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The Effect of Plant Growth Regulators on Apple Graft Union Flexural Strength and Flexibility

Stuart Adams[1,2], Brent L. Black[1,3], Gennaro Fazio[4] and Nicholas A. Roberts[5]

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Abstract

The apple rootstock 'Geneva® 41' ('G.41') forms weak graft unions with some scions. Exogenous plant growth regulators (PGR) can influence vascular differentiation and wood formation, and thus may improve graft union strength. A series of commercial and experimental PGR formulations were applied to trees on 'G.41' rootstock over two seasons in May and June, and graft union strength and flexibility were measured. Treatments included abscisic acid (S-ABA), 1-napthaleneacetic acid (NAA), prohexadione-calcium (PCa), and benzyl adenine (BA) as dilute sprays; and a concentrated formulation of BA applied in a latex paint solution to the graft union. BA in latex paint significantly increased the flexural strength per scion cross-sectional area and the flexibility of the union. Foliar applications of PCa also increased graft union flexural strength and flexibility, but temporarily limited scion extension growth. Applying PGRs in the nursery to more brittle rootstock-scion combinations may be an option for improving graft union strength and preventing tree losses. However, more efficient methods of application are needed for this approach to be commercially viable.

The United States Department of Agriculture - Agricultural Research Services (USDA-ARS), in conjunction with Cornell University has developed a series of apple rootstocks with resistance to the bacteria *Erwinia amylovora* (Norelli et al., 2003), the causal agent of fire blight (Robinson et al., 2007; Russo et al., 2007). These rootstocks are identified as Geneva® rootstocks and are given a unique number designation (e.g. 'Geneva® 11', 'Geneva® 41', 'Geneva® 935'). Geneva® rootstocks also have resistance to crown and root rots from *Phytophthora*, and induce high yield efficiency and good fruit size (Fazio et al., 2013). However, some of the Geneva® rootstocks appear to have weak or brittle graft unions that are susceptible to breakage. Some scions on 'Geneva® 41' have had losses of 20-40% in a single wind event in the nursery (R. Adams, personal communication). Due to the disease resistance and economic potential of these new Geneva® rootstocks, research to understand and remedy this brittleness problem is of great importance to the apple industry.

Application of exogenous plant growth regulators (PGRs) may provide an avenue for increasing graft union strength through improved callusing, vascular differentiation, or wood formation. However, studies on plant growth regulators and grafting can result in variable results due to differences in hormone balance among species and between graft partners. Several plant hormones have been suggested for influencing graft union development and wood strength, including: auxin, cytokinin, gibberellin inhibitors, and abscisic acid (S-ABA).

Auxin has been shown to increase callus proliferation and vascular differentiation in graft unions of vegetable and cactus grafts (Moore, 1983; Parkinson and Yeoman, 1982;

[1] Department of Plants, Soils and Climate, Utah State University, Logan, UT 84322-4820
[2] M.S. Graduate student. Present address: Willow Drive Nursery, Ephrata, WA 98823
[3] Corresponding author: brent.black@usu.edu
[4] Plant Genetic Resource Unit, USDA-ARS,Geneva, NY 14456
[5] Department of Mechanical and Aerospace Engineering, Utah State University, Logan, UT 84322-4120

Shimomura and Fuzihara, 1977; Stoddard and McCully, 1980). In a study with grapes, auxin application resulted in reduced or inhibited callus formation (Kose and Guleryuz, 2006). However, the grape study used concentrations that were 5 to 20 times higher than that of other studies, which may have been too high to induce a favorable response. Regardless, auxin may be a possible avenue for increasing graft success.

In the presence of auxin, cytokinins promote callus proliferation and differentiation of vascular tissue when many cell divisions are occurring (Aloni, 1995; Kose and Guleryuz, 2006; Parkinson and Yeoman, 1982). Exogenous cytokinins have also activated thickening growth in stems of cytokinin-deficient Arabidopsis mutants, including increased vessel number, number of cells in the phloem, and number of xylem cells with some of increased size (Matsumuto-Kitano et al. 2008).

