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The Influence of Crop Density on Annual Trunk Growth of 'Golden Delicious' Apple Trees on Three Rootstocks at 11 Locations

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Abstract

'Golden Delicious' apple trees [*Malus* x *domestica* (Borkh.) on three dwarfing rootstocks were grown at 11 locations in North America, and crops were adjusted to varying levels of crop density to determine if rootstock influenced the relationship between crop density and annual trunk growth over a 5-year period. Analysis of co-variance was used to evaluate both separate and interactive effects of crop density and rootstock on annual trunk growth. In most cases there was a negative linear relationship between crop density and trunk enlargement. There was rarely a significant interaction between rootstock and crop density, indicating that the suppression of trunk growth by cropping was similar for all rootstocks. Regardless of crop density, trees on M.26 EMLA generally exhibited the most annual trunk enlargement, trees on G.16 exhibited the least trunk enlargement, and trees on M.9 NAKBT337 were intermediate.

Cropping has long been known to suppress vegetative growth of apple trees. Fruiting suppressed shoot growth (4, 7), trunk enlargement (7, 19) and root growth (4, 11). Rootstocks also greatly influenced trunk cross-sectional area (TCA) as well as cropping (2, 3, 6, and 14). Because dwarfing rootstocks tend to induce heavier cropping than vigorous rootstocks, it is difficult to separate the effects of rootstock from the effect of crop load on vegetative growth. The influence of rootstock on seasonal vegetative growth appears at least partially independent of cropping, because trees on M.9 grew less than trees on M.16 even when trees were defruited (4). In several NC-140 rootstock trials TCA of young non-cropping trees was influenced by rootstock (unpublished data). Preston (17) also found that the annual increment in trunk girth of mature trees was about 20% less for trees on M.7 than for trees on the more vigorous M.2 rootstock whether trees were fruit-thinned or not.

Maximum orchard profitability depends on the ability to rapidly fill orchard space while avoiding excessive tree crowding and shading as trees mature. Vegetative shoots are the primary cause of tree crowding in intensive orchards, and shoot growth has been positively correlated with trunk growth (21). TCA was linearly correlated with scion weight of 17-year-old trees, and the slope was similar for four cultivars on seven rootstocks ranging in vigor from M.9 to MM.111 (6). Therefore, TCA is a good predictor of above-ground tree size.

Rootstocks are the primary method of growth control in commercial orchards. Because fruiting can also influence growth, it is desirable to understand how that influence varies with rootstock. Although the negative relationship between growth of all tree parts and cropping is well documented (10), the influence of rootstock on this relationship has not been reported. An understanding of how ultimate tree size is influenced by rootstock and cropping is necessary to design orchards for optimum profits. This study was performed to determine the influence of rootstock on the relationship between crop density (CD) and annual trunk growth at a number of locations in North America with varying growing conditions.

Materials and Methods

In spring 2003, a rootstock trial, referred to as the "NC-140 apple physiology trial", was established at 11 locations in North

America. Cooperators and locations of the plantings are listed in Table 1. At each location, 10 'Golden Delicious' (Gibson strain) trees on three dwarfing 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 adequate, crop densities (CD) were adjusted by hand thinning at about 25 to 30 days after full bloom to achieve five CD levels. Two trees per rootstock were thinned to target 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 of TCA to ensure adequate return bloom so that crop load treatments could be re-imposed 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, no chemical thinners were applied, and the cooperators adjusted the CDs appropriately. Each year, the treatments were re-randomized to the 10 trees per rootstock. Each season for each location, TCA measured 30 cm above the graft union and number of fruit harvested per tree were recorded and used to calculate CD. Additional details of the study were previously described (13).

Statistical analysis. The study was a multi-location experiment involving a repeated measures model (TCA measured on the same tree each year) with a time-varying covariate (CD). The entire data set could not be analyzed as a single experiment, because several assumptions required for analysis of covariance were violated, especially homogeneity of variances, homogeneity of slopes, and a similar range of values for the covariate. Therefore, the approach described by Allison (1) was used to analyze data by location and year. For each tree the annual increase in TCA (cm^2) was estimated as the difference in TCA between two consecutive years. An analysis of covariance (ANCOVA) was then performed for each combination of site and year, where annual TCA increase was the response variable, rootstock was the indicator or class variable, and CD (fruit/cm^2 of TCA) was the covariate. When CD as a covariate was not significant, data were analyzed by ANOVA. Although Allison (1) used SAS's REG and GLM procedures, the Mixed procedure was used in this study, because it was easier to obtain parameter estimates for the three rootstocks and because it was possible to utilize different covariance structures. Data were analyzed using ANCOVA strategies

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
(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, Matt Stasiak	Sturgeon Bay

suggested by Littell et al. (12) and Milliken and Johnson (16), and further explained by Marini and Ward (15).

