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ARTICLE

Multi-year investigation on the rate, timing, and use of surfactant for thinning apples with post-bloom applications of metamitron

John A. Cline, Catherine J. Bakker, and Amanda Beneff

Abstract: Several experiments were conducted in Simcoe, Ontario, to evaluate the efficacy of metamitron (MET) as a post-bloom thinner for Ambrosia, Gala, and Honeycrisp apple trees. Trees were treated with rates of MET ranging from 165–480 mg·L^{-1}, as well as different timings ranging from 5–22 mm fruit diameter. The effect of including a non-ionic surfactant on thinning efficacy with MET was also evaluated. Treatments were compared with untreated trees and industry standard sprays of carbaryl, 1-naphthalene acetic acid (NAA), 6-benzyladenine (6-BA), or combinations thereof. Response to MET varied by cultivar and season. In six of the seven experiments MET reduced fruit set, but only in four experiments did MET reduce the number of fruit per tree or crop load compared with the untreated control trees. Petal fall (5–7 mm) applications of MET were less effective than later timings. Thinning response increased with higher rates of MET in four of the seven studies. For Honeycrisp and Ambrosia, 175 mg·L^{-1} MET was effective in reducing fruit set and crop load, while rates at or above 263 mg·L^{-1} MET were required to thin Gala. MET improved fruit size distribution into larger categories and caused minimal leaf phytotoxicity with or without a non-ionic surfactant. Environmental factors such as nighttime temperature and solar radiation largely could not account for the seasonal or application timings in thinning response to MET. Greater understanding of the carbon balance and interplay of solar radiation, nighttime temperature, cultivar and fruitlet size on thinning response is required to improve the predictive thinning response of apple to MET.

Key words: fruit weight, crop load, grade distribution, crop density, *Malus domestica* Borkh.

Résumé : Les auteurs ont réalisé plusieurs expériences dans le comté de Simcoe, en Ontario, en vue d'évaluer l'efficacité du métamitron (MET) comme éclaircissant postfloraison sur les pommiers Ambrosia, Gala et Honeycrisp. Les arbres ont été traités à un taux de 165 à 480 mg de MET par litre quand les fruits avaient un diamètre de 5 à 22 mm. Les auteurs ont aussi déterminé si l'ajout d'un agent tensioactif non ionique exerce une influence sur l'efficacité du MET. Les arbres traités ont été comparés à des pommiers qui ne l'avaient pas été ainsi qu'au traitement usuel dans l'industrie (pulvérisation de carbaryl, de NAA, de 6-BA ou d'un de leurs mélanges). La réaction au MET varie avec le cultivar et l'année. Dans six expériences sur sept, le MET a réduit la nouaison, mais n'a diminué le nombre de fruits par arbre ou la charge fruitière qu'à quatre reprises, comparativement aux témoins non traités. L'application de MET à la chute des pétales (5-7 mm) est moins efficace qu'une application à un moment ultérieur. L'éclaircissage s'est accru avec le taux d'application dans quatre cas sur sept. Appliquer 175 mg de MET par litre réduit la nouaison et la charge fruitière des pommiers Honeycrisp et Ambrosia, mais pour qu'il y ait éclaircissage sur les pommiers Gala, le taux d'application doit être d'au moins 263 mg par litre. Le MET permet une meilleure répartition du calibre des fruits, qui se rangent parmi les plus gros, et la phytotoxicité pour les feuilles reste minime, avec ou sans agent tensio-actif non ionique. Les paramètres environnementaux comme la température nocturne et l'ensoleillement ne peuvent expliquer dans une large mesure la réaction de l'éclaircissage à l'application saisonnière ou au moment de l'application du MET. Il faudrait approfondir les effets du bilan du carbone et des interactions de l'ensoleillement, de la température nocturne, du cultivar et du calibre des jeunes fruits sur la réaction à l'éclaircissant pour mieux prévoir l'importance de l'éclaircissage avec le MET chez le pommier. [Traduit par la Rédaction]

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Mots-clés : poids des fruits, charge fruitière, répartition du calibre, densité de la récolte, *Malus domestica* Borkh.

Introduction

Profitability in apple (*Malus domestica* Borkk.) production depends on a grower's ability to produce superlative fruit and maximize pack-out. Harvesting undersized and poor coloured fruit are associated with higher harvesting and packing, sorting, and storage expenses resulting in lost revenue. Low crop density (crop load) reduces yield while excessive crop density results in small, low quality, and often poor coloured fruit, as well as reduced flowering the following production year. The potential loss when crop density is not optimized is economically significant. We have been investigating the physiology of and pragmatic means for regulating crop density using blossom and fruitlet thinners to enhance natural fruit abscission with the goal of reaching the target fruit number with greater precision.

Over the past decade a new thinning compound, metamitron (MET), first introduced by German researchers for its thinning efficacy of apple, has been in development (Köpcke 2005). The mode of action of MET is different from other thinning products such as carbaryl, 1-naphthalene acetic acid (NAA), naphthalene acetamide, and 6-benzyladenine (6-BA). MET is a triazinone systemic herbicide translocated in the xylem that disrupts the photosynthetic apparatus by blocking electron transfer between the primary and secondary quinones of photosystem II (PSII) (Corbet 1974; Abbaspoor et al. 2006). The notion that photosynthetic inhibition induces abscission of apple fruits was first introduced by Byers et al. (1985, 1990) where source-sink shading experiments were shown to be effective in shedding fruit early during fruit development. Coupled with this are studies that have shown increases in nighttime temperature during rapid apple fruit growth, when fruit are highly dependent on photoassimilate production, enhance the formation of the fruit abscission zone and consequently increase fruit drop (Kondo and Takahashi 1987; Stern 2014; Clever 2018; Rosa et al. 2021).

That foliar applications of MET to apple trees can induce a transient carbohydrate stress, and activation of the fruit abscission zone upon inter-fruit competition in the fruit corymb is a logical extension of these shading studies. An increase in the activity of the fruit abscission zone can heighten the sensitivity of young fruitlets to a chemical thinner. If activation of the fruit abscission zone is triggered by a critical threshold level of carbohydrates within the fruit, as proposed by Botton et al. (2011), then the efficacy of MET as a fruit thinner will be dependent on several factors, including carbohydrate balance in the tree at the time of application, carbon assimilation, and allocation between competing sinks such as leaves, fruit, and respiration.

Reports vary on the effect of MET on suppression of PSII. McArtney et al. (2012) reported a reduction in maximum suppression of dark-adapted chlorophyll fluorescence (Fv/Fm), quantum photosynthetic yield of PSII, and relative electron transport after application of MET to apple trees. This suppression was greatest 1–2 d after application of 300 mg L^{-1} METs and did not fully recover until 7 d after application. Gonzalez et al. (2020) also found the maximum suppression of chlorophyll fluorescence occurred 2 d following application of MET but recovery took longer. Penzel and Kröling (2020) observed that MET applied at a low concentration (165 g ha^{-1}) reduced photosynthesis for at least 2 weeks after application. The duration and extent of photosynthesis suppression and role that cultivar and incident solar radiation conceivably would influence the efficacy of MET on fruit thinning.

Application of a PSII inhibitor such as MET to apple trees can result in a transient carbohydrate stress that may persist for several days (McArtney et al. 2012; Brunner 2014; Stern 2015; Rosa 2016; Gonzalez et al. 2019) and increase the sensitivity of the fruit to a chemical thinner. In addition to this direct effect, if MET is applied in combination with a chemical thinner that has been formulated with a wetting agent, then the resulting carbohydrate stress may result in aggressive thinning compared with a chemical thinner not formulated with a wetting agent.

Improving the efficacy and reliability of chemical fruitlet thinners using surfactants is a topic of interest to growers and product registrants. The commercial formulation of MET (Brevis®) does not contain a surfactant (S. Eskelsen, personal communication, Adama USA), but empirical observations indicate higher efficacy and leaf phytotoxicity in some instances when combined with a non-ionic surfactant. McArtney et al. (2012) found the enhanced suppression of Fv/Fm when the non-ionic surfactant Silwett-L-77 was included in the foliar spray with MET. Few reports on the direct effects of surfactants on fruit thinning with MET on apple have been reported in the scientific literature.