Little research has investigated the effects of gibberellins (GA) on graft formation. Parkinson and Yeoman (1982) found that GA decreased the number of vascular connections when applied to grafted internodes in a petri dish. This negative effect suggests that GA inhibitors could be beneficial to improving graft success. Prohexadione-calcium (PCa) is a common GA inhibitor widely used for apple trees to reduce shoot growth and improve fire blight resistance. In apples, foliar PCa applications increased cortical parenchyma cell wall thickness of youngest leaves and shoots (Sundin, 2014). It is not clear to what extent this cell wall thickening would affect graft union strength.

Few studies have been published on the effect of S-ABA on the graft union. Parker et al. (2012) treated drought stressed peach trees with a soil drench of S-ABA and found that future drought tolerance was increased. S-ABA applications were also associated with increased trunk diameter, fresh weight, dry weight, and root growth. More recently, Murcia et al. (2016) found that S-ABA application to grapevines increased phloem area, but it is unclear how this would influence wood formation or strength. In poplar, exogenous S-ABA increased radial number of undifferentiated cambial cells and the formation of longer fiber cells, as well as fewer but larger, vessel cells (Arend and Fromm, 2013). S-ABA has also been shown to be synergistic with IAA and BA in promoting callus formation at the abscission zone of leaf petioles on citrus bud explants (Altman and Goren, 1971).

The objective of this study was to determine if exogenous plant growth regulator applications would have a positive effect on the growth characteristics and break strength of apple graft unions. More specifically, comparisons were made among growth regulators, and application methods. Results were compared based on both scion size (height and stem cross sectional area) and graft strength and flexibility.

Materials and Methods

2014 Study

Experiment Design. Rootstock liners of 'G.41' were chip budded in Aug. of 2013 with 'Scilate' and 'Gala' scion cultivars in a commercial apple nursery (Willow Drive Nursery, Ephrata, Washington). Within each scion, 22 blocks of 10 trees were selected for uniformity in Spring 2014 and assigned to one of 22 treatments. Treatments were not randomized within each row.

Plant Growth Regulator Application. The PGR and control treatments used in this preliminary experiment are described in Table 1. A single application of each PGR was made on 18 June. For those treatments receiving a second application, treatments were made on 15 July. Foliar applications were in dilute sprays until leaf drip, using a 4-L hand-pump spray bottle. Latex trunk paint treatments all contained 50% water and latex paint (v/v) and the PGR concentration shown in Table 1. Paint solutions were applied using 1 mL disposable pipettes so that every tree received ~ 2 mL.

Growth Measurements. Following harvest, four growth measurements were taken: root-

Table 1. Plant growth regulator treatments used in 2014. The commercial formulations, concentrations, application method, and number of applications are shown. ACC provided as experimental formulation from Valent BioSciences (Libertyville, IL).

Chemical Name	Trade Name	Concentration ($mg \cdot L^{-1}$)	Application method	# of Applications
Untreated control	–	NA	NA	NA
Painted control	Water+Paint	50:50 (v)	Graft Paint	1
NAA	Fruitone® N	20	Foliar Spray	1
NAA	Fruitone® N	20	Foliar Spray	2
NAA	Fruitone® N	250	Graft Paint	1
NAA	Fruitone® N	250	Graft Paint	2
IBA	Water+Ethanol	2600	Graft Paint	1
IBA	Water+Ethanol	2600	Graft Paint	2
ACC	Experimental	200	Foliar Spray	1
ACC	Experimental	200	Foliar Spray	2
ACC	Experimental	2500	Graft Paint	1
ACC	Experimental	2500	Graft Paint	2
Ethephon	Ethrel®	2500	Graft Paint	1
Ethephon	Ethrel®	2500	Graft Paint	2
S-ABA	ProTone® SG	320	Foliar Spray	1
S-ABA	ProTone® SG	320	Foliar Spray	2
S-ABA	ProTone® SG	4000	Graft Paint	1
S-ABA	ProTone® SG	4000	Graft Paint	2
BA	MaxCel®	2500	Graft Paint	1
BA	MaxCel®	2500	Graft Paint	2
GA_{4+7}	ProVide®	2500	Graft Paint	1
GA_{4+7}	ProVide®	2500	Graft Paint	2

stock shank diameter (5 cm below the graft union), two perpendicular graft union diameter measurements at the widest part of the graft union, scion stem diameter (5 cm above the graft union and scion height above the graft union.

