Use of Plant Growth Regulators to Improve Apple Quality and Orchard Productivity

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Abstract

Plant growth regulators are often used to improve fruit quality and orchard productivity in modern apple production systems. Commercially available formulations of four of the five classical plant hormones are currently used in apple production systems around the world. Abscisic acid is the only classical plant hormone not currently registered on apples. Successful use of plant growth regulators is dependent on a sound understanding of the underlying physiological process they regulate, and how their activity is influenced by the individual and combined effects of environmental conditions and chemical stimuli. This review focuses on the use of plant growth regulators to control four key processes in apple production that can increase orchard productivity and profitability: flower bud formation and the control of biennial bearing, crop load regulation, fruit russet, and fruit set after a frost event during bloom.

INTRODUCTION

Plant growth regulators (PGRs) related in their mode of action to four of the five classical plant hormones (auxins, gibberellins, cytokinins, ethylene, and abscisic acid) are registered for use in apple production in various countries around the world. Abscisic acid is the only PGR from this group that is not currently registered for use on apple, although it is used commercially for coloring red table grapes in some countries. Current legal uses of PGRs in apple production systems include as a frost rescue treatment, for crop load regulation, promotion of flower bud formation, reduction of fruit skin defects, enhancement of fruit shape or typiness, reduction of pre-harvest fruit drop, and delaying the rate of fruit ripening. Successful use of PGR's can increase orchard profitability by reducing the severity of alternate bearing, reducing the labor needed for hand thinning, increasing yield after a damaging frost event during bloom, increasing the crop value by obtaining a target crop load that maximizes the proportion of high value fruit meeting size expectations of the market, and increasing fruit packout by reducing the incidence of skin defects such as russet or scarf skin, minimizing preharvest fruit drop, and controlling the rate of fruit ripening to facilitate more efficient labor management during the harvest process. However, in order to consistently achieve these benefits the grower must have a sound knowledge of the underlying physiological processes that are regulated by the PGR and how the response to the PGR may be modified by environmental conditions.

FLOWER BUD FORMATION AND CONTROL OF BIENNIAL BEARING

Vegetative and reproductive structures in an apple bud are formed during the season prior to their emergence. The earliest easily-observable indication of the transition from vegetative to reproductive development in an apple bud is when the meristem changes from flat (vegetative, only leaf primordial are initiated) to domed (reproductive, lateral flower primordial are initiated first while the king flower primordia is the last flower to be initiated). The meristem apex can be observed after carefully removing the bud scales, intermediate leaves, and true leaves from dissected apple buds under 40X magnification. Reproductive development proceeds relatively rapidly after doming, with sepals present on both the lateral and king flowers within 30 days after doming. The time of doming can vary among cultivars or even between years for the same cultivar. Dissection of 'Royal Gala' apple buds sampled from two-year-old wood on the same group of trees over a period of six years revealed the earliest observation of doming varied from 72 days after bloom in the earliest year to 99 days after bloom in the latest year (McArtney et al., 2001). This variability in the onset of doming did not appear to be related to factors such as heat accumulation or crop load. Hoover et al. (2004) reported that doming occurred earlier in 'Fuji' buds compared to buds of 'Royal Gala', 'Braeburn' or 'Pacific Rose'. Since both 'Fuji' and 'Pacific Rose' exhibit a strong alternate bearing tendency, the time of doming does not appear to be related to the biennial bearing habit.

The PGR's 2-chloroethyl phosphonic acid (ethephon) and naphthaleneacetic acid (NAA) are florigenic in apple (Williams, 1972, Harley et al., 1958) and are applied in commercial practice in the heavy-cropping year of an alternate bearing cycle to promote return bloom (Anon, 2016, McArtney et al, 2007; McArtney et al, 2013). A typical NAA program for stimulating flower bud formation consists of four bi-weekly applications at 5 mg/L beginning six weeks after petal fall, once the chemical fruit-thinning window has passed. Since the concentration of NAA is constant among cultivars it is typically included with consecutive cover sprays. Return bloom sprays of ethephon can be made as a single application five to six weeks after bloom at rates ranging from 280 g/Ha to 1,275 g/Ha of active ingredient, depending on variety. Higher rates of ethephon are applied to cultivars with a strong alternate bearing tendency such as 'Fuji' whereas lower rates are applied to more regular cropping cultivars such as 'Gala'. Because the ethephon rate in a return bloom spray is cultivar dependent, it is more difficult to combine this treatment with regular cover sprays where multiple cultivars may be treated with a single spray tank. Ethephon is not recommended as a return bloom spray on early season cultivars that have a tendency for preharvest fruit drop such as 'HoneyCrisp'. NAA and ethephon are not able to promote return bloom when crop load is excessive, and should be used in combination with other factors such as chemical thinning and adequate nutrition as part of an overall program to reduce an alternate bearing tendency.