Several European, Israeli, Brazilian, and American studies have investigated MET use as an apple thinner on popular cultivars grown in these regions. A majority of these studies have focused on single or double applications of MET, and tank-mix combinations with naphthalene acetamide, NAA, 6-BA, carbaryl, and 1-aminocyclopropane carboxylic acid (Köpcke 2005; Clever 2007; Dorigoni and Lezzer 2007; Deckers et al. 2010; Lafer 2010; Basak 2011; Fernandes et al. 2013; Maas and Van der Steg 2011; Stern 2014, 2015; Maas and Meland 2016; Botton et al. 2019; Penzel and Kröling 2020). There is a paucity of research investigating the rate response of MET to determine the optimal thinning concentration of apples, as well as studies on Ambrosia, Gala, and Honeycrisp, all popular commercial cultivars grown in Canada. In addition, there are few studies in the literature investigating the impact of incorporating non-ionic surfactants with MET on thinning and leaf phytotoxicity. The objectives of this study were to determine the effect of different application timing and concentration of MET, as well as inclusion of a non-ionic surfactant, on fruit set, crop load, yield parameters, size distribution, and return bloom of several popular apple cultivars grown in Ontario over multiple growing season.

Materials and Methods

Methods common to all experiments

Experiments were conducted at the University of Guelph, Horticultural Experiment Station, Simcoe, ON (42°51′40″ N, 80°16′8″ W). Trees were supplied with trickle irrigation via 2 L h^{-1} pressure-compensating emitters spaced 45 cm apart and watered daily during the growing season with an equivalent of ∼2.5 cm of water weekly (adjusted for natural rainfall) on a schedule of six irrigation run-times per day every 4 h (20 min per event). Standard cultural and pest management practices for Ontario were followed (Ontario Ministry of Agriculture, Food and Rural Affairs 2018). Granular fertilizer (N-P-K) was applied in the spring each season prior to bud-break, and rates were based on leaf analyses recorded the prior season. Weeds were controlled within a 1-m strip on each side of the tree row using 1% (*v*/*v*) glyphosate applications made mid-May, June, and July. A permanent sod culture was established at the time of planting in the row middle using a mixture of 40% perennial rye and 60% red fescue (Vineland Growers, Vineland, ON). Daily maximum and minimum air temperatures, precipitation, and solar radiation were recorded by a weather station located within 500 m of the research orchards. Tree trunk circumference at 30 cm above the graft union was measured at the beginning and end of each growing season, from which trunk cross-sectional area (TCSA) was calculated. All treatment trees were selected for adequate and uniform bloom. Return bloom was estimated by counting the number of flowering and non-flowering spurs on four limbs per tree. Between 2017 and 2019 leaf phytotoxicity and leaf drop were assessed using a six-point phytotoxicity scale (0 = none; 1 = <10% very slight; 2 = 11%–20% or slight; 3 = 21%–50% or moderate; 4 = 51%–75% high; 5 = ≥75% very high). For 2020, leaf phytotoxicity was assessed using a nine-point scale assessed using the Brevis Rating (1 = no leaf necrosis; 2 = light yellow discoloration between the veins; 3 = yellow discoloration between the veins, beginning of necrosis on the edge and on the tip of the leaf; 4 = strong yellow discoloration between the veins and beginning of necrosis on the edge of the leaf (1–2 mm) from the tip… 9 = leaf entirely necrosed and curled, sometimes a small green area may persist around the central vein and near the stem) (scale provided by Adama Canada, Winnipeg, MB). At harvest, the total yield and number of fruit per tree were recorded. Mean fruit weight was calculated based on the total yield divided by the total number of fruit per tree.

Experiment 1 — Royal Gala/B.9 (2017)

This experiment was conducted in 2017 on a mature block of Royal Gala on B.9 rootstock planted in 2002 at a spacing of 2.5 m × 4.5 m (889 trees/ha) and trained to a vertical axe system. The orchard soil consisted predominately of a Watford fine sandy loam (Brunisolic Grey Brown Luvisol) (Presant and Acton 1984) with good drainage and soil textures consisting mainly of glaciolacustrine sands modified by wind sorting over fine sand and loamy fine sand at depths greater than 50 cm (Hohner and Presant 1989). Treatments were applied using a commercial air-blast sprayer (Model Turbomist 30 P, Slimline Manufacturing, Penticton, BC, Canada) to single tree plots, travelling at 3.1 km h^{-1}, 1380 kPa, 1020 L ha^{-1} which equated to tree row volume (TRV) dilute (Sutton and Unrath 1988). The sprayer tower boom was equipped with 12 air-induction nozzles (TRX80-VK, TeeJet Technologies, Louisville, KY, USA) per boom (side); however, the axial fan was turned off to prevent spray drift to the adjacent row. In addition, to minimize treatment interference caused by spray drift, experimental units were separated by at least one guard tree.

The experimental design comprised a random complete block with seven replications and nine treatments. Treatments consisted of: (*i*) an untreated control; (*ii*) a hand-thinned control; (*iii*) a tank mix of 1500 mg L^{-1} carbaryl (Sevin XLR Plus, Bayer CropScience, Guelph, ON, Canada) and 75 mg L^{-1} 6-BA (Maxcel, Valent BioSciences, Libertyville, IL, USA); (*iv*)–(*ix*) 175 or 350 mg L^{-1} MET (Brevis 46701; Adama Canada, Winnipeg, MB, Canada) applied at 8–10 mm, 15 mm, or 20 mm fruitlet diameter. Treatment (*iii*) and the 8–10 mm fruitlet diameter MET treatments were applied on 30 May 2017 (king = 8.8 mm, n = 26; lateral = 8.2 mm, n = 26). MET treatments targeting a fruitlet diameter of 15 mm were applied on 7 June 2017 (king = 17.3 mm, n = 26; lateral = 16.0 mm, n = 26) and the 20 mm treatments were applied on 12 June 2017 (king = 22.3 mm, n = 26; lateral = 20.2 mm, n = 26). All spray treatments included 0.125% LI 700 non-ionic spray adjuvant (Loveland Products Canada Inc., Dorchester, ON, Canada). After natural fruit drop, the hand-thinned control was thinned on 20 June 2017 by singling fruit and spacing them approximately 10 cm apart. The date of full bloom of was 15 May 2017.

Horticultural measurements

Four scaffold branches—two on the east and two on the west side of the tree—were selected prior to bloom to determine fruit set. On 11 May 2017, the number of flower clusters per branch were counted on each marked limb. The number of fruit set per limb were counted again on 7–8 Sept. 2017. These data were averaged and used to calculate percent fruit set (number of fruit set divided by number of flowers). Leaf phytotoxicity in plots treated at a fruitlet diameter of 8–10 mm with 350 mg L^{-1} MET was assessed on 8 and 15 June and 20 July 2017. Fruit were harvested on 18–20 Sept. 2017 and a sample of approximately 100 fruits (~20 kg) was placed in cold storage (~2 °C) for subsequent grading on a commercial colour sorting grading line on 12 and 15 Jan. 2018. All fruit from each sample were graded using a commercial sorting line (MAF RODA, MAF Agrobotic, Montauban Cedex, France) which relies on cameras and sensors to weigh and size each individual fruit. Individual fruit weights, sizes, and colour were recorded. Fruit length and diameter (L:D) ratios were also determined by image analyses from the grading line. Fruit were then separated according to their weight into 10 size categories expressed as an average count size category, which was the number of apples needed to fill a 20 kg box (Canadian Food Inspection Agency 2022). The total weight of fruit per tree was calculated for each count size category: (1) <96 g (count size 216); (2) 96–108 g (count size 198); (3) 109–116 g (count size 175); (4) 117–126 g (count size 163); (5) 127–137 g (count size 150); (6) 138–151 g (count size 138); (7) 152–168 g (count size 125); (8) 169–190 g (count size 113); (9) 191–215 g (count size 100); (10) 216–237 g (count size 88); (11) 238–264 g (count size 80); (12) 265–297 g (count size 72); (13) 298–339 g (count size 64); (14) 340–396 g (count size 56); and (15) ≥397 g (count size 48). Return bloom was measured in the spring of 2018 by measuring the ratio (expressed as a percent) of flowering and non-flowering spurs on four limbs per tree.