Results

Annual trunk growth varied with location and year (Tables 2-12). Most years, annual TCA enlargement was generally greatest in Kentucky (Table 6) and lowest in Ontario (Table 3), and it tended to be higher in years with low CDs. With the exception of New York and Ontario, annual TCA enlargement was always influenced by rootstock, and it was linearly related to CD for at least one year at nine of the 11 locations. The interaction of rootstock x CD was significant for at least one year at four locations, indicating that the linear relationship between CD and TCA enlargement depended on rootstock (Tables 9, 10, 11, 12). To facilitate interpretation, the locations were grouped according to the variables that affected TCA enlargement. Intercepts and slopes obtained with the solution option in Proc Mixed are presented, even when not significant (indicated by the P-value for CD), to illustrate the variation in those parameter estimates for a wide range of conditions.

Locations where TCA enlargement was affected by only rootstock. Since TCA enlargement was affected by only rootstock in Chihuahua and Ontario, data were analyzed by ANOVA. For Chihuahua, annual mean values for CD ranged from 0.5 to 7.0, and the effect of CD as the covariate was not significant in any year (Table 2). Rootstock significantly affected TCA enlargement each year. Trunk enlargement was consistently similar for G.16 and M.26 EMLA, and TCA it was usually highest for M.26 EMLA and always was lowest for M.9 NAKBT337. TCA enlargement was lowest in 2006 and 2009 when mean CD was ≥ 4.8. For Ontario, the mean CD was moderate (5.7) in 2006, but CDs were < 2.8 for the following four years (Table 3). TCA enlargement was affected by rootstock in 2009 when trees on M.26 EMLA exhibited the largest increase and in 2010 when trees on G.16 grew most.

Table 2. Chihuahua - Mean crop density (CD), regression parameters and LSmeans for annual increase in TCA (cm^2) for 'Golden Delicious' apple trees on three rootstocks over five years. [z]

	2006		2007		2008		2009		2010	
	Mean CD (fruit/cm² TCA)									
	7.0		0.5		1.8		4.8		1.1	
Rootstock	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope
G.16	7.1	-0.44	5.9	-0.16	6.3	0.41	9.2	-0.84	18.8	-7.30
M.26	7.5	-0.44	7.8	-0.38	7.3	0.20	2.1	-0.33	14.5	-1.79
M.9	7.4	-0.49	6.3	-0.21	3.4	-0.64	6.3	-0.84	4.7	-1.85
	LSmeans for TCA enlargement (cm²) adjusted for the mean value of CD									
G.16	3.64 a [y]		8.12 ab		7.22 a		5.16 a		10.24 a	
M.26	3.72 a		9.64 a		7.63 a		3.63 ab		12.07 a	
M.9	1.49 b		5.70 b		1.76 b		0.80 b		3.70 b	
	Significance (P-value) from ANCOVA									
Stock	0.008		0.001		0.002		0.012		0.001	
CD	0.198		0.211		0.954		0.391		0.127	

[z] LSmeans were not adjusted for CD because CD and the CD x rootstock interaction were not significant for any year.
[y] LSmeans with year not followed by common letters are different at the 5% level of significance, by DIFF following ANOVA.

Table 3. Ontario - Mean CD, regression parameters and LS means for annual TCA (cm^2) increase for 'Golden Delicious' apple trees on three rootstocks over five years. [z]

	2006		2007		2008		2009		2010	
	Mean CD (fruit/cm^2 TCA)									
	5.7		2.7		2.7		2.6		2.3	
Stock	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope
G.16	4.3	-0.57	0.3	0.92	0.1	0.01	2.6	0.10	5.6	-0.66
M.26	1.4	-0.06	-2.4	2.14	3.2	-1.04	3.9	-0.10	3.9	-0.25
M.9	4.3	-0.19	3.4	-0.47	0.8	-0.28	2.7	0.08	4.9	-0.84
	LSmeans for TCA enlargement (cm^2) adjusted for the mean value of CD									
G.16	0.96 [y]		2.71		0.05		2.89b		4.08a	
M.26	1.11		4.49		0.01		6.64a		3.37ab	
M.9	3.27		2.34		0.13		2.90b		2.92b	
	Significance (P-value) from ANCOVA									
Stock	0.114		0.708		0.356		0.001		0.001	
CD	0.343		0.175		0.065		0.894		0.085	

[z] LSmeans were not adjusted for CD because CD and the CD x rootstock interaction was not significant for any year.
[y] LSmeans within years not followed by common letters are different at the 5% level of significance, by DIFF following ANOVA.

