.18N latitude, -79.39W longitude, and 75 m above sea level.

Table 10. The relationship between fruit weight (FW) and crop density (CD) as influenced by three rootstocks in 2006 in New Jersey. Coefficients for intercepts and slopes along with LSmeans for FW estimated for three levels of CD are presented.

				FW(g) at CD (fruit·cm^{-2})^z		
Year	Stock	Intercept	Slope	3.0	6.0	9.0
2006	G.16	251.3	-5.4b	235ab	219b	203b
	M.26 EMLA	279.8	-6.4b	261a	241a	222ab
	M.9 NAKBT337	210.5	2.3a	217b	224ab	231a

^{z} Values within column and year followed by common letters do not differ at the 5% level of significance, by contrasts.

Table 11. The relationship between fruit weight (FW) and crop density (CD) as influenced by three rootstocks in five years in New York. Coefficients for intercepts and slopes along with LSmeans for FW estimated for three levels of CD are presented.

Year	Stock	Intercept	Slope	FW(g) at CD (fruit·cm^{-2})^z 3.0	6.0	9.0
2006	G.16	176.4	-3.1	167	158	148
	M.26 EMLA	163.2	0.6	165	167	169
	M.9 NAKBT337	176.8	-0.9	174	171	169
2007	G.16	227.9	-12.5	191	153	116
	M.26 EMLA	217.9	-8.2	193	169	144
	M.9 NAKBT337	224.5	-9.6	196	167	138
2008	G.16	203.9	-4.7	190b	176b	162b
	M.26 EMLA	261.3	-9.0	234a	207a	180a
	M.9 NAKBT337	230.2	-2.6	222a	215a	207a
2009	G.16	212.1	-9.0	185b	158b	131b
	M.26 EMLA	227.6	-5.2	212a	196a	180a
	M.9 NAKBT337	239.3	-8.6	213a	188a	162a
2010	G.16	237.7	-7.9b	216b	192b	167b
	M.26 EMLA	91.9	-12.8a	253a	215a	176b
	M.9 NAKBT337	255.5	-6.1ab	237a	219a	201a

^{z} Values within column and year followed by common letters do not differ at the 5% level of significance, by contrasts.

The soil was Vineland fine sandy loam with irrigation. The site was not fumigated and was fallow for several years after removing sweet cherries. There was an adequate crop load for analysis only in 2006 (Table 12). Trees on M.9 NAKBT337 had a slope more negative than for trees on G.16 and the influence of rootstock on FW varied depending on CD. At a CD of 3.0, the FW was higher for trees on M.9 NAKBT337 than for trees on G.16, and trees on M.26 EMLA were intermediate. At CDs of 6.0 and 9.0, rootstock did not significantly influence FW.

Pennsylvania. The planting was located at the Rock Springs Research Farm at 40.7N latitude, -77.95N longitude, and 366 m above sea level. Irrigation was provided when needed. Upon removal of apples the site was planted in row crops for three years and was not fumigated. There were high crop loads for three consecutive years (Table 13). The slopes were always least negative for trees on M.9 NAKBT337 and most negative for trees on M.26 EMLA. However, the difference was statistically significant in only 2008. At all values of CD, trees on G.16 consistently had the lowest FW, but the influence of rootstock on FW varied with year and CD. When compared at a CD of 3.0, trees on M.26 EMLA had higher FW than trees on G.16 in 2008. At a CD of 6.0, trees on G.16 had the lowest FW in 2006 and 2008. In 2007, trees on G.16 had lower

Table 12. The relationship between fruit weight (FW) and crop density (CD) as influenced by three rootstocks in 2006 in Ontario. Coefficients for intercepts and slopes along with LSmeans for FW estimated for three levels of CD are presented.

Year	Stock	Intercept	Slope	FW(g) at CD (fruit·cm^{-2})^z 3.0	6.0	9.0
2006	G.16	160.0	-0.2b	160b	159	159
	M.26 EMLA	179.7	-2.8ab	171ab	163	154
	M.9 NAKBT337	198.3	-5.2a	183a	167	152

^{z} Values within column and year followed by common letters do not differ at the 5% level of significance, by contrasts.

Table 13. The relationship between fruit weight (FW) and crop density (CD) as influenced by three rootstocks in three years in Pennsylvania. Coefficients for intercepts and slopes along with LSmeans for FW estimated for three levels of CD are presented.