Experiment 2 — Honeycrisp/B.9 (2017)

This experiment was conducted in 2017 on a mature block of Honeycrisp on B.9 rootstock planted in 2005 at a spacing of 2 m × 4.5 m (1111 trees/ha) and trained to a vertical axe system. The orchard soil consisted predominately of Oakland loamy fine sand (Presant and Acton 1984) with imperfect drainage and soil textures consisting mainly of 40–100 cm sandy sediments over gravelly sandy till (Hohner and Presant 1989). Treatments were applied using a commercial air-blast sprayer (Model Turbomist 30 P, Slimline Manufacturing, Penticton, BC, Canada) to single tree plots, travelling at 3.2 km hr^{-1}, 1380 kPa, 1246 L ha^{-1} which equated to TRV dilute (Sutton and Unrath 1988). The sprayer tower boom was equipped with 12 air-induction nozzles (TRX80-VK, TeeJet Technologies, Louisville, KY, USA) per boom (side); however, the axial fan was turned off to prevent spray drift to the adjacent row. In addition, to minimize treatment interference caused by spray drift, experimental units were separated by at least one guard tree.

The experimental design comprised a randomized complete block with seven replications and seven treatments. Treatments consisted of (*i*) a hand-thinned control; (*ii*) 1500 mg L^{-1} carbaryl; (*iii*) 10 mg L^{-1} NAA (Fruitone L, AMVAC Chemical Corporation, Los Angeles, CA, USA); (*iv*)–(*vii*) 175 or 350 mg L^{-1} MET applied at 8–10 mm or 20 mm fruitlet diameter. Treatments (*ii*), (*iii*), and the 8–10 mm diameter treatments of MET were applied on 30 May 2017 (king = 10.6 mm, n = 26; lateral = 8.7 mm, n = 26). The 15–20 mm diameter treatments of MET were applied on 12 June 2017 (king = 22.5, n = 26; lateral = 20.3, n = 26). Treatment (*iii*) included 0.125% LI 700 non-ionic spray adjuvant (Loveland Products Canada Inc., Dorchester, ON). After natural fruit drop, the hand-thinned control was thinned on 20 June 2017 by singling fruit and spacing them approximately 10 cm apart. The date of full bloom of was 15 May 2017.

Horticultural measurements

Four scaffold branches—two on the east and two on the west side of the tree—were selected prior to bloom to determine fruit set. On 12 May 2017 the number of flower clusters per branch were counted on each marked limb. The number of fruit set per limb were counted again on 8 Sept. 2017. These data were averaged and used to calculate percent fruit set (number of fruit set divided by number of flowers). Leaf phytotoxicity in plots treated at a fruitlet diameter of 8–10 mm with 350 mg L^{-1} MET was assessed on 8 and 15 June and 20 July 2017. Fruit were harvested on 12 Sept. 2017 and a sample of approximately 100 fruits (1 bushel) was placed in cold storage (~2 °C) for subsequent grading on a commercial colour sorting grading line on 17 Jan. 2018 as described for Experiment 1.

Experiment 3 — Ambrosia/M.9 2017

This experiment was conducted in 2017 on a mature block of Ambrosia on M.9 rootstock planted in 2012 at a spacing of 0.68 m × 4.0 m (3676 trees/ha) and trained to a slender spindle system. The orchard soil consisted predominately of Wilsonville sandy loam (Presant and Acton 1984) with rapid drainage and soil textures consisting of 40 cm of sandy loam over gravelly sandy till (Hohner and Presant 1989). Treatments were applied using a commercial air blast sprayer (GB Irrorazione Diserbo, Model Laser P7, Italy) to two-tree plots at 1379 kPa, 279 L ha^{-1}, which equated to TRV pesticide dilute (Sutton and Unrath 1988). The sprayer was equipped with 5=five nozzles per boom (side) and large axial fan to move the spray into the canopy. To minimize treatment interference caused by spray drift, experimental units were separated by at least one guard tree.

The experimental design comprised a randomized complete block with seven replications and seven treatments. Treatments consisted of (*i*) an untreated control; (*ii*) a hand-thinned control; (*iii*) 1500 mg L^{-1} carbaryl (Sevin XLR Plus); (*iv*) 150 mg L^{-1} 6-BA; (*v*)–(*x*) 175 or 350 mg L^{-1} MET applied at 8–10 mm, 15 mm, or 20 mm fruitlet diameter. Treatments (*iii*), (*iv*), and the 8–10 mm diameter treatments of MET were applied on 30 May 2017 (king = 7.6 mm, n = 26; lateral = 6.6 mm, n = 26). The 15 mm diameter treatments of MET were applied on 7 June 2017 (king = 14.6, n = 26; lateral = 12.6, n = 26). The 20 mm diameter treatments of MET were applied on 12 June 2017 (king = 18.6, n = 26; lateral = 17.8, n = 26). After natural fruit drop, the hand-thinned control was thinned on 20 June 2017 by singling fruit and spacing them approximately 10 cm apart. The date of full bloom of was 15 May 2017.

Horticultural measurements

Four scaffold branches—two on the east and two on the west side of the tree—were selected prior to bloom to determine fruit set. On 10 May 2017 the number of flower clusters per branch were counted on each marked limb. The number of fruit set per limb were counted again on 22 Sept. 2017. These data were averaged and used to calculate percent fruit set (number of fruit set divided by number of flowers). Leaf phytotoxicity and leaf drop in plots treated at a fruitlet diameter of 8–10 mm with 350 mg L^{-1} MET were assessed on 8 and 15 June and 20 July 2017. Fruit were harvested on 27 Sept. 2017 and a sample of approximately 100 fruits (20 kg) was placed in cold storage (~2 °C) for subsequent grading on a commercial colour sorting grading line on 15 Jan. 2018 as described for Experiment 1.

Experiment 4 — Royal Gala/B.9 (2018)

This experiment was conducted in 2018 on a mature block of Royal Gala on B.9 rootstock planted in 2002 at a spacing of 2.5 m × 4.5 m (889 trees/ha) and trained to a vertical axe system. The orchard soil consisted predominately of a Wattford fine sandy loam (Presant and Acton 1984) with good drainage and soil textures consisting mainly of glaciolacustrine sands modified by wind sorting over fine sand and loamy fine sand at depths greater than 50 cm (Hohner and Presant 1989). Treatments were applied using a commercial air blast sprayer (GB Irrorazione Diserbo) at 1379 kPa, 947 L ha^{-1}, which equated to TRV pesticide dilute (Sutton and Unrath 1988). The sprayer was equipped with five nozzles per boom (side) and large axial fan to move the spray into the canopy. To minimize treatment interference caused by spray drift, experimental units were separated by at least one guard tree. Applications were made in low wind conditions, between 0630–1030.

The experimental design comprised a random complete block with seven replications and eight treatments. Treatments consisted of (*i*) an untreated control; (*ii*) a hand-thinned control; (*iii*) a tank mix of 1500 mg L^{-1} carbaryl (Sevin XLR Plus) and 75 mg L^{-1} 6-BA; (*iv*) 165 mg L^{-1} MET (Brevis 46701), (*v*) 248 mg L^{-1} MET; (*vi*) 330 mg L^{-1} MET; (*vii*) 413 mg L^{-1} MET; and (*viii*) 480 mg L^{-1} MET. Treatment (*iii*) was applied on 30 May 2018 (king = 8.7 mm, n = 50; lateral = 7.3 mm, n = 50); and treatments (*iv*)–(*viii*) were applied on 2 June 2018 (king = 11.5 mm, n = 50; lateral = 9.9 mm, n = 50). All spray treatments included 0.05% Regulaid non-ionic spray adjuvant (2-butoxyethanol, poloxalene, monopropylene glycol, KALO, Inc., Overland Park, USA). After natural fruit drop, the hand-thinned control was thinned on 21 June 2018 by singling fruit and spacing them approximately 10 cm apart. The date of full bloom of was 20 May 2018.