Table 4. New York - Mean CD, regression parameters and LS means for annual increase in TCA (cm^2) estimated with analysis of covariance for 'Golden Delicious' apple trees on three rootstocks over four years. [z]

	2006		2007		2008		2009	
	Mean CD (fruit/cm^2 TCA)							
	4.2		6.8		6.1		5.8	
Stock	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope
G.16	7.7	-0.45	8.2	-0.61	7.9	-0.38	12.6	-0.59
M.26	8.8	-0.55	8.2	-0.41	10.5	-0.58	13.6	-0.71
M.9	7.8	-0.50	7.3	-0.43	10.4	-0.66	12.5	-0.33
	LSmeans for TCA enlargement (cm^2) adjusted for the mean value of CD							
G.16	5.93 [y]		4.14		5.90		9.10	
M.26	6.47		5.34		7.04		9.49	
M.9	5.76		4.29		6.42		10.54	
	Significance (P-value) from ANCOVA							
Stock	0.627		0.102		0.327		0.270	
CD	0.005		0.011		0.001		0.001	

[z] LSmeans were adjusted for the mean value of CD with a normal analysis of covariance because the CD x rootstock interaction was not significant.
[y] LSmeans adjusted for CD within year not followed by common letters are different at the 5% level of significance, by DIFF, following ANCOVA.

Locations where TCA enlargement was affected by only crop density. New York reported relatively high CDs and was the only location where TCA enlargement was not affected by rootstock (Table 4). However, TCA enlargement was negatively related to CD for all four years (Table 4). Slopes were relatively uniform across rootstocks and years.

Locations where TCA enlargement was affected by rootstock and crop density. TCA enlargement was influenced by both rootstock and CD at four locations and since the CD x rootstock interaction was never significant, rootstock LSmeans were adjusted for the mean value of CD using a normal ANCOVA. For British Columbia, rootstock and the covariate CD significantly affected incremental TCA every year (Table 5). Although annual TCA enlargement was generally greatest for M.26 EMLA and lowest for G.16, except in 2010, after adjusting for CD, TCA enlargement was significantly influenced by rootstock in only 2007 and 2009, both years with low CD. Within years, slopes for TCA enlargement were homogeneous and the magnitude of the slopes across years was inconsistently related to the mean value of CD. Trees in Kentucky exhibited a classic alternate-bearing pattern with mean CDs exceeding 5.0 in 2006, 2008 and 2010, and CD was zero in 2007 and only 1.6 in 2009 (Table 6). TCA enlargement was related to CD in two of the three high crop years, but not in the low crop years. For three of the four years, TCA increase was higher for trees on M.9 NAKBT337 than for trees on G.16. Trees in Massachusetts had a typical alternate bearing pattern with low CDs in 2006, 2008 and 2010 and high CDs in 2007 and 2009 (Table 7). TCA enlargement was not consistently related to CD even in years with a relatively large range of CDs, nor was the magnitude of the slope related to CD across years. TCA enlargement was generally greatest for trees on M.26 EMLA and was usually numerically lowest for trees on M.9 NAKBT337, and trunk growth tended to be lower in years with high CDs. For Wisconsin, data were avail-

Table 5. British Columbia - Mean CD, regression parameters and LS means for annual increase in TCA (cm^2) estimated with analysis of covariance for 'Golden Delicious' apple trees on three rootstocks over five years. [z]

	2006		2007		2008		2009		2010	
	Mean CD (fruit/cm² TCA)									
	7.6		1.4		5.4		2.4		6.3	
Stock	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope
G.16	4.4	-0.17	8.4	-1.93	5.5	-0.40	4.8	-0.06	4.8	-0.30
M.26	6.6	-0.32	10.3	-1.90	7.7	-0.54	11.9	-1.63	5.6	-0.32
M.9	6.6	-0.34	7.4	-0.84	3.0	0.11	8.5	-1.27	4.3	-0.30
	LSmeans for TCA enlargement (cm²) adjusted for the mean value of CD									
G.16	3.17 a[y]		5.87 b		3.28 a		3.74 b		2.91 a	
M.26	4.13 a		7.82 a		4.88 a		7.87 a		3.53 a	
M.9	4.00 a		6.39 ab		3.55 a		5.32 b		2.40 a	
	Significance (P-value) from ANCOVA									
Stock	0.010		0.001		0.001		0.001		0.001	
CD	0.001		0.001		0.008		0.001		0.032	

[z] LSmeans were adjusted for the mean value of CD with a normal analysis of covariance because the CD x rootstock interaction was not significant.

[y] LSmeans adjusted for CD within year not followed by common letters are different at the 5% level of significance, by DIFF, following ANCOVA.

