The Effects of Exogenous Bioregulators and Environment on Regular Cropping of Apple

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SUMMARY. The use of exogenous plant bioregulators or plant hormones to adjust crop load in apple (*Malus domestica* Borkh.) and promote regular cropping remains challenging to both researchers and producers. Responses to these hormones are sensitive to the rate and timing of application, to physiological status of the tree, orchard system, variety, rootstock, and a myriad of cultural practices and environmental factors. Of the environmental factors, temperature plays the most important role in determining response and efficacy of a given material. All classes of plant bioregulators have been used over the past 30 to 40 years as postbloom chemical thinning materials. Most of the standard postbloom thinning programs involve application of a synthetic auxin, such as naphthalene acetic acid (NAA) in combination with carbaryl (Sevin), a commonly used insecticide. The mode of action of these two compounds is not clearly understood. Gibberellins generally have not been effective thinning materials for apple because of their negative impact on return bloom. Ethylene-releasing compounds have been used successfully as postbloom thinning materials. Cytokinins, particularly synthetic sources such as 6-benzyladenine (6-BA), have been shown to effectively thin fruit and enhance fruit size on many commercial varieties. The rate and timing of 6-BA applications are critical to obtain desirable thinning and fruit size responses. The use of these different bioregulators is essential for regular cropping of apple, particularly for spur 'Delicious', 'Fuji' and other varieties that are difficult to thin chemically and which are prone to severe alternate bearing. The focus of this discussion is the use of these bioregulators in commercial apple production areas in the United States.

Apple trees are noted for setting more fruit than is needed for commercial harvest. If not properly thinned by flower or fruit removal the trees will develop an alternate or biennial bearing habit. Overcropping of trees, especially during the early years of establishment and production, can reduce carbohydrate reserves needed for vegetative growth and flower bud formation for next year's crop (Williams, 1994a). Overcropping results in too many small fruit because of competition for photosynthates between the developing fruit, as well as competition between vegetative growth and fruit development. These small fruit are generally undesirable in the marketplace, since fresh market apples are graded and sold on the basis of size and external color. Thus, biennial bearing has an impact on the economic survival of apple producers, as well as fruit warehouses. (Williams, 1994a).

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Chemical removal of fruit is necessary for both labor efficiency and reducing production costs. Hand thinning is labor intensive and expensive. Also, fruit thinning by hand is generally not conducted early enough in the growing season to negate effects of excessive flowering and fruit set.

Early removal of potential fruit (blossom thinning) is currently used experimentally or on a commercial-scale in many apple producing areas to enhance flower initiation for next year's crop and thus, return bloom (Fallahi, 1997; Fallahi et al., 1997), and to reduce competition for photosynthates. Blossom thinners usually have a caustic effect on floral parts. New blossom thinners include sulcarbamide (Wiltin) (Williams, 1994b; Fallahi et al., 1997), endothalic acid (Endothall), and pelargonic acid (Thinex) (Williams, 1994b; Fallahi, 1997), and hydrogen cyanamide (Dormex) (Fallahi, 1997; Fallahi et al., 1997, 1998).

The practice of postbloom thinning, generally from 3 to 18 mm (0.12 to 0.71 inch) fruit size, is used to promote return bloom, as well as to regulate crop load. However, fruit removal which occurs after the period of flower initiation, generally 30 to 45 d after full bloom, will affect crop load only. For this reason, hand thinning is used to balance crop load and to improve fruit size, rather than influence flower initiation.

The use of naphthalene acetic acid (NAA), a synthetic auxin, gained acceptance in the 1950s and 1960s. Another synthetic auxin, naphthalene-acetamide (NAD), was found to be suitable for postbloom thinning of many commercial apple varieties (Westwood and Batjer, 1964). In the 1960s, carbaryl (Sevin), a commonly used insecticide, was introduced as a postbloom thinner (Williams, 1994a). In the 1970s combinations of carbaryl and NAA, or carbaryl and NAD, were adopted as commercially acceptable postbloom thinning sprays. Also, in the 1970s most of the other plant bioregulators, i.e., gibberellins, cytokinins, and ethylene were tested for both pome and stone fruit thinning. In the 1980s, synthetic cytokinins such as 6-benzyladenine (6-BA) were used in chemical thinning experiments. Interest in finding consistent postbloom thinning materials continues into the 1990s as all of the presently available materials have limitations imposed by rate or timing.