Horticultural measurements

Four scaffold branches—two on the east and two on the west side of the tree—were selected prior to bloom to determine fruit set. On 17 May 2018, the number of flower clusters per branch were counted on each marked limb. The number of fruit set per limb were counted again on 21 June 2018. These data were averaged and used to calculate percent fruit set (number of fruit set divided by number of flowers). Leaf phytotoxicity and leaf drop were assessed in plots treated with 2.75 L ha^{-1} and 3.2 L ha^{-1} MET on 4, 12, and 19 June 2018. Fruit were harvested on 18–20 Sept. 2018, and sample of approximately 100 fruits (20 kg) was placed in cold storage (~2 °C) for subsequent grading on a commercial colour sorting grading line on 5 Mar. 2019 as described for Experiment 1.

Experiment 5 — Honeycrisp/M.26 (2018)

This experiment was conducted in 2018 on a mature block of Honeycrisp on M.26 planted in 2008 at a spacing of 1.2 m × 4.0 m (2083 trees/ha) and trained to a super spindle system. The orchard soil consisted predominately of well-drained Wattford fine sandy loam (Presant and Acton 1984) with soil textures consisting mainly of glaciolacustrine sands modified by wind sorting over fine sand and loamy fine sand at depths greater than 50 cm (Hohner and Presant 1989). Treatments were applied using a commercial air blast sprayer (GB Irrorazione Diserbo) at 1379 kPa, 917 L ha^{-1}, which equated to TRV pesticide dilute (Sutton and Unrath 1988). The sprayer was equipped with five nozzles per boom (side) and large axial fan to move the spray into the canopy. To minimize treatment interference caused by spray drift, experimental units were separated by at least one guard tree. Applications were made in low wind conditions, between 0630–1030.

The experimental design comprised a randomized complete block with seven replications and nine treatments. Treatments consisted of (*i*) an untreated control; (*ii*) a hand-thinned control; (*iii*) 1500 mg L^{-1} carbaryl (Sevin XLR Plus); (*iv*) 10 mg L^{-1} NAA (Fruitone L); (*v*) a tank mix of 1500 mg L^{-1} carbaryl and 10 mg L^{-1} NAA; (*vi*) 165 mg L^{-1} MET (Brevis 46701); (*vii*) 248 mg L^{-1} MET; (*viii*) 330 mg L^{-1} MET; and (*ix*) 413 mg L^{-1} MET. Treatments (*iii*)–(*v*) were applied on 30 May 2018 (king = 9.2 mm, n = 50; lateral = 6.7 mm, n = 50) and treatments (*vi*)–(*ix*) were applied on 2 June 2018 (king = 12.0 mm,

n = 50; lateral = 9.8 mm, n = 50). All spray treatments included 0.05% Regulaid non-ionic spray adjuvant. After natural fruit drop, the hand-thinned control was thinned on 18 June 2018 by singling fruit and spacing them approximately 10 cm apart. The date of full bloom of was 20 May 2018.

Horticultural measurements

Four scaffold branches—two on the east and two on the west side of the tree—were selected prior to bloom to determine fruit set. On 18 May 2018, the number of flower clusters per branch were counted on each marked limb. The number of fruit set per limb were counted again on 18 June 2018. These data were averaged and used to calculate percent fruit set (number of fruit set divided by number of flowers). In addition, the number of fruit set per flowering spur on the marked limbs was recorded.

Leaf phytotoxicity and leaf drop in plots treated with 2.2 and 2.75 L ha^{-1} MET were assessed on 4, 12, and 19 June 2018. Fruit were harvested on 24 Sept. 2018, and a sample of approximately 100 fruits (20 kg) was placed in cold storage (~2 °C) for subsequent grading on a commercial colour sorting grading line on 27 Feb. 2019 as described for Experiment 1.

Experiment 6 — Ambrosia/M.9 (2019)

This experiment was conducted in 2019 on a mature block of Ambrosia on M.9 rootstock planted in 2012 at a spacing of 0.68 m × 4.0 m (3676 trees/ha) and trained to a super spindle system. The orchard soil consisted predominately of Wilsonville sandy loam (Presant and Acton 1984) with rapid drainage and soil textures consisting of 40 cm of sandy loam over gravelly sandy till (Hohner and Presant 1989). Treatments were applied using a commercial air blast sprayer (GB Irrorazione Diserbo) at 1379 kPa, 620 L ha^{-1}, which equated to TRV pesticide dilute (Sutton and Unrath 1988). The sprayer was equipped with five nozzles per boom (side) and large axial fan to move the spray into the canopy. To minimize treatment interference caused by spray drift, experimental units were separated by at least one guard tree. Applications were made in low wind conditions, between 0630–1030.

The experimental design comprised a randomized complete block with seven replications and 11 treatments. Treatments consisted of (*i*) untreated control; (*ii*) hand-thinned control; (*iii*) 1500 mg L^{-1} carbaryl (Sevin XLR Plus); (*iv*) a tank mix of 1500 mg L^{-1} carbaryl + 75 mg L^{-1} 6-BA; (*v*) 175 mg L^{-1} MET (Brevis 46701); (*vi*) 263 mg L^{-1} MET; (*vii*) 351 mg L^{-1} MET; (*viii*) 2.92 L ha^{-1} MET; (*ix*)–(*xi*) 1.75 L ha^{-1} MET applied at petal fall, 8–11 mm fruitlet diameter or 16–20 mm fruitlet diameter. Treatments (*iii*)–(*viii*) were applied on 9 June 2019 targeting a fruitlet diameter of 12–14 mm (king = 12.4 mm, n = 23; lateral = 9.2 mm, n = 23). Treatment (*ix*) was applied at petal fall on 31 May 2019, treatment (*x*) on 7 June 2019 (king = 9.2 mm, n = 50; lateral = 6.8 mm, n = 50), and treatment (*xi*) on 18 June 2019 (king = 17.7 mm, n = 50; lateral = 13.5 mm, n = 50). Treatments (*iii*) and (*iv*) included 0.05% Regulaid non-ionic spray adjuvant. After natural fruit drop, the hand-thinned control was thinned on 4 July 2019 by singling fruit and spacing them approximately 10 cm apart. The date of full bloom of was 25 May 2019.

Horticultural measurements

Four scaffold branches—two on the east and two on the west side of the tree—were selected prior to bloom to determine fruit set. On 22 May 2019, the number of flower clusters per branch were counted on each marked limb. The number of fruit set per limb were counted again on 4 July 2019. These data were averaged and used to calculate percent fruit set (number of fruit set divided by number of flowers). Leaf phytotoxicity and leaf drop were assessed on 14, 20, and 28 June 2019. Fruit were harvested on 10–11 Oct. 2019, and a sample of approximately 100 fruits (20 kg) was placed in cold storage (~2 °C) for subsequent grading on a commercial colour sorting grading line on 25 Jan. 2020 as described for Experiment 1.

Experiment 7 — Ambrosia/B.9 (2020)

This experiment was conducted in 2020 on a mature block of Ambrosia/B.9 rootstock planted in 2005 at a spacing of 2 m × 4.5 m (1111 trees/ha) and trained using a spindle training system. The orchard soil was the same as that in Experiment 6. Treatments were applied using a commercial air blast sprayer (GB Irrorazione Diserbo) at 1379 kPa, 816 L ha^{-1}, which equated to TRV pesticide dilute (Sutton and Unrath 1988). The sprayer was equipped with five nozzles per boom (side) and large axial fan to move the spray into the canopy. To minimize treatment interference caused by spray drift, experimental units were separated by at least two guard trees. All applications were made in low wind conditions.