Table 6. Kentucky - Mean CD, regression parameters and LS means for annual increase in TCA (cm^2) estimated with analysis of covariance for 'Golden Delicious' apple trees on three rootstocks over five years.[z]

	2006		2007		2008		2009		2010	
Mean CD (fruit/cm^2 TCA)										
	5.5		0.0		8.8		1.6		5.4	
Stock	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope
G.16	11.8	-0.90	- - -	- - -	8.8	-0.23	21.8	-2.37	18.5	-1.66
M.26	16.5	-1.46	- - -	- - -	10.0	-0.16	28.4	-2.48	21.0	-2.34
M.9	14.9	-0.81	- - -	- - -	13.7	-0.42	22.9	0.48	11.1	-0.50
LSmeans for TCA enlargement (cm^2) adjusted for the mean value of CD										
G.16	6.86 b [y]		- - -		6.63 b		16.51 b		9.31	
M.26	9.09 ab		- - -		8.73 ab		23.35 a		8.29	
M.9	10.55 a		- - -		10.04 a		23.48 a		8.03	
Significance (P-value) from ANCOVA										
Stock	0.001		- - -		0.001		0.001		0.865	
CD	0.001		- - -		0.125		0.408		0.003	

[z] LSmeans were adjusted for the mean value of CD with a normal analysis of covariance because the CD x rootstock interaction was not significant.

[y] LSmeans adjusted for CD within year not followed by common letters are different at the 5% level of significance, by DIFF, following ANCOVA.

Table 7. Massachusetts - Mean CD, regression parameters and LS means for annual increase in TCA (cm^2) estimated with analysis of covariance for 'Golden Delicious' apple trees on three rootstocks over five years. [z]

	2006		2007		2008		2009		2010	
Mean CD (fruit/cm^2 TCA)										
	2.3		7.9		1.6		10.8		1.1	
Stock	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope
G.16	5.7	-0.12	5.1	-0.20	10.1	-1.55	4.3	-0.08	10.9	-1.34
M.26	5.8	0.50	6.1	-0.15	12.5	-1.10	4.5	0.04	15.1	-0.44
M.9	4.8	-0.45	4.0	-0.15	9.2	-1.00	4.0	-0.10	7.9	-0.48
LSmeans for TCA enlargement (cm^2) adjusted for the mean value of CD										
G.16	5.47a [y]		3.47b		7.58b		3.40b		9.31ab	
M.26	6.54a		4.92a		10.76a		4.82a		14.54a	
M.9	3.62b		2.89b		7.68b		2.88b		7.36b	
Significance (P-value) from ANCOVA										
Stock	0.001		0.001		0.001		0.001		0.001	
CD	0.318		0.006		0.004		0.109		0.178	

[z] LSmeans were adjusted for the mean value of CD with a normal analysis of covariance because the CD x rootstock interaction was not significant.

[y] LSmeans adjusted for CD within year not followed by common letters are different at the 5% level of significance, by DIFF, following ANCOVA.

Table 8. Wisconsin - Mean CD, regression parameters and LS means for annual increase in TCA (cm^2) estimated with ANCOVA for 'Golden Delicious' apple trees on three rootstocks over four years. [z]

	2006		2007		2008		2009	
Mean CD (fruit/cm² TCA)								
	1.7		5.2		4.3		4.9	
Stock	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope
G.16	14.6	-2.37	9.2	-1.41	8.2	-0.31	12.3	-0.58
M.26	6.2	0.04	11.6	0.76	14.9	-0.31	20.5	-0.92
M.9	12.6	-4.11	0.1	0.88	11.6	-0.54	19.3	-1.39
LSmeans for TCA enlargement (cm²) adjusted for the mean value of CD								
G.16	9.25		2.21b [y]		6.76c [y]		9.72c [x]	
M.26	6.26		14.40a		13.85a		16.06a	
M.9	8.47		6.11b		9.06b		12.06b	
Significance (P-value) from ANCOVA								
Stock	0.540		0.014		0.001		0.001	
CD	0.211		0.595		0.082		0.015	

[z] LSmeans were adjusted for the mean value of CD with a normal analysis of covariance because the CD x rootstock interaction was not significant.

[y] LSmeans adjusted for unequal sample size within year not followed by common letters are different at the 5% level, by ANOVA followed by DIFF.

[x] LSmeans adjusted for the average value of CD within year not followed by common letters are different at the 5% level of significance, by DIFF, following ANCOVA.

able for four years (Table 8). In 2006, TCA enlargement did not vary with rootstock, but in subsequent years was highest for trees on M.26 EMLA and usually lowest for trees on G.16. TCA increase was related to CD in only 2009. The slopes were fairly consistent regardless of year or rootstock.

