Environmental Effects on the Performance of Foliar Applied Plant Growth Regulators: A Review Focusing on Tree Fruits

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ADDITIONAL INDEX WORDS. abscission, aminoethoxyvinylglycine, apples, BA, 6-benzyladenine, 2-chloroethylphosphonic acid, *Citrus*, Ethrel, fruit set, fruit size, *Malus × domestica*, NAA, 1-naphthaleneacetic acid, PGR, surfactants, thinning

SUMMARY. Plant response to foliar application of plant growth regulators (PGRs) is often variable, in part due to environmental factors. Weather prior to application is thought to influence cuticle development and thus PGR uptake. For example, in growth chamber studies foliar uptake of 1-naphthaleneacetic acid (NAA) is sometimes increased when fruit trees are placed in low temperature and high humidity several weeks prior to application. Environmental conditions over an extended period of time after application may influence PGR conversion to active form (e.g., ethephon), PGR metabolism, or metabolic factors that affect PGR activity in the plant. The effects of environmental conditions on PGR uptake have been investigated extensively in laboratory studies. In many cases, uptake is clearly increased by high temperatures immediately after application. Laboratory studies report a linear positive correlation between temperature and uptake and greater temperature response above 25 °C (77.0 °F). High humidity and longer drying time often are also reported to increase PGR uptake in laboratory studies. These results are consistent with many grower observations on effects of weather on chemical thinning and have been incorporated into many product labels and extension recommendations. However, relatively few field experiments have been reported in which the relationship between PGR response and environmental conditions were assessed. Wash-off studies have demonstrated that rain shortly after application may reduce efficacy of NAA. Several studies demonstrate environmental interaction with metabolic activity involved in PGR action. For example, shading after thinner application is reported to increase fruitlet abscission and enhance effectiveness of some thinning agents. Chemical thinning of apples (*Malus × domestica*) with ethephon is reported to correlate strongly with temperature in the days after application, while studies suggest that higher temperatures after aminoethoxyvinylglycine (AVG) application may reduce control of preharvest drop. However, the stage of fruitlet development at apple thinning often appears to be more important than environmental conditions at the time of PGR application. In addition, field experiments indicate that longer drying times at lower temperatures seem to largely compensate for greater uptake rates at higher temperatures. This paper discusses data from published and previously unpublished experiments in order to understand the effects of environment on PGR response variability.

Since the 1950s, there have been numerous published studies investigating factors contributing to inconsistent performance of foliar applied PGRs. These factors include environmental conditions, application variables, and the trees' physiological status. Environmental conditions shown to influence PGR uptake and/or performance include temperature, humidity, sunlight, and rainfall. These factors may be important prior to, during, immediately after, or for an extended period after application.

EFFECT OF ENVIRONMENTAL CONDITIONS PRIOR TO APPLICATION. Chemical thinners for deciduous fruits are typically applied to very young foliage at early fruit development, and environmental conditions during leaf growth may influence the uptake of these PGR. During expansion of the leaf there is a continual extrusion and deposition of waxes on the leaf surface (Martin, 1960). While surface deposition usually ceases when the leaves become fully expanded, there is a continual deposition of waxes within the cutin matrix (Schieferstein and Loomis, 1956). It is generally accepted that the amount, structure, and composition of epicuticular waxes influence leaf wettability and penetration of foliar applied substances (Bukovac, 1973; Holloway, 1969).

Florida Agricultural Experiment Station Journal Series No. R-10127.

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Williams (1979) listed a number of environmental conditions including low light intensity, high humidity, frost damage, and low temperatures during leaf growth that can increase the response to a thinner. Conversely, high temperature and dry conditions prior to thinner application make it more difficult to thin adequately. The environmental factors that influence the response to chemical thinners also influence the rate of growth and leaf development (Darnell and Ferree, 1983). Therefore the environmental factors that influence foliar penetration may accomplish this indirectly, at least in part, by affecting the rate of leaf and cuticle development.