Further complicating the efficacy of postbloom thinning materials are the effects of environmental factors, particularly temperature and light levels. If cool, cloudy weather predominates during the fall, carbohydrate reserves may be reduced for the next spring (Byers et al., 1990). This lower level of reserves affects the vigor of the tree, perhaps even its survival during extremely cold winter stress periods. Lower carbohydrate reserves may so weaken the tree that bloom is erratic. Winter damage can affect the translocation of nutrients from the root system to the growing points during the subsequent spring. If there is considerable spur damage, flowering and fruit set will be diminished. And finally, temperatures during bloom influence the rate of bud emergence, as well as fruit set. If temperatures are warm during bloom, carbohydrate reserves are used at a faster rate than in a cool or normal bloom period. With fewer reserves available to both vegetative and fruit growth, fruit set and thus, yield, may be reduced. (Robinson et al., 1998; Williams and Edgerton, 1981).

Photosynthetic rate (and carbohydrate allocation) affects the amount of fruit set and the response to fruit thinning. Cultural practices that reduce light interception, such as poor pruning, will lower fruit set and yield (Byers et al., 1990; Lehman et al., 1987).

NAPHTHALENEACETIC ACID AND OTHER SYNTHETIC AUXINS. The exact nature of NAA's mode of action is unclear. Several mechanisms appear to be involved in the fruit thinning response. It is thought that NAA (and other synthetic auxins) may increase the rate of metabolic activity of developing embryos. NAA may also stimulate ethylene biosynthesis when applied at relatively high rates. This endogenous ethylene may also decrease the photosynthetic rate (Robinson et al., 1998) and fruit growth rate. The inhibition of fruit growth is correlated with abscission of weaker fruit. Competition between fruit appears to be moderated by seed numbers, although the amount of thinning is not correlated with seed number *per se* (Williams, 1993).

Fruit size has generally been considered to be the most important factor for timing NAA application, with 7.5 to 10 mm (0.30 to 0.39 inch) being considered optimum for thinning response (Robinson et al., 1998;

Williams, 1999). However, Byers (1990) has shown that environmental factors, particularly temperature, are far more important than an exact fruit size in achieving a thinning response. Although temperature effects may differ slightly from the Pacific Northwest to the northeastern United States, it is generally suggested that NAA works most effectively, without the risk of overthinning, at 20 to 25 °C (≈70 to 80 °F).

Drying conditions after NAA application also may affect the response of the fruit tissue. If relative humidity is low, and temperatures are warm [>15 °C (59 °F)], drying of the spray is accelerated. Ebert and Kreuz (1988) found that with high rates of NAA [$15 \text{ mg}\cdot\text{L}^{-1}$ (ppm)] applied during warm weather, the absorption of the material decreased, particularly with low relative humidity. Addition of a wetting agent, such as Regulaid, to the spray solution slows the rate of drying and increases the uptake of NAA into leaf and fruit tissue (Westwood and Batjer, 1960).

In the Pacific Northwest (PNW), NAA is used primarily as a postbloom thinning material for spur 'Delicious' at fruit sizes of 8 to 10 mm (0.32 to 0.39 inch) at rates of 2 to 5 $\text{mg}\cdot\text{L}^{-1}$ (Williams, 1999). NAA has not performed consistently as a blossom thinning material in the PNW, but has been found to be a mild blossom-thinning material under northeastern conditions (Robinson et al., 1998). Relatively high temperatures during the bloom period in most areas of the PNW growing region allow use of lower rates of NAA for postbloom thinning. Rates of NAA that would be appropriate for the northeastern U.S. can cause excessive fruit thinning in the PNW. The faster drying conditions in the PNW are countered with the addition of a surfactant such as Regulaid. Temperatures are often in the 20 to 28 °C (68 to 82 °F) range from full bloom through 20 mm (0.79 inch) fruit size. The high light intensity and low relative humidity also affect the rates of NAA used for postbloom thinning of spur 'Delicious'. When compared to postbloom thinning programs used in New York and Michigan, the rates of NAA used in the PNW are generally reduced by 50% (Williams, 1999; Schwallier, 1996; Robinson et al., 1998).