Sample Preparation. In November, trees were harvested mechanically using standard commercial practices and kept in cold storage for later graft strength analysis. When ready for analysis, trees were topped to an overall length of about 70 cm and the roots, leaves and lateral shoots were removed. Trees were then bundled according to tree number, packed in ice and transported to a laboratory at Utah State University in Logan, Utah.

Break Strength Testing. In the laboratory, each specimen was loaded to failure using a 3-point bend apparatus with a 16 cm separation (Fig. 1). The apparatus was used in conjunction with a Bench Testing Machine (Tinius Olsen H50KS, Horsham, PA) operating in compression mode. The tests were performed with a fixed strain rate (25 cm/min) as per the ASTM Standard D790 and D7264, which are commonly used for testing of flexural strength of polymer composites and concrete (ASTM, 2010; ASTM, 2015). A pre-load condition of 10 N was used to bring the crosshead into contact with the specimen at a constant rate of 50 cm/min. Force measurements were acquired through the equipment software (Tinius Olsen Test Navigator) at 1-second intervals throughout the measurement until a failure condition was achieved. Upon achieving the failure condition, the fracture strength was obtained from the data based on the geometry of the 3-point

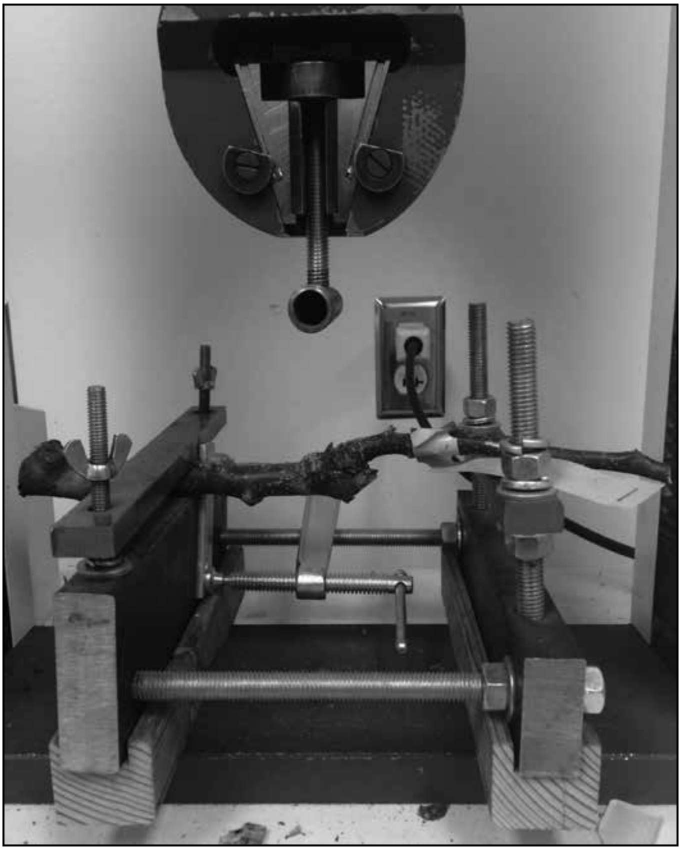

Fig. 1: Apparatus used for 3-point flexural strength testing. Sample supported with 16 cm separation with flexural strength and rigidity measured with a bench-testing machine. The sample shown is in "bud up" position where the chip bud is situated proximal to the displacement force.

bend apparatus and the specimen. For each treatment, five replicate samples were broken with the chip bud proximal to the displacement force (bud up), and five replicate samples were broken with the chip bud distal to the displacement force (bud down).

Each sample was categorized according to the nature and location of the resulting break. A clean break at the graft union was categorized as a 1st order break. A break just above the graft union but that included part of the graft union was categorized as a 2nd order break, as was a break just below the graft but including part of the graft union. A break at the graft union but with significant scion and rootstock tissue remaining attached was categorized as a 3rd order break. Finally, trees that broke well above or below the graft union, or that did not break under maximum test displacement were categorized as 4th order.