A few experiments have explored the effect of pretreatment environment on PGR response. Donoho et al. (1961) examined ^{14}C -NAA uptake through the adaxial surface of leaves from young peach (*Prunus perisca*) and apple trees maintained in high or low humidity and temperature prior to treatment. They found that low temperature [15.6 vs. 21.1 °C (60 vs. 70 °F)] increased uptake by 7% to 11% in both trees. High humidity increased foliar uptake in peach, but not in apple.

Edgerton and Haeseler (1959) studied the effect of supplemental

light on uptake of ^{14}C -NAA and ^{14}C -NAAm by leaves of potted apple trees. Foliar uptake of NAA and NAAm was reduced 27% and 49%, respectively, for trees receiving supplemental light for 3 weeks prior to treatment.

EFFECT OF ENVIRONMENTAL CONDITIONS DURING AND IMMEDIATELY AFTER APPLICATION ON PGR UPTAKE. Numerous laboratory studies have examined the effects of environmental conditions on PGR uptake by leaves, leaf disks, and isolated cuticles. One set of experiments (Greene and Bukovac, 1971) is representative of this large body of study, with most studies with different PGRs and plant species showing similar results (e.g., Black et al., 1995; Flore and Bukovac, 1982; Greene and Bukovac, 1972). Greene and Bukovac (1971) reported that penetration of NAAm (naphthaleneacetamide) into pear (*Pyrus communis*) leaf disks increased with temperature, which agrees with most of the literature and with numerous observations made under field conditions (Fig. 1A). They identified an inflection point at 25 °C showing that penetration is much more rapid above this temperature. This change in slope is attributed to phase changes in cuticular components that result in decreased cuticular viscosity above this temperature (Price, 1982).

Frequently, penetration of growth substances is greater through the lower leaf surface than through the upper (Bukovac, 1965; Luckwill and Lloyd-Jones, 1962). This difference increases as leaves age, due mainly to the deposition of a continuous layer of embedded waxes in the cuticle on the upper surface (Norris and Bukovac, 1969). During droplet drying there was a pronounced increase in uptake (Fig. 1B) that appears to be due to increased PGR concentration associated with droplet drying (Norris and Bukovac, 1969; Price, 1982). Uptake from the lower surface was greatly increased in the presence of light (Fig. 1C). Although this is the only leaf surface that contains stomata, the effect is not attributed to mass flow of the applied NAAm into the leaf through open stomata. Rather, photosynthesis in the guard cells provided energy that enhanced transport across the plasma-lemma and within the plant (Greene and Bukovac, 1972).

Findings from these and related experiments have been incorporated into many product label recommendations. Many PGR labels include temperature recommendations to avoid low uptake of the product at low temperatures and to reduce the risk of overresponse from excessive

Fig. 1. (A, above left) Effect of temperature [$1.8(^{\circ}\text{C}) + 32 = ^{\circ}\text{F}$]; (B, above right) drying; and (C, next page, top) light (1 lx = 0.0929 fc) on uptake of ^{14}C -naphthaleneacetamide by upper and lower surfaces of pear leaf disks (Greene and Bukovac, 1971).

Fig. 1. (A, *previous page*, bottom left) Effect of temperature [$1.8(^{\circ}\text{C}) + 32 = ^{\circ}\text{F}$]; (B, *previous page*, bottom right) drying; and (C, *above*) light ($1 \text{ lx} = 0.0929 \text{ fc}$) on uptake of ^{14}C -naphthaleneacetamide by upper and lower surfaces of pear leaf disks (Greene and Bukovac, 1971).

uptake at very high temperatures. Some PGR products recommend times of application that favor long drying periods (Valent BioScience, 2004a, 2004b, 2004c). Many product labels suggest delaying application if rain is forecast to occur within a few hours, or reapplication if rain occurs (e.g., Valent BioScience, 2004a, 2004b, 2004c). Inclusion of a surfactant is also recommended with some PGRs (Valent BioScience, 2004b, 2004c) to provide more rapid uptake. Many label recommendations for PGR use are based on results from controlled laboratory studies, and are supported by anecdotal observations made in the field. There are relatively few field reports on environmental factors influencing PGR response because the interactions between factors are often complex and it is extremely difficult to examine environmental factors under field conditions without potential confounding effects.