Locations where the rootstock x crop density interaction was significant. The interaction of CD x rootstock was significant at four locations in at least one year, indicating that the relationship between TCA enlargement and CD depended on the rootstock. In Iowa, CD approached a typical alternate-bearing pattern with CDs exceeding 4.0 in 2006, 2008 and 2010, whereas CD was less than 2.8 in 2007 and 2009 (Table 9). TCA increase was affected by rootstock every year and CD was significant in 2006, 2008 and 2009. TCA enlargement was usually highest for trees on M.26 EMLA. In 2006 the slope was most negative for trees on M.26 EMLA, indicating that TCA enlargement was most negatively influenced by CD for M.26 EMLA. In Maine, trees were defruited in 2006 and 2008, but mean CD exceeded 6.2 in 2007 and 2009 (Table 10). TCA enlargement was greatest for trees on M.26 EMLA for three of the five years, but in the other two years trees on M.26 EMLA grew less than trees on G.16 Although TCA enlargement was affected by rootstock in all five years, the interaction of CD x rootstock was significant in only 2009. Despite exhibiting the greatest TCA enlargement in 2009, trees on M.26 EMLA also had the most negative slope, indicating that the rootstock was most affected by cropping.

For Pennsylvania, a wide range of CD was achieved in three of the first four years, so crop load was not adjusted in 2010 (Table

Table 9. Iowa - Mean CD, regression parameters and LS means for annual increase in TCA (cm^2) estimated with analysis of covariance for 'Golden Delicious' apple trees on three rootstocks over five years. [Z]

	2006		2007		2008		2009		2010	
	Mean CD (fruit/cm^2 TCA)									
	6.0		2.0		4.2		2.7		4.1	
Stock	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope
G.16	4.9	-0.29 b [y]	8.7	-0.54	8.9	-0.88	13.2	-1.76	15.7	-1.18
M.26	9.9	-0.98 a	12.0	0.27	14.0	-1.62	20.3	-3.20	13.9	0.44
M.9	5.6	-0.39 b	8.2	0.01	6.9	-0.01	17.7	-2.53	19.2	-1.45
	LSmeans for TCA enlargement (cm^2) adjusted for the mean value of CD									
G.16	3.11 b [x]		7.31 b		6.04 b		9.00 b		10.10 b	
M.26	4.04 a		12.39 a		8.94 a		12.07 a		15.21 a	
M.9	3.30 ab		8.16 b		6.90 ab		10.99 ab		12.66 ab	
	Significance (P-value) from ANCOVA									
Stock	0.001		0.001		0.001		0.001		0.001	
CD	0.001		0.882		0.027		0.001		0.089	
CDxStock	0.001		0.894		0.070		0.613		0.330	

[z] LSmeans were adjusted for the mean value of CD with a normal analysis of covariance.
[y] Slopes not followed by common letters are different at the 5% level of significance, by contrasts.
[x] LSmeans adjusted for the average value of CD within year not followed by common letters are different at the 5% level of significance, by DIFF, following ANCOVA.

11). Trunk growth was similar for trees on M.26 and M.9 NAKBT337 for all four years and trunk growth was higher for trees on M.26 than on G.16 for all years. In all four years, TCA enlargement was linearly related to CD and was also affected by rootstock. In 2009, the interaction of CD x rootstock was significant. Although TCA enlargement was greatest for trees on M.26 EMLA, trunk growth was also most negatively related to CD for trees on M.26 EMLA and least related to CD for trees on G.16. Slopes were also most negative in the relatively low cropping season of 2009.

For Utah, moderate crops were reported for all five years and the only year with high CD was 2006 with an average CD of 5.3 (Table 12). TCA enlargement was affected by rootstock every year and was generally lowest for trees on G.16. TCA enlargement was negatively related to CD every year except 2009 when the range of CD was narrow (1.2 to 3.2 cm^2). In 2008 and 2010 the interaction of CD x rootstock was significant, when slopes were most negative for trees on M.26 EMLA.

Discussion

This study provided a unique opportunity to evaluate the effect of rootstock and CD on vegetative growth of apple trees because data were collected at locations with diverse growing conditions and trees were thinned to provide a wide range of crop loads over a 5-year period. Although results were not always consistent between locations or even for years within location, some general observations can be reported. First, it is difficult to conduct multi-year crop-load adjustment experiments because crops can be reduced below desired levels by frost, hail, pollinating conditions, or unknown factors. Additionally, a number of cooperators expressed frustration with their inability to hand-thin trees to the desired CDs, because it was difficult to accurately count small fruits on the tree. Achieving the highest CDs was also complicated by the fact that at the time of hand thinning, TCA measured the previous fall was used to determine how much fruit to retain, but data were analyzed using TCA of the current season which had increased in size. Thus, CD was often lower than planned. The lack of measurable effect of CD on trunk growth in some cases may have been due to late timing of crop load manipulation in comparison to other studies in which crop load was adjusted at bloom (4). In this study, crop loads were adjusted around the time of "June drop" or up to 30 days after bloom, which shortened the duration in which crop load varied. Where a narrow range of CD occurred, the impact of CD on tree growth may be too small to detect.