The experimental designed consisted of a randomized complete block with four replications and 13 treatments. Treatments were applied to single tree plots and consisted of (*i*) an untreated control; (*ii*) a hand-thinned control; (*iii*) 1500 mg L^{-1} carbaryl; (*iv*) 1500 mg L^{-1} carbaryl tank mixed with 75 mg L^{-1} 6-BA; (*v*)–(*xiii*) four rates of MET: 175.5 mg L^{-1}, 263 mg L^{-1}, 351 mg L^{-1}, and 438 mg L^{-1} applied with or without the non-ionic surfactant Agral 90 (Norac Concepts Inc, Guelph, ON) applied at a rate of 0.05% (*v*/*v*).

The MET treatments were applied on the mornings of 1 June and repeated on 9 June corresponding to a target fruitlet diameter of 6–7 mm and 12–16 mm, respectively. A single application of carbaryl and carbaryl + 6-BA treatments were applied on the morning of 9 June. Actual fruitlet diameters on 1 June were king = 5.0 mm (n = 50) and lateral = 4.2 mm (n = 50). Fruitlet diameters on 9 June were king = 12.5 mm (n = 25) and lateral = 10.1 mm

(n = 25). The hand-thinned control trees were hand thinned on 8 July by removing all but one fruit per cluster and spacing fruit ~10 cm apart. The date of full bloom of was 25 May 2020. Agral 90 surfactant at 0.05% (*v*/*v*) was included in the carbaryl alone and tank-mix of carbaryl and 6-BA treatments.

Horticultural measurements

On 11 May prior to full bloom, a total of four main scaffold branches, two on each of the east and west sides of the tree, were selected and marked to determine fruit set by counting the number of flower clusters per branch. On 22 June, after June drop, the number of fruit set per flower cluster was counted. These data were averaged and used to calculate percent fruit set (number of fruit set divided by number of flowers). Leaf phytotoxicity and leaf drop were assessed on 16 June 2020. Fruit were harvested on 13 Oct. 2020, and a sample of approximately 100 fruits (20 kg) was placed in cold storage (~2 °C) for subsequent grading on a commercial colour sorting grading line on 7 Nov. 2020 as described for Experiment 1. Return bloom was assessed in the spring of 2021 by counting the number of spurs with and without flowers on four limbs per tree between 1.5 m and 2 m above the ground. Return bloom was expressed as the percentage of spurs with flowers.

Statistical analyses

Data were subjected to analysis of variance using the PROC GLIMMIX procedure of SAS version 9.4 (SAS Institute, Cary, NC, USA). Average fruit weight was adjusted by using crop load as a covariate (Marini et al. 2012). Comparisons of treatments lsmeans were made using a Tukey's multiple means comparison test and statistical significance was reported at a Type I error rate of $\propto = 0.05$. Single degrees of freedom orthogonal comparison were performed to evaluate the rate and timing effects of MET. A Shapiro-Wilk test was used to test the normality of residuals. Scatterplots of studentized residuals were visually observed to test the assumption that errors were not heterogeneous. In cases where there were large deviations from the assumptions, data were transformed using log- or square root-transformation prior to analysis.

Results

Experiment 1 — Royal Gala/B.9 (2017)

Thinning treatments had a significant effect on Royal Gala fruit set (P = 0.0002), yield (P = 0.0092), total number of fruit per tree (P = 0.0366), but no effect on TCSA, percent marketable yield, adjusted average fruit weight, crop load, and return bloom the year following treatment applications (Table 1). Trees that were untreated had the highest fruit set compared to any of the other thinning treatments. Trees treated with 350 mg L^{-1} MET applied at 15- and 20-mm fruitlet diameter had the lowest fruit set, which was similar to the hand-thinned treatment and the treatments receiving fruitlet thinners. Based on orthogonal contrasts, MET at 15 mm and 20 mm were more effective than when applied at the 8–10 mm fruitlet stage. Fruit set was similar when MET was applied at 175 or 350 mg L^{-1}. Trees that were thinned with MET at 8–10 mm had higher yields, more fruit per tree, and higher crop loads compared with the untreated control, hand-thinned, and the other MET application timings. It is unclear why MET, when applied at 8–10 mm, would have resulted in higher fruit numbers per tree and crop loads compared to the untreated trees. Fruit size distribution was not influenced by any of the thinning treatments (data not shown). There was minimal effect of MET on leaf phytotoxicity (data not shown).

Experiment 2 — Honeycrisp/B.9 (2017)

Thinning treatments had a significant effect on the total number of Honeycrisp fruit per tree (P = 0.0131) but had no effect on TCSA, fruit set, total yield, percent marketable yield, adjusted average fruit weight, crop load, and return bloom the year following applications (Table 2). Trees that were hand-thinned had the highest fruit set compared with any of the other trees treated with chemical thinners. Based on orthogonal contrasts, trees treated with MET at both the 8–10 mm and 15–20 mm timings had lower fruit set compared with the hand-thinned trees and were both equally effective in reducing fruit set. The response to MET applied at 175 or 350 mg L^{-1} was similar. Trees that were hand thinned had the lowest number of fruit per tree. Trees treated with 1500 mg L^{-1} carbaryl, 10 mg L^{-1} NAA, or any of the MET treatments at 8–10- or 15–20-mm fruitlet diameters had similar numbers of fruit per tree, with the exception of those treated with 175 mg L^{-1} MET applied at 8–10 mm. However, based on orthogonal contrasts, the number of fruit per tree was significantly lower for the hand-thinned trees compared with MET treatments at both the 8–10 mm and 15–20 mm stages. Orthogonal contrasts indicated that MET applied at 15–20 mm were more effective in reducing crop load than when MET was applied at 8–10 mm compared with the hand-thinned controls. Overall, there was only minor treatment effects on fruit size distribution and leaf phytotoxicity (data not shown).

Experiment 3 — Ambrosia/M.9 2017

Thinning treatments had a significant effect on Ambrosia TCSA (P = 0.0146), fruit set (P = 0.0054), total number of fruit per tree (P = 0.0008), crop load (P < 0.0001), and return bloom (P < 0.0001), but no effect on total yield, percent marketable yield, and adjusted average fruit weight (Table 3). Fruit set was similar among all treatments, except the hand-thinned control treatment, which was slightly lower, but not statistically different from the untreated, carbaryl or 6-BA grower control treatments, or most MET treatments. Based on orthogonal contrasts, fruit set in trees treated with MET

Table 1. Influence of carbaryl (CB), 6-benzyladenine (6-BA), and various rates of metamitron applied at three different fruitlet sizes on tree growth, fruit set, and yield in 2017 of Royal Gala/B.9 apples planted in 2002.

Treatment (mg L^{-1})[a]	Application timings/fruitlet diameter	TCSA fall 2017 (cm^2)	Fruit set (no. fruit per 100 flower clusters)	Total fruit yield (kg per tree)	Total number of fruit (no. per tree)	Percent marketable yield (%)	Adjusted average fruit weight (g)	Crop load (no. fruit per TCSA)[b]	Return bloom 2018 (% of spurs with flowers)
Untreated control		119.6	123a	26.1ab	167a	52	140	2.2	64
Hand-thinned control	June drop	142.1	58bc	19.0ab	134a	56	151	1.1	69
1500 CB + 75 6-BA	8–10 mm	142.7	72abc	18.3ab	126a	62	153	1.6	70
175 Metamitron	8–10 mm	132.4	91abc	31.4a	231a	59	146	2.9	67
350 Metamitron	8–10 mm	105.0	107ab	30.6ab	239a	61	136	2.6	63
175 Metamitron	15 mm	158.7	63bc	18.2ab	120a	61	151	1.1	75
350 Metamitron	15 mm	117.4	44c	12.5ab	96a	58	146	1.0	69
175 Metamitron	20 mm	150.8	84abc	23.7ab	189a	48	120	1.4	69
350 Metamitron	20 mm	154.4	38c	12.1b	90a	40	152	0.9	73
P		0.0884	0.0002	0.0092	0.0366	0.8529	0.0993	0.1162	0.7610
Contrasts									
Hand-thinned vs. Metamitron 8–10 mm		NS	**	*	*	NS	NS	*	NS
Hand-thinned vs. Metamitron 15 mm		NS	NS	NS	NS	NS	NS	NS	NS
Hand-thinned vs. Metamitron 20 mm		NS	NS	NS	NS	NS	NS	NS	NS
175 vs. 350 Metamitron		NS	NS	NS	NS	NS	NS	NS	NS

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. TCSA, trunk cross-sectional area. NS, *, **, ***, indicates not significant, and significant differences at $P = 0.05$, $P = 0.01$, and $P = 0.001$, respectively.