Data Analysis. Means were calculated and ranked for 2014 growth and break strength data. The following variables were analyzed: force (F), graft cross-sectional area (GCSA), scion cross-sectional area (SCSA), F/GCSA, and F/SCSA and height. Some of the trees had the top few centimeters broken during commercial harvest, so height measurements in 2014 may not be accurate.

Table 2. The plant growth regulators treatments used in 2015, their concentration, application method, and number of applications.

Chemical Name	Trade Name	Concentration a.i. (mg·L^{-1})	Application method	Application #
Control paint	Water+paint	50:50 (v)	Graft paint	2
BA	MaxCel®	5000	Graft paint	2
Control spray	Water+surfactant	NA	Foliar spray	2
Prohexadione-Ca	Apogee®	250	Foliar spray	1
Prohexadione-Ca	Apogee®	500	Foliar spray	1
NAA	Fruitone® N	20	Foliar spray	2
S-ABA	Protone® SG	400	Foliar spray	2

2015 Study

Experiment Design. Rootstock liners of 'G.41' chip budded with 'Scilate' and 'Gala' in Aug. of 2014 were selected in a commercial apple nursery (Willow Drive Nursery, Ephrata, Washington) in Spring 2015. Four adjacent rows were selected for each scion . Within each row, 96 trees were selected for uniformity and divided into 8 groups of 12 consecutive trees. The eight blocks in each row were then randomly assigned one of the eight treatments described in Table 2, such that each cultivar received all eight treatments with four replications, making a split plot design where the main plot treatments were scion cultivar and the sub-plot treatments were PGR.

Plant Growth Regulator Application. The PGR and control treatments are summarized in Table 2. For abscisic acid (ProTone® SG, Valent USA, Walnut Creek, CA), NAA (Fruitone® N, AMVAC Chemical, Newport Beach, CA), and the controls, the commercial non-ionic surfactant Regulaid® (Kalo, Inc. Overland Park, KS) was included at a concentration of 0.1% (v/v). A single application of PGR was applied on 14 May. A second application was made on 4 June for all treatments except PCa, due to concern that a second application of PCa could result in unacceptable reductions in tree height. Foliar applications were made in the same manner as 2014. Trunk spray was applied in a similar manner to foliar application except the spray was directed at the trunk, graft union, and about eight cm of scion stem until thoroughly coated and allowed to drip. For the first latex paint application, one-mL disposable pipettes were used to apply paint so that every tree received about two mL. Paint treatments were mixed such that half of the solution volume was latex paint. However, when BA (MaxCel®, Valent USA, Walnut Creek, CA) was mixed with the paint, the mixture was too thick to be applied with the pipettes, so the paint was applied using a paintbrush such that 5 cm of the rootstock, the graft union, and 1-2 cm of the scion stem were evenly coated. Although this did not allow for precise metering of the quantity of solution applied, it was estimated that approximately 2 mL was applied per tree. The second application of each paint treatment was then applied using just the paintbrushes to apply an even coat over the previous treatment area.

Growth Measurements. Rootstock, graft and scion diameters and stem height were measured 8 May (pre-treatment), 13 July (mid-season), and 12 Oct. (end of season), as described for 2014.

Sample Preparation. In Nov., trees were dug mechanically and kept in cold storage for later analysis. Six trees from each treatment group within each row were selected and topped to an overall length of 70 cm and the roots, leaves and lateral shoots removed. Diameters were re-measured to account for any changes during storage. Trees were then bundled according to replication number, packed in ice and transported to Utah State

University in Logan, Utah.

Break Strength Testing. Break strength was measured in the same manner as described for 2014. However, for 2015 only six trees were sampled per treatment group and replication, with three samples broken with the chip bud proximal to the displacement force and three samples broken with the chip bud distal to the displacement force. Deflection, or the maximum displacement of the testing machine between contact with sample and graft failure, was acquired in addition to the fracture strength described above. This measure was included to determine if any PGR treatments affected the flexibility of the graft union.