EFFECT OF ENVIRONMENTAL CONDITIONS AFTER APPLICATION. The effect of environmental conditions after PGR application is somewhat more difficult to study and usually includes a combination of factors. Effect of en-

vironment on plant response may result from uptake effects, influence on PGR conversion to active form, and/or physiological processes through which PGR action is mediated.

EFFECT OF ENVIRONMENTAL CONDITIONS AFTER APPLICATION: UPTAKE. In addition to laboratory studies, which explore factors affecting uptake during and for several days after application, there have been a few related studies on field or potted trees. Field observation suggests that if a spray droplet dries before rain occurs, there is likely to be a substantial amount of PGR activity retained, due in part to enhanced uptake as the droplet dries. Studies examining the effect of "wash-off" typically reveal that PGR activity is reduced if residues are washed from the

foliage too soon after application. A study by Westwood and Batjer (1960) is representative. The authors report results from five studies in which apple trees were sprayed with NAA and then residues were removed by washing at various intervals after spraying. In this report NAA uptake was measured by leaf curvature: washing off residues within 2 h reduced leaf curvature in all three studies which included this timing, while wash-off at 6–8 h reduced leaf curvature in only one of the three relevant studies.

Inherent water solubility of the PGR and product formulation may influence the reduction in activity following wash-off. Greene et al. (2000) applied aminoethoxyvinylglycine (AVG) to trees in an orchard to reduce preharvest apple drop and then thoroughly washed treated trees with water at various times after application. If no surfactant was included in the original spray, thorough washing as long as 24 h after application resulted in some loss of preharvest drop control. However, if the organosilicone surfactant Silwet L-77 (Loveland Industries, Greeley, Colo.) was included in the original AVG spray application, there was no loss of

preharvest drop control even if trees were washed 1 h after application.

Rain or rewetting may also enhance PGR response. Bukovac (1965) applied the auxin ^{14}C -chlorophenoxy acetic acid to peach leaves and rewetted the leaves following droplet drying. Rewetting twice increased uptake into the leaves by 17% and rewetting five times increased uptake by 47%. Field observations made in apple orchards following the application of blossom thinners dinitrocresol and ammonium thioisulfate show enhanced phytotoxicity of leaves following rewetting (D. Greene, unpublished).

EFFECT OF ENVIRONMENTAL CONDITIONS AFTER APPLICATION: CONVERSION TO ACTIVE FORM. Most PGRs do not require chemical conversion to be effective, since the applied moiety is already in active form. The most obvious exception is ethephon which must decompose and release ethylene to be physiologically active. This decomposition process is temperature and pH dependent (Olien and Bukovac, 1978). Jones and Koen (1985) examined the effect of temperature on practical use of ethephon by assessing post-bloom thinning response when ethephon was applied to fruiting potted trees maintained at a range of different temperatures for 4 h prior to application and for 24 h thereafter. Thinning response increased linearly with temperature from 8 to 24 $^{\circ}\text{C}$ (46.4 to 75.2 $^{\circ}\text{F}$) with virtually no thinning at 8 $^{\circ}\text{C}$ or below (Fig. 2).

It should be noted that plant response to ethephon is especially temperature dependent, since temperature influences both uptake (Flore and Bukovac, 1982) as described above and rate of ethephon decomposition to release ethylene (Olien and Bukovac, 1978). While ethephon is widely used to enhance fruit abscission of sweet cherry (*Prunus avium*) and sour cherry (*P. cerasus*), the optimal temperature range for use is quite narrow, with little response below 16 $^{\circ}\text{C}$ (60.8 $^{\circ}\text{F}$) and phytotoxicity symptoms often apparent above 20 $^{\circ}\text{C}$ (68.0 $^{\circ}\text{F}$) (Olien and Bukovac, 1978).