[a]Treatment application dates were as follows: 8–10 mm (30 May 2017), 15 mm (7 June 2017), 20 mm (12 June 2017).

[b]Determined by dividing the total number of fruit harvested with the TCSA measured in fall.

Table 2. Influence of carbaryl (CB), 1-naphthaleneacetic acid (NAA), and various rates and application timings of metamitron on tree growth, fruit set, and yield in 2017 of Honeycrisp/B.9 apples planted in 2005.

Treatment (mg L^{-1})[a]	Application timings/fruitlet diameter	TCSA fall 2017 (cm^2)	Fruit set (no. fruit per 100 flower clusters)	Total fruit yield (kg per tree)	Total number of fruit (no. per tree)	Percent marketable yield (%)	Adjusted average fruit weight (g)	Crop load (no. fruit per TCSA)[b]	Return bloom 2018 (% of spurs with flowers)[c]
Hand-thinned control	June drop	18.9	139	12.1	70b	84.7	171	4.6	1.20 (86.6)
1500 CB	8–10 mm	30.1	77	22.4	124ab	71.4	164	4.9	1.10 (79.0)
10 NAA	8–10 mm	29.8	76	18.9	113ab	74.1	152	5.4	1.23 (88.9)
175 Metamitron	8–10 mm	20.8	91	21.5	172a	72.3	146	8.3	1.08 (77.7)
350 Metamitron	8–10 mm	14.8	80	18.5	148ab	74.9	169	10.3	1.07 (76.8)
175 Metamitron	15–20 mm	25.5	83	13.0	107ab	68.1	132	7.0	1.16 (84.3)
350 Metamitron	15–20 mm	22.1	68	16.4	96ab	69.1	153	5.0	1.23 (88.8)
P		0.7031	0.0701	0.2215	0.0131	0.5326	0.3636	0.1247	0.7615
Contrasts									
Hand-thinned vs. Metamitron 8–10 mm		NS	*	NS	***	NS	NS	*	NS
Hand-thinned vs. Metamitron 15–20 mm		NS	**	NS	NS	*	NS	NS	NS
Metamitron 8–10 mm vs. 15 mm		NS	NS	NS	**	NS	NS	*	NS
175 vs. 350 Metamitron		NS	NS	NS	NS	NS	NS	NS	NS

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. TCSA, trunk cross-sectional area. NS, *, **, ***, indicates not significant, and significant differences at $P = 0.05$, $P = 0.01$, and $P = 0.001$, respectively.

[a]Treatment application dates were as follows: 8–10 mm (30 May 2017), 15–20 mm (12 June 2017).

[b]Determined by dividing the total number of fruit harvested with the TCSA measured in fall.

[c]Data were transformed using an arcsine square root transformation prior to analysis. Values in brackets are mean values back-transformed to the original scale.

Table 3. Influence of carbaryl (CB), 6-benzyladenine (6-BA), and two rates of metamitron applied at various fruitlet diameters on tree growth, fruit set, and yield in 2017 of Ambrosia/M.9 apples planted in 2012.

Treatment (mg L^{-1})[a]	Application timings/fruitlet diameter	TCSA fall 2017 (cm^2)	Mean fruit set (no. fruit per 100 flower clusters)	Total fruit yield (kg per tree)	Total number of fruit (no. per tree)	Percent marketable (%)	Adjusted average fruit weight (g)	Crop load (no. fruit per TCSA)[b]	Return bloom 2018 (% of spurs with flowers)[c]
Untreated control		7.8ab	64ab	6.5	70ab	100	98bc	9.2a	0.53d (25.6)
Hand-thinned control	June drop	8.7ab	40b	5.6	46bc	100	118a	5.4b	1.09a (78.5)
1500 CB	8–10 mm	7.4ab	45ab	3.9	34c	100	112abc	4.8b	1.03ab (73.3)
150 6-BA	8–10 mm	7.9ab	64ab	5.7	57abc	100	106abc	7.2ab	0.73cd (44.1)
175 Metamitron	8–10 mm	7.8ab	61ab	6.4	65abc	100	99bc	8.3ab	0.68cd (39.2)
350 Metamitron	8–10 mm	7.3ab	51ab	6.1	60abc	100	101bc	8.1ab	0.81bc (52.0)
175 Metamitron	15 mm	7.5ab	59ab	5.2	53abc	100	97c	7.1ab	0.78bcd (49.2)
350 Metamitron	15 mm	7.7ab	47ab	4.8	42bc	100	116ab	5.4ab	0.87abc (58.2)
175 Metamitron	20 mm	8.8a	67a	7.3	76a	100	103abc	8.8ab	0.61cd (32.8)
350 Metamitron	20 mm	7.2b	63ab	6.2	62abc	100	105abc	8.7ab	0.75cd (46.0)
P		0.0146	0.0054	0.0615	0.0008	-	0.0017	0.0007	$<$0.0001
Contrasts									
Hand-thinned vs. Metamitron 8–10 mm		*	*	NS	*	-	***	**	***
Hand-thinned vs. Metamitron 15 mm		*	NS	NS	NS	-	*	NS	***
Hand-thinned vs. Metamitron 20 mm		NS	***	NS	**	-	**	***	***
175 vs. 350 Metamitron		*	NS	NS	NS	-	*	NS	*

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. TCSA, trunk cross-sectional area. NS,*, **, ***, indicates not significant, and significant differences at $P = 0.05$, $P = 0.01$, and $P = 0.001$, respectively.

[a]Treatment application dates were as follows: 8–10 mm (30 May 2017), 15 mm (7 June 2017), 20 mm (12 June 2017).

[b]Determined by dividing the total number of fruit harvested with the TCSA measured in fall. The mean separation does not reflect all significant comparisons. The following additional treatments are significantly different: 350 Metamitron (20 mm) and 1500 CB.

[c]Data were transformed using an arcsine square root transformation prior to analysis. Values in brackets are mean values back-transformed to the original scale.

at 8–10 mm and 20 mm fruitlet diameters were higher than that in the hand-thinned control trees. Trees treated with 175 mg L^{-1} had the greatest number of fruit per tree while trees treated with 1500 mg L^{-1} carbaryl had the lowest number of fruit per tree. All trees treated with MET had a similar number of fruit per tree as trees left untreated or hand-thinned. The untreated trees and those treated with MET at any time or concentration had similar crop loads. In contrast, the hand-thinned and carbaryl treated trees had the lowest crop loads; these, however, were similar to trees receiving a MET treatment. There was a marked treatment effect on return bloom the following year; trees left untreated had 26% of spurs with flowers whereas hand-thinned trees had 79% of spurs with flowers. Based on the ANOVA, trees receiving MET had similar return bloom values, regardless of application timing or concentration, all of which were lower than the hand-thinned trees. However, based on orthogonal contrasts, trees which received 350 mg L^{-1} MET had a slightly higher percentage of spurs with flowers than those treated with 175 mg L^{-1} MET. There was minimal effect of MET on leaf phytotoxicity (data not shown).

There was a significant treatment effect on fruit size distribution (Table 4). Overall, trees that were hand-thinned had the largest fruit weights, which exceeded those from the untreated control and any trees treated with MET. These effects were largely observed in the 125, 138, and 150 size categories. There was no MET concentration or timing effect on grade size distribution compared to the untreated control trees in any of the size categories between 88 and 198; however, in the 216 count size categories, the untreated control trees and those treated with 175 mg L^{-1} MET at 20 mm had the greatest number of fruit.