The relationship between trunk growth and cropping was less consistent in this study than previously reported (5, 8, 18). Part of the reason may be because this study was more complicated, involving three rootstocks and 11 locations with varying climatic conditions and production practices. The diverse growing conditions are reflected in the average TCA of the 7-year-old trees, which varied from 25.2 cm^2 in Ontario to 80.7 cm^2 in Kentucky in 2010. There were 51 year-site combinations in this study and there was a significant rootstock x CD interaction for only five of those combinations, indicating that the effect of CD on TCA enlargement was usually similar for the three rootstocks. TCA increase was negatively related to CD for 26 year-site combinations and at nine of the 11 locations. Therefore, TCA increase was affected by CD only about 51% of the time, possibly because average CD exceeded 6.0 fruit/cm^2 of TCA only 24% of the time. For unknown reasons, TCA increase was never affected by CD in Ontario and New York. The effect of rootstock on TCA enlargement was fairly consistent. For the 51 year-site combinations, TCA

Table 10. Maine - Mean CD, regression parameters and LS means for annual increase in TCA (cm^2) estimated with analysis of covariance for 'Golden Delicious' apple trees on three rootstocks over five years. [z]

	2006		2007		2008		2009		2010	
	Mean CD (fruit/cm^2 TCA)									
	0		6.3		0		6.4		4.5	
Stock	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope
G.16	- - -	- - -	8.2	-0.31	- - -	- - -	9.7	-0.39b[y]	15.3	-0.27
M.26	- - -	- - -	1.1	0.62	- - -	- - -	16.4	-1.04a	1.73	0.13
M.9	- - -	- - -	5.9	-0.05	- - -	- - -	8.1	-0.33b	16.4	-1.51
	LSmeans for TCA enlargement (cm^2) adjusted for the mean value of CD									
G.16	7.27a[x]		6.04a		7.70b		7.23b		13.97a	
M.26	7.96a		4.62b		14.38a		9.77a		2.40b	
M.9	4.92b		5.58ab		7.02b		5.96b		8.72a	
	Significance (P-value) from ANCOVA									
Stock	0.001		0.003		0.001		0.001		0.008	
CD	- - -		0.871		- - -		0.001		0.601	
CDxStock	- - -		- - -		- - -		0.011		- - -	

[z] LSmeans were adjusted for the mean value of CD with a normal analysis of covariance.
[y] Slopes not followed by common letters are different at the 5% level of significance, by contrasts.
[x] LSmeans adjusted for the average value of CD within year not followed by common letters are different at the 5% level of significance, by DIFF, following ANCOVA.

Table 11. Pennsylvania - Mean CD, regression parameters and LS means for annual increase in TCA (cm^2) estimated with ANCOVA for 'Golden Delicious' apple trees on three rootstocks over four years. [z]

	2006		2007		2008		2009	
				Mean CD (fruit/cm² TCA)				
	6.0		5.5		5.6		3.3	
Stock	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope
G.16	7.9	-0.31	7.0	-0.36	6.9	-0.38	10.9	-0.91b[y]
M.26	11.4	-0.64	22.2	-2.64	9.6	-0.23	21.9	-3.01a
M.9	9.2	-0.40	9.4	-0.25	9.8	-0.43	16.3	-1.57ab
				LSmeans for TCA enlargement (cm²) adjusted for the mean value of CD				
G.16	6.06b[x]		5.04b		4.71b		7.90b	
M.26	7.59a		7.68a		8.28a		11.87a	
M.9	6.76ab		7.97a		7.39a		11.10a	
				Significance (P-value) from ANCOVA				
Stock	0.001		0.001		0.001		0.001	
CD	0.001		0.033		0.025		0.001	
CDxStock	0.332		0.183		0.086		0.015	

[z] LSmeans were adjusted for the mean value of CD with a normal analysis of covariance.
[y] Slopes not followed by common letters are different at the 5% level of significance, by contrasts.
[x] LSmeans adjusted for the average value of CD within year not followed by common letters are different at the 5% level of significance, by DIFF, following ANCOVA.

enlargement was numerically greatest for M.26 EMLA 73% of the time and smallest for G.16 61% of the time.