Data Analysis. Final CSA, deflection, and break strength data were analyzed in SAS using the GLIMMIX procedure and the Tukey-Kramer adjustment for multiple comparisons with nesting for each treatment per block. Height data showed a significant sampling time×PGR interaction and were analyzed by sampling time using the GLM procedure. For break type categorization, the GLIMMIX procedure was used for a multinomial analysis to determine the probability of lower order break types to occur based on the numeric order described above, where a clean break at the graft union was categorized as 1st order, and an unbroken sample or a break on the rootstock or scion not involving the graft union was categorized as 4th order.

Results and Discussion

2014 Study. Due to the lack of randomization or true replication, results from 2014 should be considered preliminary, but were used to identify PGR treatments that warranted further investigation in the subsequent study in 2015. Generally, few large numerical differences were measured for force, GCSA, SCSA, F/GCSA, or F/SCSA (Table 3). However, there were some interesting numerical trends. NAA foliar2, ABA foliar1, and BA latex2 tended to require greater force than the respective controls, regardless of scion or break direction. ACC foliar1 was the weakest treatment and lower than the untreated control.

NAA foliar2 tended to have a larger GCSA, while ABA foliar1 was only slightly larger than the control. Since ABA foliar1 did not increase the GCSA, there may be a stronger connection in the graft union relative to the graft union area. This is confirmed with F/GCSA, which shows that ABA foliar1 had break strength 24% higher than the untreated control. NAA foliar2 had essentially the same F/GCSA as the untreated control, which suggests that the greater strength could simply be due to tissue proliferation at the graft union, as indicated by increased GCSA.

BA latex2 on the other hand appeared to more directly affect the cross-sectional areas at the graft and the scion. As seen in Table 3, both BA treatments were among the largest for SCSA, with repeat applications resulting in the highest per-tree break strength. This suggests that the increase in strength of these trees is due to an increase in size or an expansion of the union rather than a strengthening of the tissue. This is confirmed in both the F/GCSA and F/SCSA being at an intermediate level.

Trends in this preliminary data suggested that an S-ABA foliar spray might actually increase the strength of the wood tissues in or around the graft union. On the other hand, NAA applied as a foliar spray, or BA applied in latex may increase the graft size, which leads to an increase in force required to break the tree.

2015 Study. Based on preliminary results in 2014, the 2015 treatments focused on S-ABA, NAA, and BA, with the addition of PCa. In 2015, there were no significant main effects on break force (Table 4), and only the scion cultivar had an effect on the GCSA. Also, no significant differences in break type were detected between PGR treatments. However, for SCSA, F/SCSA, and deflection there were significant PGR main effects, with SCSA showing a significant scion×PGR interaction. The PGR treatments that were among the highest in flexural strength cor-

Table 3. The effect of plant growth regulator (PGR) treatments on flexural strength (Force in Newton), graft cross-sectional area (GCSA), scion cross-sectional area (SCSA), force per graft cross-sectional area (F/GCSA), force per scion cross-sectional area (F/SCSA), and height of 'Scilate' and 'Gala' apples grafted on 'Geneva 41' rootstock. Values are averaged over scion cultivar, and treatments are ranked for each parameter.