Year	Stock	Intercept	Slope	FW(g) at CD (fruit·cm^{-2})[z]		
				3.0	6.0	9.0
2006	G.16	195.9	-5.3	180	164b	148b
	M.26 EMLA	212.9	-5.3	197	181a	165ab
	M.9 NAKBT337	203.1	-4.1	191	179a	167a
2007	G.16	187.6	-6.8	167	147b	126
	M.26 EMLA	205.6	-9.0	179	152ab	125
	M.9 NAKBT337	188.9	-3.4	179	169a	159
2008	G.16	185.6	-7.2ab	164b	142b	121b
	M.26 EMLA	241.6	-11.7b	206a	171a	136ab
	M.9 NAKBT337	197.6	-5.7a	180b	163a	146a

[z] Values within column and year followed by common letters do not differ at the 5% level of significance, by contrasts.

FW than trees on M.9 NAKBT337. At a CD of 9.0, trees on M.9 NAKBT337 had higher FW than trees on G.16 in 2006 and 2008 but the difference was not significant in 2007.

Utah. The planting was located at the Utah Agricultural Experiment Station Farm in Kaysville at 41.2N latitude, -111.93W longitude, and 1,334 m above sea level. The soil was Kidman fine sandy loam and well drained. The site was irrigated, but soil was not fumigated before planting. CD was adequate for analysis in 2006 and 2008 (Table 14), but slopes and FW were not significantly influenced by rootstock in either year.

Wisconsin. The planting was located at the Peninsular Agricultural Research Station in Sturgeon Bay at 44.9N latitude, -87.33W longitude, and 220 m above sea level. This site was planted to apples for more than 50 years. Trees were removed in 2000, ploughed and planted to sod in fall 2000. Irrigation was provided but soil was not fumigated. CD never exceeded 9.0, but exceeded 7.5 in three years (Table 15). 'Golden Delicious' historically does not set heavy crops on this site (personal communication with M. Stasiak). The slopes did not significantly differ in any year, but FW was highest for trees on G.16 in 2008. Although not often significant, the other two years, FW tended to be highest for trees on M.9 NAKBT337.

Discussion

It is difficult to compare results from this study with most of the previous reports where data were not subjected to ANCOVA, where data were analyzed with inappropriate software, or where a typical ANCOVA was performed with no indication that the underlying assumptions were verified. In only two previous rootstock studies were assumptions reportedly tested (16, 18) and in both cases, the hypothesis of homogeneous slopes was rejected. Since the hypothesis of homogeneous slopes was again rejected in this study, the evidence is very strong that a typical ANCOVA used to adjust FW values for differences in CD is inappropriate for multi-location rootstock trials and an unequal slopes model is needed to account for the interaction

Table 14. The relationship between fruit weight (FW) and crop density (CD) as influenced by three rootstocks in two years in Utah. Coefficients for intercepts and slopes along with LSmeans for FW estimated at CD= 6.0 are presented.

Year	Stock	Intercept	Slope	FW (g)[z]
2006	G.16	250.5	-8.5	200
	M.26 EMLA	221.7	-2.0	210
	M.9 NAKBT337	239.2	-6.2	202
2008	G.16	202.1	-8.2	153
	M.26 EMLA	193.8	-8.7	141
	M.9 NAKBT337	184.6	-6.1	148

Table 15. The relationship between fruit weight (FW) and crop density (CD) as influenced by three rootstocks in three years in Wisconsin. Coefficients for intercepts and slopes along with LSmeans for FW estimated at CD= 6.0 are presented.

Year	Stock	Intercept	Slope	FW (g)
2007	G.16	201.8	-4.4	175
	M.26 EMLA	221.6	-5.7	187
	M.9 NAKBT337	219.6	-4.8	191
2008	G.16	220.0	-7.8	173
	M.26 EMLA	211.1	-10.7	147
	M.9 NAKBT337	268.1	-16.7	168
2009	G.16	187.1	-5.5	154
	M.26 EMLA	199.8	-9.1	145
	M.9 NAKBT337	204.9	-7.3	161

of rootstock and CD.

In this study, slopes for the regression of FW on CD generally ranged from 0 to -12.0 and are similar to previously reported slopes. Treder (23) studied the influence of CD on FW for 'Gala' trees on P.60 rootstock for 7 years when CD ranged from about 2.0 to 10.5 fruit•cm^{-2} and slopes ranged from -1.35 to -8.17. Webb et al. (25) hand-thinned 'Golden Delicious' trees on MM.106 rootstock to CDs ranging from 2.7 to 18.6 and reported a slope of -2.38 with an R^2 of 0.85.

The effect of rootstock on FW was inconsistent in this study. Rootstock significantly affected FW for 20 of the 29 combinations of location and rootstock. There was a significant rootstock x CD interaction for 13 of the 29 combinations, so 45% of the time the relationship between FW and CD was affected by rootstock. At the highest CD, trees on M.9 NAKBT337 produced the largest fruit for 11 of the combinations (38% of the time) and trees on G.16 produced the smallest fruit 41% of the time. At the moderate CD, the largest fruit were produced on trees budded to G.16, M.26 EMLA and M.9 NAKBT337, 10%, 10% and 31% of the time, respectively. Trees on G.16 produced the smallest fruit 34% of the time. For the low CD, the largest fruit were produced on trees budded to G.16, M.26 EMLA and M.9 NAKBT337, 3%, 14% and 17% of the time, whereas trees on G.16 produced the smallest fruit 17% of the time.