Somewhat surprisingly, NAA or ethephon applications later than the period when doming is normally completed have also resulted in enhanced flower bud formation and return bloom. These results suggest that the transition to floral development can be triggered by a florigenic signal relatively late in the season i.e., either during the month leading up to harvest (McArtney et al., 2007; 2013; Fig. 1) or even during the postharvest period (Williams, 1972). The quality of these flower buds that develop late in the summer compared to those that develop in mid-summer has not been adequately determined. It might be expected that the limited time for development and reduced temperatures during the differentiation process might result in poor quality of vegetative e.g. spur leaf number and area, and floral tissues in late-developing flower buds.

CROP LOAD REGULATION

A successful chemical thinning program may have multiple benefits including ensuring that fruit size is within commercially desired and profitable targets, reducing the labor required for hand thinning to achieve a desired crop load, and partial mitigation of the negative effect of crop load on return bloom. PGR's that are approved for chemical thinning of apple include naphthaleneacetic acid (NAA), nahthaleneacetamide (NAD), 2-chloroethyl phosphonic acid (ethephon), and 6-benzyladenine (6-BA). Other, registered non-PGR chemical thinners of apple include caustic bloom thinners such as lime sulfur or ammonium thiosulfate, and post bloom thinners such as the photosynthetic inhibitor metamitron. PGR's exhibiting post bloom thinning activity but not currently registered include S-Abscisic acid (S-ABA) and the ethylene precursor 1-aminocyclopropane-1-carboxylic acid (ACC).

Post bloom thinners are normally applied when the mean diameter of fruitlets is between 5 mm and 15 mm. Prior to and after this time, the flowers and growing fruit are relatively insensitive to most chemical post bloom thinning agents. This interval also coincides with the period when young fruit are most sensitive to a transient carbohydrate stress such as that resulting from imposition of artificial shading treatments or to application of a photosynthetic inhibitor. The response to post bloom thinner applications can be erratic, and are commonly influenced by environmental conditions around the time of application. High night temperatures and/or cloudy days are often associated with excessive chemical thinning responses. These responses can be related to a low carbohydrate status in the fruit, which are weak carbohydrate sinks at this time relative to rapidly growing extension shoots.

Various researchers have speculated there is a direct link between the carbohydrate status of the fruit and the sensitivity of the abscission zone in the fruit pedicel to ethylene, and ultimately to fruit abscission. High night temperatures, cloudy days, or application of a photosynthetic inhibitor will reduce the carbohydrate status of the fruit, increasing the sensitivity of the abscission zone to ethylene. However, both a reduced carbohydrate status and an ethylene source are needed to trigger the abscission response. In my research experience I have encountered situations where a chemically-induced burst in ethylene production in the fruit was not associated with an increase in fruit drop. In these situations it could be speculated that an elevated carbohydrate status in the fruit rendered the abscission zone relatively insensitive to the ethylene burst. A low carbohydrate status in the fruit can be induced by various environmental and chemical stimuli including high night temperatures, cloudy days, shading treatments, 6-BA, NAA, metamitron or S-ABA. Chemical stimuli such as 6-BA, NAA, ethephon or ACC have been shown capable of providing the ethylene burst needed to activate the abscission zone in the fruit pedicel. The probability of over-thinning or under-thinning can be reduced when the individual and combined effects of environmental and chemical stimuli on the fruit abscission process are considered, and the rate or time of chemical thinner application is adjusted accordingly.