PGR	Application	Force (N)		GCSA (cm^2)		SCSA (cm^2)		F/GCSA ($N \cdot cm^{-2}$)		F/SCSA ($N \cdot cm^{-2}$)		Height (cm)	
		Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank
BA	Latex2	566	1	8.56	1	1.94	1	65.9	7	292	4	204	4
S-ABA	Foliar1	511	2	6.78	12	1.71	9	75.3	1	301	2	204	5
GA_{4+7}	Latex1	483	3	7.27	6	1.93	2	65.2	9	249	17	196	11
NAA	Latex1	468	4	7.29	5	1.63	11	63.1	12	289	6	206	1
S-ABA	Latex1	461	5	6.89	10	1.81	6	66.4	6	252	16	205	2
Ethephon	Latex1	460	6	7.70	2	1.77	7	60.3	19	264	12	200	6
BA	Latex1	451	7	6.90	9	1.84	4	65.2	8	242	20	193	19
Control	Latex1	451	8	6.73	13	1.60	12	67.1	4	287	8	196	12
NAA	Foliar2	445	9	7.49	4	1.74	8	62.9	13	261	13	195	14
S-ABA	Foliar2	444	10	6.23	20	1.53	15	70.7	3	290	5	193	17
S-ABA	Latex2	441	11	7.57	3	1.92	3	57.9	20	229	21	199	7
GA47	Latex2	439	12	7.04	7	1.83	5	62.3	15	242	19	197	8
IBA	Latex1	428	13	6.02	22	1.44	20	73.3	2	302	1	205	3
ACC	Latex1	428	14	6.98	8	1.69	10	62.4	14	257	14	194	16
ACC	Foliar2	428	15	6.69	14	1.47	18	63.7	10	293	3	190	21
NAA	Foliar1	417	16	6.26	18	1.50	16	66.5	5	280	9	193	18
Ethephon	Latex2	404	17	6.23	19	1.48	17	63.5	11	271	10	192	20
ACC	Latex2	396	18	6.43	16	1.58	13	61.0	17	252	15	196	10
IBA	Latex2	394	19	6.86	11	1.42	22	56.6	21	270	11	194	15
NAA	Latex2	394	20	6.49	15	1.42	21	61.1	16	288	7	197	9
Control	Untreated	362	21	6.05	21	1.46	19	60.5	18	247	18	190	22
ACC	Foliar1	345	22	6.26	17	1.56	14	55.9	22	224	22	195	13

Table 4. A comparison of scion cultivar ('Scilate' and 'Gala') and PGR main effects for 2015 treatments. Comparisons are for flexural strength (Force), graft cross-sectional area (GCSA), scion cross-sectional area (SCSA) force per scion cross-sectional area (F/SCSA), and deflection. Main effect means followed by the same letter are not significantly different at $p < 0.05$. A dash indicates $p > 0.1$. Deflection is a measure of flexibility where greater deflection prior to failure indicates greater flexibility.

Effect		Force (N)	GCSA (cm^2)	SCSA (cm^2)	F/SCSA ($N \cdot cm^{-2}$)	Deflection (cm)
Scion	Gala	518	9.24 a	2.54 a	208 b	0.344
	Scilate	496	8.36 b	2.24 b	228 a	0.433
PGR	Control - paint	525	8.78	2.61 a	208 b	0.363 b
	BA paint	531	9.51	2.21 cd	250 a	0.601 a
	Control - water	514	8.95	2.50 ab	209 b	0.337 b
	BA spray	533	8.60	2.47 abc	226 ab	0.426 ab
	PCa 250	477	8.92	2.28 bcd	213 ab	0.403 ab
	PCa 500	498	8.63	2.15 d	236 ab	0.415 ab
	S-ABA	492	8.46	2.44 abcd	206 b	0.314 b
	NAA	486	8.48	2.48 abc	199 b	0.373 ab
Direction	Down	495	8.86	2.42	209 b	0.445 a
	Up	519	8.72	2.36	228 a	0.354 b
ANOVA p-values	Scion	–	0.006	0.002	0.083	–
	PGR	–	–	0.019	0.013	0.014
	Scion×PGR	–	–	0.033	–	–
	Direction	–	–	–	0.059	0.031
	Scion×Direction	–	–	0.006	–	–
	PGR×Direction	–	–	–	–	–
	Scion×PGR×Direction	–	–	–	–	–

rected for SCSA were BA applied as graft paint, BA as a trunk spray, and the high rate of PCa. The other PGR treatments, S-ABA, NAA and the low rate of PCa, showed little difference in F/SCSA compared to the controls (Table 4).

BA applied as a latex paint increased F/SCSA compared to both controls. However, break force per tree was the same as the painted control, indicating that the difference was due to a reduction in SCSA. Although the SCSA showed a significant scion×PGR interaction (Table 5), the BA paint treatment was smaller than the paint control for both scions. Kose and Guleryuz (2006) reported that cytokinin increases callus proliferation at the graft union. Although the paint applications of BA resulted in the largest measured GCSA in both years, these differences were not statistically significant.

Table 5. Interaction effects of plant growth regulator and scion treatment on scion cross-sectional area (SCSA) in the 2015 study. Separated by scion, main effect means followed by the same letter are not significantly different at $p < 0.05$.