NAA-induced ethylene production is closely related to thinning response in apples (Walsh et al., 1979). Curry (1991) examined the effect of temperature on the time course and quantity of ethylene evolved from excised apple spurs that had been treated with NAA in the field. When spurs

Fig. 2. Effect of 28-h controlled temperature (4 h before and 24 h after) on thinning of apple with 400 mg·L⁻¹ (ppm) ethephon (Jones and Koen, 1985); 1.8(°C) + 32 = °F.

were maintained at 30 °C (86.0 °F), peak ethylene evolution was both much earlier and higher than when spurs were maintained at 20 °C, which in turn produced an earlier and higher ethylene peak than from spurs maintained at 10 °C (50.0 °F) (Fig. 3).

EFFECT OF ENVIRONMENTAL CONDITIONS AFTER APPLICATION: DEGRADATION AND VOLATILIZATION. Some PGRs are readily degraded or volatilized, and environmental conditions can play an important role in these processes. Best documented is the effect of ultraviolet light on NAA. NAA can be 75% to 80% decarboxylated in 3 h of exposure to full sunlight (Bukovac et al., 1986). It is not obvious how important this is when residues are in the diversely illuminated and cooler environment of tree canopies, especially since light enhances uptake as discussed above. Another example of active PGR loss is volatilization of 2,4-D esters (Marth and Mitchell, 1949), which is likely influenced by environmental parameters such as temperature, sunlight, and wind, and may contribute to variable plant response.

EFFECT OF ENVIRONMENTAL CONDITIONS ON MECHANISM OF ACTION. Environmental conditions before, during and after application may markedly influence the physiological

processes through which PGR action is mediated. A number of examples are described below.

A proposed mechanism of action of chemical thinners is that a transient reduction in resources available to developing fruitlets increases interfruit competition and enhances post-bloom drop (Stopar, 1998; Yuan and Greene, 2000). Environmental conditions, especially those that reduce carbohydrate availability to young fruit, are likely to act synergistically with the thinning agent to induce greater cropload reduction. Sustained warm and/or cloudy conditions may compromise the physiological status of the developing fruitlets, making them less active sinks for tree resources. Application of thinners to such fruitlets may result in excessive thinning and reduced rates are often recommended (Williams, 1979). Byers et al. (1990a, 1990b, 1991) have extensively tested the effect of shading and application of photosynthesis-inhibiting chemicals in early fruit growth, to assess the role of suppressed photosynthesis on degree of fruit thinning both with and without application of chemical thinners. They propose (Byers et al., 1990b) that cloudy periods for as little as 3 d or fewer during the physiological drop period may significantly decrease fruit

Fig. 3. Effect of temperature on ethylene evolution of NAA-treated excised apple spurs (Curry, 1991); 1.8(°C) + 32 = °F.

retention and may influence response to chemical thinners.

Yuan and Greene (2000), working with postbloom applications of the chemical thinner 6-benzyladenine (6-BA) to 'McIntosh' apple, reported that this material increased foliar respiration and thus reduced net photosynthesis at 30 °C, but not at 20 °C. The resultant reduction in carbohydrates to young fruitlets may provide the mechanism for 6-BA-induced fruit abscission. These data also suggest the likelihood of a strong interaction between temperature after application and response to 6-BA as a chemical thinner.