FRUIT RUSSET

Russet occurs as a normal part of the wound-healing process when microcracks in the fruit cuticle develop and expand as fruit enlarge, exposing the underlying hypodermal cells to air. This exposure triggers a wound healing response that results in formation of the cork cambium that is russet. While russet can develop in response to various stimuli including environmental conditions such as cloudy weather or high humidity, insect or pathogen attack, or caustic aggravation resulting from certain chemical sprays, cultivars may vary in their susceptibility to this fruit skin defect. In addition, the location and type of russet may vary between cultivars. 'Gala' typically develops russet at the stem end or within the shoulder of the fruit whereas 'Golden Delicious' can develop lenticel russet on the sides of the fruit. The severity of russet, and therefore the incidence of fruit that does not meet grade standards, can be reduced by three to four applications of 5-30 mg/L of a proprietary formulation of GA4+GA7 at seven to ten day intervals beginning at petal fall. This period is marked by the highest relative rates of area expansion at the fruit surface, resulting in significant strain on the cutin and epicuticular waxes that make up the fruit cuticle. The thickness of the fruit cuticle is approx. 2-3 microns at this time, and it is not uncommon for stresses to result in the development of microcracks in the fruit cuticle. Studies comparing the effect of lime sulfur thinning sprays on russet development between growing regions characterized by either a low humidity or a high humidity in the spring (McArtney, unpubl. data) revealed that multiple applications of lime sulfur thinning sprays during bloom increased the incidence of stem end russet in 'Gala' apples in both climates, however there was a much higher incidence of russet at harvest in the region with the more humid climate. These findings suggest that use of caustic sprays are more likely to exacerbate russet in more humid climates where the cuticle is thinner and the incidence of microcracks is expected to be higher compared to dry climates where the fruit cuticle tends to be better developed. These responses suggest that exposure of hypodermal cells not only to air, but also to potentially caustic active or inert ingredients in formulated chemical products can stimulate russet development.

The mechanism whereby gibberellins reduce the development of fruit russet is not clearly understood. Curry (2012) reported that multiple applications of GA4+GA7 on 'Golden Delicious' in a russet control program increased the epidermal planar cell density by up to 27% and reduced the planar area of individual epidermal cells by approx. 30%. It has been speculated that an increase in epidermal cell density resulting from GA4+7 sprays is associated with a structurally stronger fruit cuticle (Knoche et al. 2011) that will develop shorter and less invasive microcracks (Curry, 2012). Thus, it could be argued that a GA4+GA7 program reduces russet by stimulating cell division in epidermal cells in such a way that results in a fruit cuticle that is more capable of withstanding the strains resulting from rapid relative fruit expansion rates that would normally result in development of microcracking.

Somewhat paradoxically, the GA biosynthesis inhibitor prohexadione calcium (P-Ca) can itself inhibit the development of both fruit russet (McArtney, 2007) and a separate defect of the apple fruit cuticle referred to as scarf skin (McArtney, 2006). Combining P-Ca with the initial petal fall application of GA4+GA7 in a russet control program resulted in an additive reduction in the incidence of russet on 'Golden Delicious'. It is curious to speculate why an anti-gibberellin and GA4+GA7 might have similar, rather than antoagonistic, effects on apple fruit russet. Rademacher and Kober (2003) suggested that inactivation of exogenously applied

GA4 by 2β-hydroxylation could be inhibited by simultaneous treatment with P-Ca, resulting in increased GA activity. Thus, the rate of inactivation of exogenously applied GA4+GA7 in a russet control program may be reduced when P-Ca is included with one or more of the gibberellin applications, resulting in enhanced control of fruit russet.