PGR	SCSA (cm^2) 'Gala'		SCSA (cm^2) 'Scilate'	
Control - paint	2.90	a	2.3	ab
BA paint	2.50	abc	1.9	b
Control - water	2.67	abc	2.33	ab
BA spray	2.43	abc	2.51	a
PCa 250	2.30	bc	2.26	ab
PCa 500	2.26	c	2.04	ab
S-ABA	2.77	ab	2.11	ab
NAA	2.51	abc	2.45	ab

In addition to increased F/SCSA, BA paint also had a significantly higher deflection, or maximum lateral displacement before fracturing, than both controls. This indicates greater flexibility, which would contribute to reduced risk of breaking in the field. Part of this could be due to the reduced SCSA, however, the high rate of PCa had a similar reduction in SCSA without any increase in flexibility.

The high rate of PCa had a F/SCSA that was numerically higher than the control, but this difference was not significant (Table 4). Further, PCa temporarily reduced shoot growth by shortening internodes. The high rate PCa trees averaged 37 cm shorter than the control at the July measurement date, representing a 29% reduction in growth (Table 6). However, by harvest, these trees were only 13 cm shorter than the control, a difference less than 7% and not statistically significant. However, PCa treated trees continued to have a smaller SCSA and a section of shortened internodes that may be undesirable to growers. PCa also had a 23% increase in deflection compared to the control, which may help reduce damage in windy conditions.

This temporary reduction in scion growth is not surprising as PCa is a GA inhibitor used commercially to reduce vegetative growth in apple (Evans et al., 1997). How this reduction in stem elongation affects nursery tree value is not known. It is not clear whether or not PCa had any strengthening effect on the graft union.

Although F/SCSA for BA in a dilute trunk spray did not differ significantly from the water control, this treatment may merit further investigation. Compared to BA paint, BA in a directed aqueous spray could be more easily adopted by growers due to ease of application. The main challenge of any PGR use is efficient delivery of active ingredient to the appropriate plant tissue. Over both seasons, BA applied to the graft union appeared to be the most effective for increasing break strength. Additional work to improve delivery may make this approach the most commercially viable method of increasing graft union strength and flexibility.

Conclusion

These results indicate a possible strengthening to the graft union through the use of PGRs. In particular, results from both 2014 and 2015 showed BA applied in a latex paint increased GCSA leading to an increased break force requirement. However, BA paint did have reduced SCSA, which may be undesirable to the nursery. Applications in latex paint were more effective than aqueous trunk

Table 6. A comparison of tree height (cm) over three sampling times in 2015. PGR effect means followed by the same letter for each measurement period are not significantly different at $p < 0.05$.

	Height (cm)					
PGR	May		July		October	
Control - paint	18.8	a	129	ab	196	a
BA paint	19.3	a	128	b	181	b
Control - water	18.5	a	136	a	192	ab
BA water	18.0	a	133	ab	190	ab
PCa 250	19.6	a	109	c	178	b
PCa 500	18.5	a	99	d	179	b
S-ABA	18.2	a	133	ab	190	ab
NAA	17.6	a	129	ab	188	ab
ANOVA p-values						
Scion	–		–		–	
PGR	–		<.0001		0.0007	
Scion×PGR	–		–		–	

application, indicating that better methods for delivery are needed. PCa at higher rates may be another good option to increase strength per SCSA. However, reduced scion growth could reduce the value of the nursery tree. Increased flexibility of the graft would also allow more movement in the wind, and both BA and PCa increased graft flexibility as indexed by lateral displacement.

Lastly, while S-ABA and NAA treatments were among the strongest in 2014, these results did not occur in 2015. Results in previously published studies suggest that NAA has greater effect on graft strength. Our results may again highlight the difficulty of PGR delivery in a field application setting. However, our results from 2015 follow more of the results of Kose and Guleryuz (2006) who found cytokinin had more of a positive effect on the grape graft union than auxin. Additional research is needed to find more efficient methods of PGR delivery, and also to determine whether there is any long-term effects of the PGR treatments on subsequent orchard establishment before this approach can be recommended for nurseries to increase graft union strength.

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