Experiment 4 — Royal Gala/B.9 (2018)

Thinning treatments had a significant effect on Royal Gala TCSA ($P = 0.0009$), fruit set ($P < 0.0001$), the percentage of flowering spurs with zero, one, two, three and four fruits, but had no effect on return bloom (Table 5). Trees that were hand-thinned had the greatest TCSA while trees that were treated with 165 mg L^{-1} MET ($P = 0.0235$) had the smallest TCSA. There were no differences in TCSA between any of the trees treated with MET and the untreated trees. Fruit set decreased with increasing rate of MET in a linear fashion ($P = 0.001$). Trees treated with 1500 mg L^{-1} carbaryl combined with 75 mg L^{-1} 6-BA and those that were hand-thinned had the lowest fruit set. Trees treated with 248 mg L^{-1} MET or higher had similar fruit set as the hand-thinned trees, while trees treated with 165 and 248 mg L^{-1} MET had fruit set similar to the untreated trees. With increasing rates of MET, the percentage of spurs with no fruit, two fruit, three fruit, and four fruit decreased in a highly significant fashion. Trees that had the highest percentage of fruits with more than one fruit per cluster where those left untreated and those treated with 165, 248, and 330 mg L^{-1} MET.

Thinning treatments also had a highly significant effect on Royal Gala total yield ($P < 0.0001$), number of fruit per tree ($P =< 0.0001$), percent marketable fruit ($P < 0.0001$), adjusted average fruit weight ($P < 0.0001$), and crop load ($P < 0.0001$) (Table 6). Increasing rates of MET decreased total yield, number of fruit per tree, and crop load in a linear fashion, but increased percent marketable fruit and adjusted average fruit weight in a quadratic and linear fashion, respectively. Trees treated with 330 mg L^{-1} MET or higher had similar yields, fruit numbers, percent marketable fruit, and crop load as the hand-thinned control trees. Trees treated with 413 mg L^{-1} MET or higher had similar fruit weights as the hand-thinned control and the grower control treatment of 1500 mg L^{-1} carbaryl combined with 75 mg L^{-1} 6-BA. There was minimal effect of MET on leaf phytotoxicity (data not shown).

Thinning treatments had a significant effect on fruit size distribution in the 88 and 125 through 198 categories (Table 7). The untreated trees had the greatest number of small fruit while trees that were hand-thinned had the greatest number of large fruit.

Experiment 5 — Honeycrisp/M.26 (2018)

Thinning treatments had a significant effect on Honeycrisp fruit set ($P < 0.0001$), the percentage of flowering spurs with zero, one, two, and three fruits, and return bloom ($P < 0.0001$), but had no effect on TCSA (Table 8). Fruit set decreased with increasing rates of MET in a linear fashion ($P = 0.001$). Trees treated with 1500 mg L^{-1} carbaryl combined with 10 mg L^{-1} NAA had the lowest fruit set followed by trees treated with 10 mg L^{-1} NAA or 1500 mg L^{-1} carbaryl. Trees treated with rates of 168 mg L^{-1} MET and higher had similar fruit set as the hand-thinned trees. All trees that were hand-thinned or treated with fruitlet thinners, including MET, had lower fruit set than trees left untreated. With increasing rates of MET, the percentage of spurs with zero fruit, one fruit, two fruit, and three fruit decreased. Trees that had the highest percentage of fruits with two fruit per cluster were those left untreated or those treated with 165, 248, and 330 mg L^{-1} MET. Trees that were hand-thinned, left untreated, or treated with 165, 248, and 413 mg L^{-1} MET had the greatest percentage of spurs with one fruit. Overall, return bloom was poor for all treatments, except those treated with 10 mg L^{-1} NAA and 1500 mg L^{-1} carbaryl. Even trees that were hand-thinned or treated with 10 mg L^{-1} NAA combined with 1500 mg L^{-1} carbaryl had poor return bloom (31% and 28%, respectively), albeit higher than that observed for the untreated control. Trees treated with any of the rates of MET had similar return bloom as the untreated control trees.

Thinning treatments also had a highly significant effect on Honeycrisp total yield ($P < 0.0001$), number of fruit per tree ($P < 0.0001$), percent marketable fruit

Table 4. Influence of carbaryl (CB), 6-benzyladenine (6-BA), and two rates of metamitron applied at various fruitlet diameters on the weight of fruit per count size in 2017 of Ambrosia/M.9 apples planted in 2012.

Treatment (mg L^{-1})[a]	Application timings/fruitlet diameter	Amount of fruit in each size category (kg per tree)[b]									
		88	100	113	125	138	150	163	175	198	216
Untreated control		0.00	0.00	0.0	0.0b	0.1b	0.4	0.5	0.8	1.7	3.1a
Hand-thinned control	June drop	0.00	0.02	0.0	0.7a	0.9a	1.2	1.0	0.5	0.9	0.5b
1500 CB	8–10 mm	0.00	0.04	0.2	0.3ab	0.4ab	0.8	0.5	0.4	0.6	0.3b
150 6-BA	8–10 mm	0.00	0.00	0.0	0.1b	0.3ab	0.5	0.7	0.6	1.2	1.6ab
175 Metamitron	8–10 mm	0.00	0.00	0.0	0.0b	0.2b	0.4	0.5	0.9	1.4	2.3ab
350 Metamitron	8–10 mm	0.00	0.00	0.0	0.0b	0.2ab	0.4	0.6	0.7	1.4	2.6ab
175 Metamitron	15 mm	0.00	0.00	0.0	0.0b	0.1b	0.4	0.7	0.8	1.6	1.3ab
350 Metamitron	15 mm	0.00	0.00	0.1	0.3ab	0.5ab	0.7	0.8	0.6	0.9	0.6b
175 Metamitron	20 mm	0.00	0.00	0.1	0.5ab	0.6ab	0.6	0.6	0.4	1.2	3.4a
350 Metamitron	20 mm	0.03	0.00	0.0	0.0b	0.2ab	0.7	0.9	0.7	1.7	1.8ab
P		0.3609	0.1872	0.3353	0.0007	0.0108	0.1248	0.2911	0.3386	0.0825	0.0002
Contrasts											
Untreated vs. Metamitron 8–10 mm		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Untreated vs. Metamitron 15 mm		NS	NS	NS	NS	NS	NS	NS	NS	NS	***
Untreated vs. Metamitron 20 mm		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Hand-thinned vs. Metamitron 8–10 mm		NS	NS	NS	***	***	**	*	NS	NS	***
Hand-thinned vs. Metamitron 15 mm		NS	NS	NS	**	**	**	NS	NS	NS	NS
Hand-thinned vs. Metamitron 20 mm		NS	NS	NS	**	**	*	NS	NS	NS	***
175 vs. 350 Metamitron		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. NS, *, **, ***, indicates not significant, and significant differences at $P = 0.05$, $P = 0.01$, and $P = 0.001$, respectively.

[a]Treatment application dates were as follows: 8–10 mm (30 May 2017), 15 mm (7 June 2017), 20 mm (12 June 2017).

[b]Fruit diameter equivalents for each count size: 88 = 82–89 mm, 100 = 79–82 mm, 113 = 76–79 mm, 125 = 73–76 mm, 138 = 70–73 mm, 150 = 67–70 mm, 163 = 64–67 mm, 175 = <64 mm.

Table 5. Influence of carbaryl (CB), 6-benzyladenine (6-BA), and various rates of metamitron on fruit set in 2018 of Royal Gala/B.9 apples planted in 2002.