There are numerous additional published accounts, based on observations rather than controlled comparisons, suggesting an influence of environmental conditions on physiological processes through which PGR action is mediated. Stover et al. (2003) reported on experiments in which effects of the ethylene inhibitor AVG on preharvest fruit drop were studied in similar 'McIntosh' orchards in two very different climactic regions in eastern New York. Their data suggest that environmental influences on apple endogenous ethylene evolution markedly influenced tree response to AVG in the period following application (Fig. 4). Similarly, 2,4-D has generally been much more effective in controlling citrus (*Citrus* spp.) fruit drop in California, and other regions of Mediterranean climate with

Fig. 4. Comparison of preharvest drop suppression by aminoethoxyvinyl glycine (AVG) in two ‘Marshall McIntosh’/‘M.9’/‘MM.111’ orchards of the same age and similar management in the same year, but in the warm mid-Hudson Valley (mid-Hudson) vs. the much cooler Champlain Valley (Champlain) of eastern New York. AVG was applied in mid-Hudson on 18 Aug. 1996 and in Champlain on 26 Aug. 1996 (Stover et al., 2003).

cool winter conditions, compared to subtropical Florida which experiences intermittent warm weather throughout the winter (Wilson, 1984). A very different example of post-application environment directly influencing the physiology of PGR action is the observation that ethephon does not enhance apple color in shaded parts of the canopy (Forshey and Edgerton, 1974; Greene and Lord, 1975). Light is necessary for color development and its effect can be enhanced, but not replaced by greater ethylene production.

PREVIOUSLY UNPUBLISHED FIELD STUDIES: EFFECT OF ENVIRONMENTAL CONDITIONS ON THINNER UPTAKE AND RESULTANT CHEMICAL THINNING. Numerous laboratory studies, represented by those described above, document

that PGR uptake is increased at higher temperatures. These data provide part of the rationale for recommendations that postbloom chemical thinners for apple trees should ideally be applied at temperatures between 21.1 and 23.9 °C (70 to 75 °F) and that application is not recommended below 15.6 °C (AMVAC Chemical Corp., 2004). These recommendations create a dilemma for growers regarding timing of thinner applications. Firstly, if a substantial acreage needs to be sprayed over a few days, is the temperature at application the most important factor, or does maximum temperature in the period following application have the greatest effect? This relates to the issue of how time of application influences uptake since under field conditions,

there is generally an inverse relationship between temperature and drying time. Secondly, if ideal thinning conditions do not coincide with the recommended stage of fruit development, how great is the effect of adverse conditions on thinning?

The effect of diurnal timing on thinner uptake, and correlation between uptake and environmental parameters, were studied through application of ^{14}C 6-BA on leaves of orchard ‘McIntosh’ trees, at 3-h intervals from 0600 to 2100 HR within a single day. In two separate trials, 6-BA was applied to healthy leaves four to six down from the apex, with applications to adaxial and abaxial surfaces of different leaves. Treated leaves were harvested 24 h later and washed to remove material which was not absorbed or adsorbed. The epicuticular wax was peeled off and both wax and the remaining leaf tissue were separately oxidized, permitting quantification of the ^{14}C 6-BA retained in the wax as well as that which entered the leaves. Temperatures at application ranged from 15 °C (59.0 °F) to 33 °C (91.4 °F), while drying time ranged from 3 to 25 min. Time of application did not result in a significant effect on the uptake of 6-BA, suggesting that there was compensation between drying time and temperature on rate of uptake (Table 1). When correlation coefficients were measured between 6-BA uptake, environmental parameters, and epicuticular wax retention of 6-BA, temperature correlated with retention in wax, but only related to uptake on the adaxial surface (Table 2).

These results are consistent with Cline and Bijl (2002), who found no

Table 1. Effect of time of application on uptake of ^{14}C 6-benzyladenine (6-BA) by intact leaves of ‘McIntosh’. Data are averaged over two trials on separate days, with applications 2 and 17 July 1990 (D.W. Greene and Z.Y. Mao, unpublished). Differences are not statistically significant at $P \leq 0.05$.

Time applied (HR)	Total applied 6-BA penetrating leaf (%)	
	Abaxial surface	Adaxial surface
0600	12.7	23.6
0900	11.4	21.1
1200	13.0	18.2
1500	11.9	22.4
1800	11.0	16.8
2100	14.2	16.9

Table 2. Correlation between environmental factors or retention in epicuticular wax on uptake of ^{14}C 6-benzyladenine (6-BA) or epicuticular wax retention in intact leaves of ‘McIntosh’. Data are averaged over two trials on separate days, with applications 2 and 17 July 1990 (D.W. Greene and Z.Y. Mao, unpublished).