FROST RESCUE

Apple flowers are most sensitive to cold temperatures at the full bloom stage when -2°C and -4°C are predicted to kill 10% and 90% of blooms, respectively (Ballard et al., 1998). Foliar gibberellin sprays increase fruit set and cropping in pears after cold injury has occurred during bloom (Ouma, 2008; Yarashnykov and Blanke, 2005) by stimulating parthenocarpic fruit development (Deckers and Schoofs, 2002; Luckwill, 1960). Gibberellins must be applied to pears within four days after a frost event to enhance fruit set, and gibberellic acid (GA3) is a more effective frost rescue treatment compared to GA4+GA7 (Deckers and Schoofs, 2002). Compared with pears, little is known regarding the effects of gibberellins as a frost rescue treatment of apple. McArtney et al (2014) demonstrated that application of 25 mg/L of a proprietary formulation of 6-BA plus GA4+GA7 to ‘Taylor Spur Rome’ apple trees the morning after a -4.5°C frost during bloom significantly increased fruit set, yield, fruit number per tree and crop value due to an increase in the number of parthenocarpic fruit. Increases in either fruit set, fruit number per tree, yield or crop value were also observed when 6-BA plus GA4+7 was applied to ‘Ginger Gold’, ‘Gala’ or ‘Jonagold’ as a frost rescue treatment.

Application of 25 mg/L 6-BA plus GA4+GA7 after frosts on two consecutive days during bloom significantly increased fruit set of ‘Gala’/M.7 in 2014 (Table 1). Minimum air temperatures of -3.0°C and -2.5°C were recorded on April 16 and April 17, respectively (Fig. 2). Air temperatures below freezing were recorded for a total of 9.5 h and 3.5 h on these two days, respectively. Application of 6-BA plus GA4+GA7 as late as five days after the initial frost increased fruit set of ‘Gala’/M.7 apples (Table 2), similar to what has been reported previously for pears. A separate study was conducted in the same orchard in 2014 to compare the individual and combined effects of 25 mg/L 6BA plus GA4+GA7 and/or 125 mg/L aminoethoxyvinylglycine (AVG) on fruit set of ‘Early Red One Delicious’/M.7 apple trees. There was a significant positive effect of 6-BA plus GA4+GA7 on fruit set. However AVG had no effect on fruit set after these frost events (Table 2).

These data demonstrate that 6-BA plus GA4+GA7 can be an effective frost rescue treatment on apples for frost events occurring during bloom. Limited data indicates that this treatment increases fruit set by stimulating parthenocarpic fruit development i.e. set of fruit that would normally abscise. 6-BA plus GA4+GA7 will enhance fruit set of apples when air temperatures during bloom are as low as -4.5°C. It is important to note that although there is a positive effect of 6-BA plus GA4+GA7 on fruit set after a frost, the crop load was not restored to commercially acceptable levels when air temperatures were -4.5°C. The proportion of parthenocarpic fruit resulting from 6-BA plus GA4+GA7 treatment may be very high when frosts are severe, and it is not known at this time if the postharvest quality of such parthenocarpic fruit after long term storage is compromised in any way compared to fruit with a normal seed complement.

Literature Cited

Anon. 2016. Integrated Orchard Management Guide for Commercial Apples in the Southeast. https://entomology.ces.ncsu.edu/wp-content/uploads/2014/02/2016-orchard-guide.pdf?fwd=no

Ballard, J.K., Proebsting, E.L. and Tukey, R.B. Critical temperatures for blossom buds: Apples. Washington State Univ. Bul. 0913.

Curry, E. 2012. Increase in epidermal planar cell density accompanies decreased russeting of 'Golden Delicious' apples treated with Gibberellin A4+7. HortScience 47:232-237.

Deckers, T. and Schoofs, H. 2002. Improvement of fruit set on young pear trees cultivar Conference with gibberellins. Acta Hort. 596:735-743.

Harley, C.P., Moon, H.H. and Regeimbal, L.O. 1958. Evidence that postbloom apple thinning sprays of naphthaleneacetic acid increase blossom bud formation. Proc. Amer. Soc. Hort. Sci. 72:52-56.

Hoover, E., De Silva, N., McArtney, S. and Hirst, P. 2004. Bud development and floral morphogenesis in four apple cultivars. J. Hort Sci. Biotechnol. 79:981-984.

Knoche, M., Khanal, B. and Stopar, M. 2011. Russeting and microcracking of 'Golden Delicious' apple fruit concomitantly decline due to gibberellin A4+7 application. J. Amer. Soc. Hort. Sci. 136:159-164.

Luckwill, L.C. 1960. The effect of gibberellic acid on fruit set in apples and pears. Long Ashton Res. Stn. Annu. Rpt. 1959:59-64.