In Michigan, rates of NAA in the

10 to 20 mg·L⁻¹ range are suggested for most commercial varieties, with the easier to thin varieties (e.g., 'Gala', 'Empire' and standard 'Delicious') requiring the 10 ppm rate while difficult to thin varieties, such as 'Fuji' and 'Golden Delicious', require 20 ppm NAA. In New York, 2.5 to 15 mg·L⁻¹ NAA is used for thinning (Robinson et al., 1998).

Excessive NAA may result in reduced fruit size, as well as abnormally small fruit called pygmy fruit. This negative effect on fruit size commonly occurs when the NAA is applied when the temperature is too cool (Williams, 1999) or too high (Robinson et al., 1998) or when fruit is too large, generally in excess of 20 mm. In the PNW, the risk of pygmy fruit formation in spur 'Delicious' is increased if NAA is applied when fruit size exceeds 15 mm (0.59 inch) in diameter. Under northeastern conditions, pygmy fruit formation increases when fruit size exceeds 20 mm (0.79 inch). High rates of NAA may also reduce the rates of fruit growth in varieties, such as 'Delicious', 'Empire' and 'Gala'.

NAD is used commonly on varieties that are considered difficult to thin, such as 'Fuji' at rates of 25 to 50 mg·L⁻¹ (Robinson et al., 1998; Schwallier, 1996; Williams, 1999). Like NAA, late applications often result in pygmy fruit formation. Both standard and spur 'Delicious' strains are sensitive to NAD and excessive pygmy fruit formation may result from NAD applications. Generally, NAD is not used as a solo application; it is considered a relatively mild postbloom thinning material.

MCPB-ethyl, an ethyl ester of butyric acid (4-[4-chloro-2-methylphenoxy]-butyric acid), another synthetic auxin, has been tested in British Columbia by Looney et al. (1998) as a potential postbloom thinning material for 'Fuji'. Carbaryl and NAA were shown to be more consistent than MCPB in postbloom response of 'Fuji'. Also, the lack of availability of MCPB in either Canada or the U.S. will limit its usefulness to the North American apple industry.

CARBARYL. Carbaryl (Sevin XLR+, Sevin 4F, carbaryl formulations), a carbamate, is the main postbloom thinning material used throughout the apple producing regions of the U.S. It is considered to be a relatively safe thinning material when

used at the correct rates and timing, in that the risk of overthinning is minimal. The optimum timing for carbaryl is generally in the 8 to 10 mm (0.32 to 0.39 inch) fruit size range, although petal fall (3 to 5 mm) (0.12 to 0.20 inch) applications have also been shown to be effective as well.

The rates for most carbaryl postbloom thinning programs in the United States are 300 to 600 mg·L⁻¹. Carbaryl has not been shown to be a strongly rate responsive material. Doubling or tripling the rate of carbaryl applied for fruit thinning does not double or triple the rate of thinning response (Dennis, 1996). Optimum temperatures for thinning after a carbaryl application range from 15 to 25 °C (≈60 to 80 °F). Apple producers in the PNW have observed that carbaryl applied during cool weather may still thin fruit, albeit the response is considerably slower, whereas NAA will remain relatively ineffective during cool weather (Williams, 1993). However, carbaryl applied during cool weather may increase phytotoxic responses, such as fruit deformation in 'Bisbee' and 'Vallee Spur' strains of spur 'Delicious' (Williams, 1999).

The main drawback of carbaryl at the petal fall or early timing is its toxicity to bees. However, newer formulations, such as Sevin XLR+, have minimal impact on bees due to the particle size technology used in the manufacturing process (D. Mayer, personal communication). Carbaryl is often used in combination with NAA or NAD (Grausland, 1981; Micke et al., 1991; Robinson et al., 1998; Schwallier, 1996; Williams, 1999) to reduce rates and increase the effectiveness or synergy of both materials.