Variable	Abaxial surface	Adaxial surface
----- Correlation (r^2) -----		
Penetration of leaf		
Drying time	0.05 ^{ns}	0.48 ^{ns}
Photosynthetically active radiation	0.29 ^{ns}	0.11 ^{ns}
Relative humidity	0.00 ^{ns}	0.02 ^{ns}
Temperature	0.20 ^{ns}	0.58*
Wax layer retention	0.31 ^{ns}	0.88**
Wax layer retention		
Drying time	0.30 ^{ns}	0.38 ^{ns}
Photosynthetically active radiation	0.45 ^{ns}	0.23 ^{ns}
Relative humidity	0.25 ^{ns}	0.09 ^{ns}
Temperature	0.70*	0.64*

^{ns}, *, ** Nonsignificant or significant at $P \leq 0.05$ or 0.01, respectively.

Table 3. Environmental conditions in field trial comparing thinning responses of ‘Empire’ apple on three consecutive days with very different environmental conditions.

Day	High temp (°C) ^z	Drying time, etc.
25 May 1995	18.9	Moderate drying time and rain 2–2.6 h after application
26 May 1995	15.6	Prolonged drying
27 May 1995	21.1	Moderate drying

^z1.8(°C) + 32 = °F.

difference in ‘Empire’ apple croplod reduction when NAA, 6-BA, or carbaryl were applied to different trees at 6-h intervals when the largest fruitlets were 10–12 mm (0.394–0.472 inch) in diameter, even though temperature at application varied by as much as 13.5 °C (24.30 °F). Jones et al. (1988) compared thinning of ‘Golden Delicious’ using NAA + Tween 20 (DAKO Ltd., Ely, U.K.), with applications on a single day at four 4-h intervals. They found somewhat greater thinning with the high humidity/low temperature [85% relative humidity (RH), 8.0 °C (46.40 °F)] early morning application vs. the low humidity / high temperature [20% RH, 19.5 °C (67.10 °F)] mid-afternoon. In all of these studies, temperature was inversely related to drying time, and it appears that the longer drying times associated with lower temperatures resulted in equal or better response than was observed at higher temperature and a shorter drying time. It should also be noted that in all these studies, the high temperature on each day of application exceeded 18 °C (64.4 °F). This suggests that conditions at application may be less important than achieving sufficiently high temperature on the day of treatment.

The next study, investigating interaction of environmental conditions and adjuvants on chemical thinning, was previously described only in an abstract (Stover et al., 1997). Chemical thinners were applied to ‘Empire’ apple on ‘Malling 9’/‘Malling Merton 111’ when king fruitlet diameter ranged from 9.8 to 10.2 mm (0.386 to 0.402 inch). Applications were made on consecutive days when environmental conditions changed greatly due to a passing cold front (Table 3). In addition to studying the effect of environmental conditions on thinning, adjuvants were combined with Accel (10:1 ratio of 6-BA:GA₄₊₇; Valent BioSciences Corp., Libertyville, Ill.) to see if their use could compensate

for suboptimal thinning conditions (Table 4). Previous reports support this approach, but they focused on PGR absorption rather than thinning performance. Additionally these experiments were conducted on potted trees (e.g., Westwood and Batjer, 1960), in the laboratory on model systems (e.g., Lownds et al., 1987), or compared effects in consecutive years with different weather (Horsfall and Moore, 1961). In the Stover et al. (1997) field experiment, trees were blocked by number of blossom clusters per unit trunk cross-sectional area. Spray treatments were applied near the daily high temperature with all applications made between 1200 and 1500 HR. All treatments significantly reduced fruit number and enhance fruit size compared to non-thinned controls (Table 5). Within a PGR/adjuvant treatment, no significant difference was found between day of treatment for any response. However, when rain followed application (day 1), use of Accel or Accel with Regulaid resulted in significantly smaller fruit size compared to day 1 application of Accel with other surfactants or day 2