In previous studies, trees on M.26 EMLA usually had larger trunks than trees on M.9 NAKBT337 (3, 6), but this is the first report showing that annual TCA enlargement, even after adjusting for CD, was usually greater for trees on M.26 EMLA than for trees on M.9 NAKBT337. Data reported after 5 years (2) and after 10 years (3) of a rootstock experiment at 10 locations can be used to compare TCA and cumulative yield efficiency (YE, kg fruit/cm^2 of TCA) (2, 3). After 5 and 10 years, TCA was 18% and 26% larger for trees on M.26 EMLA compared to trees on G.16, respectively and YE was 49% and 17% higher for trees on G.16 than for trees on M.26 EMLA after 5 and 10 years, respectively. Although differences in YE for the two rootstocks declined during the second half of the study, rootstock differences in TCA continued to increase. Those data (2, 3) support results from the current study, where TCA enlargement was greatest for trees on M.26 EMLA regardless of tree age and cropping, and indicates that as trees age, annual trunk growth continues to be positively related to rootstock vigor even when there is little difference in YE.

In previous studies (5, 9), trunk growth was greater in nonbearing or lightly cropped trees compared to bearing or heavily cropped trees. In peach, trunk growth was also related to crop load with little or no change in slope due to level of nitrogen fertility or from year to year (18). Webster and Brown (20) used data from a 10-year nutrition experiment with eight-year-old 'McIntosh'/M.7 trees, to study the effect of the natural year-to-year variation in cropping on trunk growth and found no relationship between TCA increase and 10-year

Table 12. Utah - Mean CD, regression parameters and LS means for annual increase in TCA (cm^2) estimated with ANCOVA for 'Golden Delicious' apple trees on three rootstocks over four years. [z]

	2006		2007		2008		2009		2010	
	Mean CD (fruit/cm^2 TCA)									
	5.3		3.0		4.8		2.2		3.6	
Stock	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope	Int.	Slope
G.16	7.7	-0.46b[y]	11.6	-2.01	7.03	-0.37b	5.84	-0.46	9.4	-0.71b
M.26	15.4	-1.78a	12.1	-1.49	14.5	-1.70a	16.7	-2.52	28.2	-6.10a
M.9	10.5	-0.73ab	8.3	-0.72	13.2	-1.25a	14.9	-3.16	19.1	-2.38b
	LSmeans for TCA enlargement (cm^2) adjusted for the mean value of CD									
G.16	5.57		5.72b[x]		5.25		4.81b[x]		6.83b	
M.26	7.73		7.67a		6.28		9.90a		6.50b	
M.9	6.55		6.44ab		7.14		9.70a		10.60a	
	Significance (P-value) from ANCOVA									
Stock	0.001		0.001		0.001		0.001		0.001	
CD	0.001		0.001		0.001		0.170		0.001	
CDxStock	0.076		0.277		0.032		0.705		0.007	

[z] LSmeans were adjusted for the mean value of CD with a normal analysis of covariance.
[y] Slopes not followed by common letters are different at the 5% level of significance, by contrasts.
[x] LSmeans adjusted for the average value of CD within year not followed by common letters are different at the 5% level of significance, by DIFF, following ANCOVA.

mean yields. However when the mean change in TCA was plotted against CD for the first and second 5-year-periods of the experiment, they found significant linear relationships and the two slopes were identical with R^2s of 0.98. Although the slope of -0.42 was derived with 5-year means, it is within the range of slopes obtained in the present study.

Rootstock can affect the impact of cropping on apple tree growth (4, 8). However, rootstock studies are complicated by the fact that trees on some rootstocks are inherently more fruitful than others (5). In this study, which measured the impact of varying crop densities that were artificially manipulated by hand thinning, we found that in some cases, rootstock influenced tree growth response to crop load with M.26 being more sensitive than G.16 or M.9. Greater sensitivity to crop density may be considered a negative trait in high density systems when it induces greater tree growth in years with little or no cropping such as occurs in years with frost, poor pollination or insufficient chill chilling. Avery (5) found that when rootstock differences in fruitfulness were accounted for with container-grown 'Worcester Pearmain' trees, the effect of fruiting on growth of roots or aboveground parts of the tree were similar for all rootstocks. These data generally support data from the current study, where TCA increase was affected by rootstock 69% of the time and by CD only about half of the time, and the negative impact of CD on trunk growth was rarely influenced by rootstock.

In conclusion, important results from this study can be summarized as follows.

1. The effect of rootstock on vegetative growth varied with location.
2. Vegetative growth was related to rootstock vigor regardless of CD.
3. Vegetative growth was affected by CD

only about half the time, even with moderate to moderately high CD.

4. The effect of CD on vegetative vigor was usually similar for rootstocks varying in vigor.
5. Because the effect of rootstock and CD on vegetative growth was so variable, developing general strategies to manage vigor in intensive orchards will be challenging.