Combinations of carbaryl with 6-BA have been used successfully in the northeastern U.S. for postbloom thinning of many commercial apple varieties (Greene and Autio, 1994; Greene et al., 1990; Elfving and Cline, 1993a, 1993b; Robinson et al., 1998; Schwallier, 1996). The thinning response of difficult to thin varieties such as spur 'Delicious' and 'Fuji' has been fairly consistent with carbaryl, but the addition of 6-BA does not increase the thinning response. The lack of a strong thinning response of spur 'Delicious' and 'Fuji' to 6-BA application, even in combination with carbaryl, suggests that the labelled rates are too low for warmer areas and for the varieties that

are produced in those areas.

A related carbamate, oxamyl (Vydate), is labelled for use as a postbloom apple thinning compound in the northeastern U.S. Its thinning activity is considered to be milder than that of carbaryl. However, it is disruptive of integrated mite control programs because it is toxic to predatory mites and other beneficial predators required in an integrated fruit production program. Robinson et al. (1998) suggest that Vydate could be combined with Accel for thinning. However, the efficacy of this combination has not been well-documented. Oxamyl combined with NAA is currently under test in Washington for thinning spur 'Delicious'. Although the initial results with oxamyl and NAA as a postbloom thinning treatment are promising, the concern remains that integrated mite control will be disrupted.

6-BENZYLADENINE (ACCEL, PROMALIN). The mode of action of synthetic cytokinins as fruit thinning agents is not understood. The metabolic activity of the fruit tissue may be altered due to the increased cell division rate stimulated by the cytokinin application. Under northeastern conditions, the thinning and size enhancement response to 6-BA has been documented in round-type apples such as 'McIntosh' (Greene and Autio, 1989) and 'Empire' (Elfving and Cline, 1993a). With spur 'Delicious', a cultivar known for an elongated L/D ratio, the thinning and size effects of 6-BA, marketed as Accel (Abbott Laboratories, Chicago, Ill.) are weak or inconsistent at the currently labeled rate of 148 g·ha⁻¹ (2.11 oz/acre) of active ingredient. As much as 247 g·ha⁻¹ (3.53 oz/acre) of 6-BA per acre may be necessary to produce a thinning response in 'Delicious' (Elfving and Cline, 1993a; Greene and Autio, 1994). In the PNW, the size enhancing effects of 6-BA are also fairly mild with 'Delicious' and 'Fuji', but have been dramatic with 'Gala' in some cases (R. Fritts, personal communication).

Another advantage of 6-BA is its pronounced enhancement of return bloom by stimulating flower bud initiation and reducing excessive lateral shoot growth (Elfving and Cline, 1993b; Greene and Autio, 1990). Although 6-BA has been observed to stimulate lateral branch development in young trees, the application of Accel or Promalin at higher rates (150 mg·L⁻¹

also increases flowering. The application of 6-BA can occur over a wide range of time, from 80% full bloom until ≈ 10 mm (0.39 inch) fruit size. For Promalin, which is used mainly for affecting fruit type (shape), application from 80% full bloom until about petal fall (3 to 5 mm) (0.12 to 0.20 inch) is recommended. Promalin has been observed to cause mild thinning under certain conditions, but its thinning effect has not been consistent. The optimum timing for Accel applications is at the 5 to 10 mm (0.20 to 0.39 inch) fruit size range. It is critical that the spray solution contacts the fruit, rather than the leaves, as uptake occurs primarily through the fruit surface (Greene and Autio, 1994). One of the negative interactions observed with Accel is increased formation of pygmy fruit in sensitive varieties such as spur 'Delicious' when NAA is applied either in combination with the Accel, or as a separate spray within a few days of Accel application (Greene and Autio, 1994). The cause of increased pygmy fruit formation from combinations of 6-BA and NAA is not understood.

The use of Accel for fruit thinning is fairly new to the apple industry, and much more experience on the producers' part will be required to establish its efficacy and practicality as part of a thinning program. It is certain that carbaryl will be necessary to enhance the fruit thinning effects of Accel (Greene and Autio, 1994). The drawback of 6-BA as a chemical thinning agent is its lack of performance under the growing conditions in the PNW, so its use in that region may be limited to small-fruited varieties such as 'Gala'.