or 3 application of Accel or Accel with Regulaid (data not shown). Analysis of variance without the nontreated control permits a better assessment of the environmental effects on PGR response. While *P* values are below 0.05 for PGR/adjuvant treatment for almost every response variable, *P* values assessing effect of day or interaction between treatment and day are never below 0.14 (Table 5). As in the 6-BA uptake study described above, it is postulated that prolonged drying times can compensate for reduced uptake rates due to low temperatures.

Conclusion

Examples from the literature clearly indicate that environmental conditions before and after PGR application can have a pronounced influence on the resulting PGR action. Changing environmental conditions in the field result in modifications of multiple parameters simultaneously, such as temperature and humidity, which often make it difficult to translate results from controlled experiments into practical decisions for growers. In the apple thinning field trials discussed here, which compared effects of environmental conditions on thinning and related uptake, the inverse relationship between temperature and drying time apparently resulted in very similar responses under diverse conditions. In other apple thinning trials which compared applications at various dates, the stage of fruitlet development often appears to be more important than environmental conditions (Greene, 2002; Stover et al., 2001a). This is

Table 4. Plant growth regulator (PGR) and adjuvant composition in field trial comparing thinning responses of ‘Empire’ apple on three consecutive days with very different environmental conditions (see Table 3 for description of days). All thinners were applied between 1200 and 1500 HR using a handgun with timed application simulating airblast by spraying “out square” at 1.5x concentration. All concentrations listed are on a dilute basis calculated for tree-row volume (Byers, 1987), actual concentrations were 1.5x those listed.

Treatment code	PGR [mg·L ⁻¹ (ppm)] ^z	Adjuvant (% v/v) ^y
Control	none	none
Accel ^x	6-BA (75), GA ₄₊₇ (7.5)	none
AccReg	6-BA (75), GA ₄₊₇ (7.5)	Regulaid (0.125)
AccSil	6-BA (75), GA ₄₊₇ (7.5)	Silwet L-77 (0.027)
AccOil	6-BA (75), GA ₄₊₇ (7.5)	ultra-fine spray oil (0.125)
AccSev	6-BA (75), GA ₄₊₇ (7.5), carbaryl (600)	none
NAASEv	NAA (7.5), carbaryl (600)	none

^z6-BA = 6-benzyladenine; GA₄₊₇ = a mixture of gibberellins 4 and 7; NAA = 1-naphthaleneacetic acid.

^yRegulaid is a product of Kalo Inc. (Overland Park, Kans.), Silwet L-77 is a product of Loveland Industries Inc. (Greeley, Colo.).

^xAccel is a product of Valent BioSciences (Libertyville, Ill.).

Table 5. Thinning-related responses in 'Empire' apple to plant growth regulator (PGR)/adjuvant combinations applied over three consecutive days with divergent environmental conditions at 9.8–10.2 mm (0.386–0.402 inch) average king fruit diameter. Since nontreated control was different from all other treatments for most response variables, an additional analysis of variance (ANOVA) was conducted to compare only PGR/adjuvant combinations.