McArtney, S.J., Hoover, E.M., Hirst, P.M. and Brooking, I.R. 2001. Seasonal variation in the onset and duration of flower development in 'Royal Gala' apple buds. J. Hort Sci. Biotechnol. 76:536-540.

McArtney, S., Ferree, D. Schmid, J. and Obermiller, J.D. 2006. Effects of prohexadione-Ca and GA4+7 on scarf skin and fruit maturity in apple. HortScience 41:1602-1605.

McArtney, S., Unrath, D., Obermiller, J. and Green, A. 2007. Naphthaleneacetic acid, ethephon, and gibberellin A4+A7 have variable effects on flesh firmness and return bloom of apple. HortTechnol. 17:32-38.

McArtney, S., Obermiller, J.D. and A. Green. 2007. Prohexadione-Ca reduces russet and does not negate the efficacy of GA4+7 sprays for russet control in 'Golden Delicious' apples. HortScience 42:550-554.

McArtney, S., Greene, D., Schmidt, T. and Yuan, R. 2013. Naphthaleneacetic acid and ethephon are florigenic in the biennial apple cultivars Golden Delicious and York Imperial. HortScience 48:742-746.

McArtney, S., Greene, D., Robinson, T. and Wargo, J. 2014. Evaluation of GA4+7 plus 6-benzyladenine as a frost rescue treatment for apple. HortTechnol. 24:171-176.

Ouma, G. 2008. Use of gibberellins to improve fruit set in pears after frost damage. J. Biol. Sci. 8:213-216.

Rademacher, W. and Kober, R. 2003. Efficient use of prohexadione-Ca in pome fruits. Europ. J. Hort. Sci. 68:101-107.

Williams, M.W. 1972. Induction of spur and flower bud formation in young apple trees with chemical growth retardants. J. Amer. Soc. Hort. Sci. 97:210-212.

Yarushnykov, V.V. and Blanke, M.M. 2005. Alleviation of frost damage to pear flowers by application of gibberellin. Plant Growth Regulat. 45:21-27.

Figures

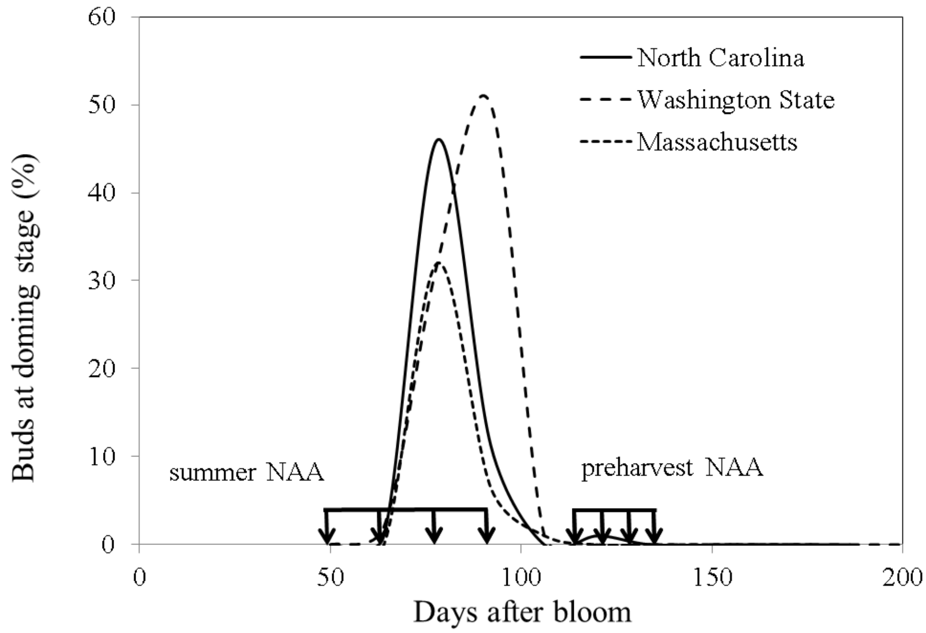

Fig. 1. Schematic representing time of application of summer NAA and preharvest NAA programs for promotion of return bloom in apple in relation to the time of doming in the meristem of floral buds of 'Golden Delicious' apple. Buds were sampled every two weeks beginning 50 d after petal fall in three different apple production regions in the US. Arrows indicate the time of NAA applications in relation to the time of doming. Four applications of 5 mg/L NAA are typically made at two week intervals beginning around 50 d after bloom in a summer NAA program. A preharvest NAA program consisting of four applications of 5 mg/L NAA made at weekly intervals beginning four weeks before harvest has also shown to increase return bloom.