Rootstock or the interaction of rootstock and CD was significant for 8 of the 12 locations in this study, but results were not very consistent from one location to another or from year to year within a location, as was previously reported for FW (18). An extreme example was Chihuahua, where trees on M.9 NAKBT337 produced the largest fruit and trees on G.16 produced the smallest fruit in 2006, but the opposite occurred in 2009. Therefore other factors such as drought stress, time of fruit thinning, or other factors likely affect the influence of rootstock on FW.

Other recent reports also indicate that rootstock can affect apple FW. Autio and Krupa (3) compared 10 rootstocks over a five-year period with 'Ginger Gold' as the scion cultivar. Although trees on B.469 had yields 80% lower and yield efficiency 23% lower than trees on M.9 NAKBT337, FW was 40% lower for trees on B.469. Univer et al. (24) compared 12 rootstocks with the scion cultivar 'Auksis' in two locations in Lithuania. FW for trees on M.9 NAKBT337 and M.26 EMLA was significantly higher than for trees on P.59 and P.67 at both locations. Larson et al. (12) compared two strains of 'Delicious' and 'Golden Delicious' in Washington over four seasons and found that trees on M.26 EMLA usually

Table 16. The effect of rootstock on mean fruit weight estimated at three levels of CD averaged over all years and locations. Also presented are the regression coefficients for each rootstock obtained from a typical ANCOVA.

	Regression coefficients		CD (fruit•cm^{-2} trunk cross-sectional area)		
Rootstock	Intercept	Slope	3.0	6.0	9.0
G.16	209.9	-7.49ab[z]	186b[z]	164b	142b
M.26 EMLA	221.4	-7.93a	197a	173ab	148ab
M.9 NAKBT337	219.8	-6.74b	198a	178a	158a

[z] Slopes and LSmeans within columns followed by common letters do not differ at the 5% level of significance, by DIFF.

produced larger fruit than trees on seedling, M.7 or MM.109. In a 17-year study with a spur-type and standard strain of ‘Golden Delicious’, FW was not significantly different for trees on M.26 EMLA and M.9 EMLA, but averaged over all years, FW was 4.6% higher for trees on M.26 EMLA and CD was 16.7% higher for trees on M.9 EMLA (6). In other rootstock trials, trees on M.9 NAKBT337 were among those with the highest FW (2, 4, 9, 16, 18, 22).

In an attempt to summarize the main effect of rootstock, a typical ANCOVA was performed ignoring all the significant interactions. Regardless of CD, FW was lowest for trees on G.16 and highest for trees on M.9 NAKBT337 (Table 16). Averaged over all locations, years and CDs, FW was 171 g, 180 g, and 184 g, respectively for trees on G.16, M.26 EMLA and M.9 NAKBT337, and this translates to an average box count (fruit/19.05 kg unit) of 112, 106 and 103, respectively. Average annual yield was 18.2 kg, 19.9 kg and 20.1 kg, respectively for trees on G.16, M.26 EMLA and M.9 NAKBT337. Despite attempts to adjust crop load to specified levels, trees on G.16 averaged 9% less yield and produced fruit that were about 7% smaller than trees on M.9 NAKBT337. The combination of higher yields and larger fruit would likely lead to higher profitability for orchards using M.9 NAKBT337 compared to G.16 rootstock.

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Physiological responses of kiwifruit vines (*Actinidia chinensis* Planch. var. *chinensis*) to trunk girdling and root pruning

Hydraulic conductance and photosynthesis were measured in kiwifruit (*Actinidia* sp.) vines to observe responses to the horticultural practices of trunk girdling and root pruning. Little is understood regarding the physiological effects of these practices in kiwifruit. Combined reductions in hydraulic conductance and photosynthesis were expected following root pruning. The primary response to trunk girdling was expected to be photosynthetic. Measurements of transpiration and xylem pressure potentials (Ψ) were used to calculate hydraulic conductance (K). Stomatal conductance (g_s) and photosynthesis (A) were measured periodically. Neither treatment affected fruit growth. The response to root pruning was primarily hydraulic with significant reductions in midday Ψ indicating reduced K; reductions in A and g_s were small. Girdling resulted in significant reductions in g_s and A, with little effect on Ψ or K. Reduced A following girdling was considered to be a consequence of stomatal and biochemical limitation, with biochemical down-regulation following reduced carbohydrate demand. Abstract from M.Z. Black et al., 2012. New Zealand Journal of Crop and Horticultural Science 40(1): 31-41.