Treatment ^z (day no.) ^y	Final cropload (fruit/cm ² TCSA) ^x	Fruit wt (g) ^w	Spurs with single fruit (%)	Red color (% surface)	Seeds (no./fruit)	Value per ha (\$) ^{v,u}	Cartons largest sizes (no./ha) ^{v,u}	Blooming spurs 1996 (%)
control	20.2	115.2	62.2	83.2	5.5	2805	165	54.0
Accel(1)	14.2	146.9	66.1	84.5	5.0	8005	1005	89.6
Accel(2)	12.9	160.5	71.7	83.5	3.7	9783	1306	85.9
Accel(3)	12.9	154.6	79.5	85.5	4.2	7134	890	87.6
AccReg(1)	15.8	142.9	64.4	84.7	5.2	8157	972	80.5
AccReg(2)	13.5	158.6	71.0	86.8	5.3	10,355	1374	84.0
AccReg(3)	13.2	159.4	71.6	80.4	4.5	10,176	1355	79.7
AccSil(1)	11.5	161.6	75.3	82.6	4.0	8975	1211	80.4
AccSil(2)	13.0	164.8	71.8	83.0	4.4	9969	1367	85.7
AccSil(3)	11.7	161.2	79.6	83.5	4.0	8217	1120	87.1
AccOil(1)	11.2	162.8	71.8	81.6	3.6	8549	1159	90.4
AccOil(2)	11.9	165.4	69.0	83.3	3.4	9497	1306	84.6
AccOil(3)	11.8	166.0	79.6	82.6	2.9	8925	1224	87.6
AccSev(1)	10.2	178.6	74.7	81.1	2.1	8216	1177	96.7
AccSev(2)	6.8	181.7	82.2	82.5	2.4	6254	914	97.1
AccSev(3)	8.0	176.5	77.1	87.6	2.0	7345	1061	98.6
NAASEv(1)	10.3	159.9	83.8	81.9	5.2	7718	1022	96.9
NAASEv(2)	9.3	165.4	81.1	89.4	5.1	7911	1093	93.2
NAASEv(3)	10.3	162.8	85.5	87.2	5.3	8136	1098	95.2
LSD _{0.05}	3.8	17.7	15.1	6.0	1.1	2538	385	11.0

P values for ANOVA conducted without control

Treatment (T)	0.0001	0.0001	0.0498	0.5101	0.0001	0.0471	0.3369	0.0001
Day (D)	0.3599	0.1442	0.2778	0.2134	0.4337	0.3273	0.2036	0.8871
T × D	0.7969	0.9368	0.9014	0.1498	0.5248	0.2866	0.2585	0.7465

^zTreatment codes (detailed in Table 4): Accel = 75 mg·L⁻¹ (ppm) 6-benzyladenine + 7.5 mg·L⁻¹ gibberellic acid; AccReg= Accel treatment + 0.125% Regulaid; AccSil= Accel treatment + 0.027% Silwet L-77; AccOil= Accel treatment + 0.125% ultra-fine spray oil; AccSev= Accel treatment + 600 mg·L⁻¹ carbaryl; NAASEv= 7.5 mg·L⁻¹ naphthaleneacetic acid + 600 mg·L⁻¹ carbaryl.

^yDay 1 (25 May 1995) had a high temperature of 18.9 °C (66 °F), moderate drying time and rain 2–2.6 h after application; day 1 (26 May 1995) had a high temp. of 15.6 °C (60 °F) and prolonged drying time; and day 1 (27 May 1995) had a high temp. of 21.1 °C (70 °F) and moderate drying time.

^xTCSA = trunk cross-sectional area; 1 fruit/cm² = 0.155 fruit/inch².

^w1.0 g = 0.035 oz.

^v1 ha = 2.47 acres.

^uCalculated using the method of Stover et al., 2001b.

consistent with reports in peach that NAA thinning susceptibility was highly correlated with length of developing fruit pericarps, with maximum thinning at 30–31 mm (1.18–1.22 inch) when endogenous indole acetic acid (IAA) levels reached a maximum and IAA-oxidase activity was greatly reduced (Leuty and Bukovac, 1968). Field results that superficially contradict the many laboratory studies demonstrating effects of environment on PGR response actually underscore the likelihood that PGR effectiveness is influenced collectively by many environmental factors interacting with plant physiological status. Synthesis of these many factors into a predictive model may contribute greatly to more consistent and predictable commercial

responses to PGR. Unfortunately, despite more than 40 years of intensive research on this subject, considerable additional effort will be needed to reach this goal.

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