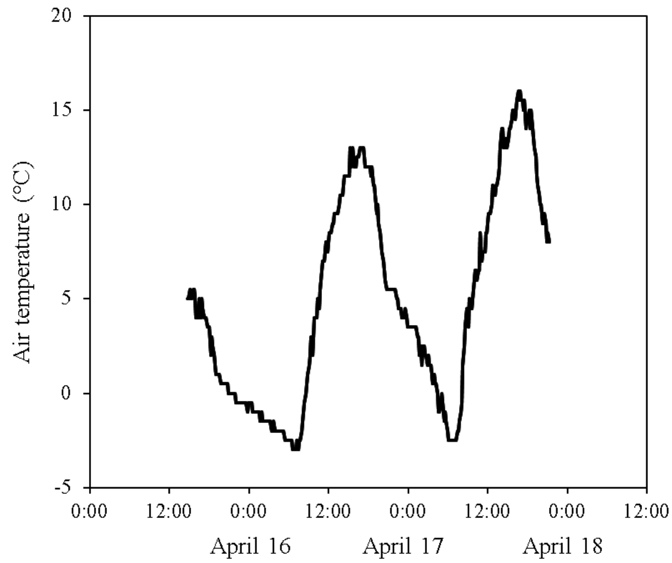

Fig. 2. Air temperatures during bloom full bloom of Brookfield 'Gala' in North Carolina, 2014. Air temperatures were below 0°C for 9.5 h and reached a minimum of -3.0°C on April 16, and were below 0°C for 3.5 h and reached a minimum of -2.5°C on April 17. Temperatures were recorded every 10 minutes on calibrated loggers placed in a radiation shield at a height of 1 m in the canopy.

Tables

Table 1. Effect of time of 6-BA plus GA4+GA7 (Promalin) application after frost events during bloom on fruit set of 'Brookfield Gala'/M.7 apple trees. Frosts were recorded on April 16 and April 17, 2014 as described in Fig. 2.

Treatment[1]	Fruit set (fruit/100 clusters)
Control	11.7 a[3]
Promalin[2] (April 16)	20.2 bc
Promalin (April 17)	21.9 bc
Promalin (April 18)	16.1 ab
Promalin (April 20)	18.9 bc
Promalin (April 21)	24.1 c
Significance	0.002

[1]Treatments were applied to four-tree plots arranged in a randomized complete block design experiment with five replications.
[2]6-BA plus GA4+7 was applied at 25 mg/L as Promalin in a spray volume of 950 L/Ha.
[3]Means within a column followed by the same letter are not significantly different at $P \leq 0.05$.

Table 2. Effect of 6-BA plus GA4+GA7 (Promalin) and AVG (ReTain) applied individually or in combination on April 16, 2014 after a frost event during bloom on fruit set of 'Early Red One Delicious'/M.26 apple trees. Frosts were recorded on April 16 and April 17, 2014 as described in Fig. 2.

Treatment[1]	Fruit set (fruit/100 clusters)
Control	44.1 a[4]
Promalin[2]	54.5 b
ReTain[3]	46.8 b
Promalin + ReTain	55.9 b
Significance	
Promalin	0.01
ReTain	NS
Interaction	NS

[1]Treatments were applied to four-tree plots arranged in a randomized complete block design experiment with five replications.
[2]6-BA plus GA4+7 was applied at 25 mg/L as Promalin in a spray volume of 950 L/Ha.
[3]AVG was applied at 125 mg/L as ReTain in a sprat volume of 960 L/Ha.
[4]Means within a column followed by the same letter are not significantly different at $P \leq 0.05$.