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Literature Cited

1. Allison, P.D. 2005. Fixed effects regression methods for longitudinal data using SAS®. SAS Institute Inc., Cary, NC.
2. Autio, W., T. Robinson, B.H. Barritt, J.A. Cline, R.M. Crassweller, C.G. Embree, D.C. Ferree, M.E. Garcia, G.M. Greene, E.E. Hoover, R.S. Johnson, K. Kosola, J. Masabni, M.L. Parker, R.L. Perry, G.L. Reighard, S.D. Seeley, and M. Warmund. 2005. Performance of 'Fuji' and 'McIntosh' apple trees after 5 years as affected by several rootstocks in the 1999 NC-140 apple rootstock trials. J. Amer. Pomol. Soc. 59:202-214.
3. Autio, W., T. Robinson, B. Black, T. Bradshaw, J.A. Cline, R.M. Crassweller, C.G. Embree, E.E. Hoover, S.A. Hoying, K.A. Iugerman, R.S. Johnson, G. Lang, M.L. Parker, R.L. Perry, G.L. Reighard, J.R. Schupp, M. Stasiak, and M. Warmund. 2011. Performance of 'Fuji' and 'McIntosh' apple trees after 10 years as affected by several rootstocks in the 1999 NC-140 apple rootstock trials. J. Amer. Pomol. Soc. 59:2-20.
4. Avery, D.J. 1969. Comparisons of fruiting and deblossomed maiden apple trees and of non-fruiting trees on a dwarfing and an invigorating rootstock. New Phytol. 68:323-326.
5. Avery, D.J. 1970. Effects of fruiting on the growth of apple trees on four rootstock varieties. New Phytol. 69:19-30.
6. Barden, J.A. and R.P. Marini. 2001. Comparisons of methods to express growth, size, and productivity of apple trees. J. Amer. Pomol. Soc. 55:251-256.
7. Barlow, H.W.B. 1964. An interim report on a long-term experiment to assess the effect of cropping on apple tree growth. Rep. E. Malling Res. Sta. 1963: 84-93.
8. Barlow, H.W.B. 1975. Effects of cropping on the growth of orchard trees. In: H.C. Pereira ed. Climate and the Orchard. Commonw. Bur. Hort. Plant. Crops Res. Rev. No. 5, 141 pp.
9. Boynton, D. and L.C. Anderson. 1956. Some effects of mulching, nitrogen fertilization, and liming on McIntosh apple trees, and the soil under them. Proc. Amer. Soc. Hort. Sci. 67:26-36.
10. Forshey, C.G. and D.C Elfving. 1989. The relationship between vegetative growth and fruiting in apple trees. Pp. 229-287. In: J. Janick. (ed.). Hort Rev. John Wiley & Sons, Hoboken, NJ. 229-287.
11. Head, G.C. 1969. The effects of fruiting and defoliation on seasonal trends in new root production on apple trees. J. Hort. Sci. 44:175-181.
12. Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. SAS for Mixed Models. 2nd Ed. 2006. SAS Inst., Cary, NC.
13. Marini, R.P., W.R. Autio, B. Black, J. A. Cline, W. Cowgill, Jr., R. Crassweller, P. Domoto, C. Hampson, R. Moran, R.A. Parra-Quezada, T. Robinson, M. Stasiak, and D. Wolfe. 2012. 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. J. Amer. Pomol. Soc. 66:78-90.
14. 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. Rom. 2001. Performance of 'Gala' apple on eight rootstocks: ten-year summary of the 1990 NC-140 rootstock trial. J. Amer. Pomol. Soc. 55:197-204.
15. Marini, R.P. and D. Ward. 2012. Using analysis of covariance with unequal slopes to increase ef-

ficiency and information obtained from designed experiments. J. Amer. Pomol. Soc. 66:91-100.
16. Milliken, G.A. and D.E. Johnson. 2002. Analysis of messy data. Vol. III: Analysis of covariance. Chapman and Hall/CRC, New York, NY.
17. Preston, A.P. 1969. Pruning trials with Laxton's Superb apple. Ann. Rept. East Malling Res. Sta. 1968: pp. 75-79.
18. Proebsting, E.L. 1958. A quantitative evaluation of the effect of fruiting on growth of Elberta peach trees. Proc. Amer. Soc. Hort. Sci. 71. 103-109.
19. Rogers, B.L. and A.H. Thompson. 1962. Yield, fruit size and growth of York Imperial trees as affected by chemical thinning and differential nitrogen nutrition for 6 years. Proc. Amer. Soc. Hort. Sci. 80:50-67.
20. Webster, D.H. and G.L. Brown. 1980. Trunk growth of apple trees as affected by crop load. Can. J. Plant Sci. 60:1383-1391.
21. Wilcox, J.C. 1937. Field studies of apple tree growth and fruiting. II. Correlations between growth and fruiting. Sci. Agr. 17:573-586.

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