GIBBERELLINS. One of the components of Accel and Promalin is a proprietary mixture of gibberellins, specifically GA_{4+7} . The gibberellins have not been effective as pome fruit thinning materials, but have been used for their effects on fruit type (shape). Gibberellins elongate cells, rather than increase cell division (Edgerton, 1981). Gibberellins have been shown to be antiflowering in stone and pome fruit in the sense that flower initiation is reduced by exogenous applications of GA_3 or GA_{4+7} (Southwick et al., 1995). Since GA_{4+7} is present in low concentrations in both Accel and Promalin, flower bud initiation is promoted because of the 6-BA in the mixture (Greene and Lord, 1985). This positive effect on return bloom, despite the

presence of GA_{4+7} in these formulations, appears to be occurring in commercial orchards as well.

ETHYLENE (ETHREL, ETHEPHON). The mode of action of ethylene, or ethylene-releasing compounds, such as ethephon, is well understood. The high concentrations of ethephon applied during bloom or postbloom (generally 300 to 450 mg·L⁻¹ stimulate endogenous ethylene production. The ethylene then promotes the formation of abscission layers in the pedicels of developing fruitlets. Like all of the plant bioregulators discussed in preceding sections of this paper, temperature plays a critical role in the degree of response to ethephon application (Jones and Koen, 1985). Optimum temperatures for ethylene production and fruit thinning are in the 20 to 25 °C (68 to 77 °F) range. With temperatures in excess of 28 °C (82.4 °F), which can occur occasionally in all apple producing areas in the United States, the risk of overthinning with ethephon has been a deterrent for its use as an early postbloom thinning material (Robinson et al., 1998; Williams, 1999). Drying conditions are also critical for ethylene generation after an ethephon application. It is recommended that a drying time of at least 4 to 6 hours occurs. High humidity increases the length of drying, and thus, uptake. Ethephon is not particularly selective in which fruit is removed, unlike carbaryl or NAA which target the weaker fruit.

Fruit size at time of application does not appear to be as important for a fruit thinning response with ethephon as compared to NAA or carbaryl. Because ethephon is a nonselective fruit thinning material, a wide range of application timing from petal fall up to 20 mm (0.79 inch) is allowed. Generally, the earlier sprays of ethephon have been unpredictable in the degree of thinning, so mid [10 mm (0.39 inch)] to late [up to 20 mm (0.79 inch)] application timing is generally preferred by apple producers. In New York, bloom and postbloom thinning treatments with ethephon are discussed in the production guide. Elfving and Cline (1993a) found that ethephon in combination with 6-BA increased postbloom thinning activity only slightly. Combinations of ethephon and 6-BA have not been adequately tested in the PNW.

Ethephon is commonly applied

in combination with NAD to thin varieties such as 'Golden Delicious', 'Fuji' and 'Gala' in the PNW (Williams, 1999). Ethephon is used on spur 'Delicious' in the southeastern U.S. (C.R. Unrath, personal communication). However, ethephon applied to spur 'Delicious' in Washington causes flattening of the fruit, and reduced fruit size. NAD appears to have a negative synergistic effect in combination with ethephon when used for postbloom thinning of spur 'Delicious'.

Ethephon is also used in young trees to promote flower initiation (Williams, 1999). Application generally occurs 5 to 6 weeks after full bloom to avoid overthinning the current crop. 'Fuji' and 'Gala' trees are responsive to early summer applications of ethephon after the postbloom thinning period, or generally 45 d after full bloom.

Williams and Edgerton (1981) described the many factors that affect apple thinning in both the northeastern and western United States. The effects of tree vigor, crop load, stress events and variety/rootstock combinations are not to be discounted. However, the common theme throughout this seminal publication is the importance of timing of application, proper concentration (rate) and environment (especially temperature and relative humidity) on the degree of postbloom thinning. The effects of temperature and light on the degree of postbloom thinning and carbohydrate reserves for fruit development and subsequent flower initiation remain critical to the successful elimination of biennial bearing in apple. Despite the 50 or more years of research with postbloom thinning materials, pomologists must continue to learn about and master the art and science of chemical thinning. The authors would like to acknowledge the considerable scientific and industry contributions made by pomologists such as Jack Batjer, Mel Westwood, Louis Edgerton, Frank Dennis, and Max Williams.

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