Treatment (mg/L)[a]	TCSA fall 2018 (cm^2)	Fruit set (no. fruit per 100 flower clusters)	Percentage of flowering spurs with indicated number of fruit						Return bloom 2019 (% of spurs with flowers)
			0	1	2	3	4	5	
Untreated control	146.3abc	116.7a	28.6c	40.2ab	21.8ab	6.6a	1.9a	0.9	58
Hand-thinned control	164.1a	48.7cd	52.0ab	48.0a	0.0e	0.0c	0.0b	0.0	64
1500 CB + 75 6-BA	152.1ab	37.0d	67.6a	26.7b	5.1de	0.4bc	0.0b	0.0	69
165 Metamitron	120.7c	109.2a	30.4c	39.3ab	22.5a	6.5a	1.3ab	0.0	65
248 Metamitron	140.5abc	96.1ab	32.9bc	43.4a	18.8abc	4.5ab	0.4ab	0.0	47
330 Metamitron	141.4abc	69.4c	47.5abc	37.8ab	13.1bcd	1.0bc	0.6ab	0.0	60
413 Metamitron	135.2abc	69.6bc	49.0abc	36.0ab	12.2cd	2.5abc	0.3ab	0.2	55
480 Metamitron	129.2bc	58.5cd	54.0a	35.0ab	9.6d	1.4bc	0.0b	0.0	58
P	0.0009	<0.0001	<0.0001	0.0071	<0.0001	<0.0001	0.0059	0.1831	0.4610
Rate of metamitron	C*	L***	L***	NS	L***	L***	L***	L*	NS

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. TCSA, trunk cross-sectional area. NS, *, ***, indicates not significant, and significant differences at $P = 0.05$ and $P = 0.001$ respectively. L, C refer to linear and cubic relationships.
[a]Treatment application dates were as follows: CB + 6-BA (30 May 2018), Metamitron (2 June 2018).

Table 6. Influence of carbaryl (CB), 6-benzyladenine (6-BA), and various rates of metamitron on fruit yield in 2018 of Royal Gala/B.9 apples planted in 2002.

Treatment (mg/L)[a]	Total fruit yield (kg per tree)	Total number of fruit (no. per tree)	Percent marketable yield (%)	Adjusted average fruit weight (g)	Crop load (no. fruit per TCSA)[b]
Untreated control	57.0a	394a	55bc	145bc	2.8ab
Hand-thinned control	33.6cd	200de	71ab	168a	1.3d
1500 CB + 75 6-BA	23.3d	140e	72ab	167a	1.3d
165 Metamitron	49.7ab	332ab	54c	152bc	2.9a
248 Metamitron	42.2bc	302bc	50c	141c	2.4abc
330 Metamitron	42.5bc	282bcd	63abc	152bc	2.1a–d
413 Metamitron	33.5cd	210de	64abc	156ab	1.8cd
480 Metamitron	34.3cd	219cde	74a	157ab	1.9bcd
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Rate of Metamitron	L***	L***	L***, Q**	L**	L***

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. TCSA, trunk cross-sectional area. **, *** , indicates significant differences at $P = 0.01$ and $P = 0.001$, respectively. L, Q refer to linear and quadratic relationships.
[a]Treatment application dates were as follows: CB + 6-BA (30 May 2018), Metamitron (2 June 2018).
[b]Determined by dividing the total number of fruit harvested with the TCSA measured in fall.

($P < 0.0001$), adjusted average fruit weight ($P < 0.0001$), and crop load ($P < 0.0001$) (Table 9), however most of these effects can be attributed to the hand-thinned, carbaryl, NAA, and carbaryl combined with NAA sprays as most trees treated with MET, especially at lower rates, had little or no effect compared with the untreated control trees. While MET had little effect on yield per tree, increasing rates of MET above 248 mg L^{-1} reduced fruit set below the untreated control and to a level similar to the hand-thinned control. Overall, the percentage of marketable fruit were low (because of poor colour; data not shown), and with respect to trees receiving the MET treatments, only those treated with 413 mg L^{-1} MET had slightly improved marketable fruit above the untreated. None of the MET treatments improved fruit weight over the untreated control treatments. Increasing rates of MET reduced crop load in a quadratic fashion, but only trees treated with 330 or 413 mg L^{-1} MET had lower crop

Table 7. Influence of carbaryl (CB), 6-benzyladenine (6-BA), and various rates of metamitron on the amount of fruit in each size category in 2018 of Royal Gala/B.9 apples planted in 2002.

	Amount of fruit in each size category (kg per tree)[b]										
Treatment (mg/L)[a]	80	88	100	113	125	138	150	163	175	198	216
Untreated control	0.0	0.4b	5.1	10.0	13.2a	11.3a	7.8a	4.3a	2.1a	2.2a	0.5
Hand-thinned control	0.5	2.3a	6.5	9.3	6.1ab	4.7cd	2.1bc	1.2ab	0.3a	0.3b	0.2
1500 CB + 75 6-BA	0.7	1.6ab	5.0	6.8	4.3b	2.6d	1.2c	0.5b	0.2a	0.1b	0.2
165 Metamitron	0.0	0.8ab	4.5	10.1	10.7ab	11.0ab	6.0ab	3.6ab	1.5a	1.3ab	0.3
248 Metamitron	0.3	0.3b	4.6	7.2	11.3ab	8.9abc	4.2abc	2.7ab	1.5a	0.6ab	0.6
330 Metamitron	0.0	0.5ab	3.4	11.0	11.9ab	10.3abc	3.2bc	1.2ab	0.7a	0.2b	0.1
413 Metamitron	0.2	0.4b	5.0	10.4	7.9ab	5.5bcd	1.8c	1.6ab	0.2a	0.2b	0.3
480 Metamitron	0.1	0.7ab	3.4	9.0	8.5ab	6.3a–d	3.2bc	2.0ab	0.5a	0.4b	0.1
P	0.3428	0.0121	0.8004	0.7331	0.0361	<0.0001	<0.0001	0.0070	0.0381	0.0042	0.5934
Rate of Metamitron	NS	NS	NS	NS	NS	L***	L***	L**	L**	L***	NS

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. NS, **, ***, indicates not significant, and significant differences at $P = 0.01$ and $P = 0.001$, respectively. L refers to linear relationships.

[a]Treatment application dates were as follows: CB + 6-BA (30 May 2018), Metamitron (2 June 2018).

[b]Fruit diameter equivalents for each count size: 80 = 84.5–89 mm, 88 = 83–84.5 mm, 100 = 79–83 mm, 113 = 76–79 mm, 125 = 73–76 mm, 138 = 70–73 mm, 150 = 67–70 mm, 163 = 64–67 mm, 175 = 60–64 mm, 198 = 57–60 mm, 216 = 53–57 mm.

Table 8. Influence of various rates and combinations of metamitron, carbaryl (CB), and naphthaleneacetic acid (NAA) on fruit set in 2018 of Honeycrisp/M.26 apples trees planted in 2008.

Treatment (mg/L)[a]	TCSA fall 2018 (cm^2)	Fruit set (no. fruit per 100 flower clusters)	Percentage of flower spurs with indicated number of fruit: 0	1	2	3	4	5	Return bloom 2019 (% of spurs with flowers)
Untreated control	30.0	73.0a	45.6d	41.9ab	10.0a	1.6a	0.4	0.5	10c
Hand-thinned control	28.8	48.1bcd	53.5cd	46.5a	0.0d	0.0a	0.0	0.0	16bc
1500 CB	26.6	38.9de	64.4bc	31.6bc	4.0bcd	0.0a	0.0	0.0	31b
10 NAA	30.7	33.9e	68.8ab	28.3cd	2.6cd	0.3a	0.0	0.0	28b
1500 CB + 10 NAA	30.1	10.8f	84.2a	15.7d	0.2d	0.0a	0.0	0.0	60a
165 Metamitron	26.1	56.5b	52.2cd	39.4abc	7.6abc	0.8a	0.0	0.0	7c
248 Metamitron	29.0	54.1bc	53.6cd	36.6abc	9.5ab	0.2a	0.0	0.0	11c
330 Metamitron	29.4	43.6cde	61.9bc	32.8bc	5.3a-d	0.0a	0.0	0.0	11c
413 Metamitron	31.6	44.4cde	60.5bc	35.5abc	3.3cd	0.7a	0.0	0.0	5c
P	0.0660	<0.0001	<0.0001	<0.0001	<0.0001	0.0363	0.0589	0.1101	<0.0001
Rate of Metamitron	Q*	L***	L***	L*	L***	L*	L**, Q*	L**	NS

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. TCSA, trunk cross-sectional area. NS, *, **, ***, indicates not significant, and significant differences at $P = 0.05$, $P = 0.01$, and $P = 0.001$, respectively. L, Q refer to linear and quadratic relationships.

[a]Treatment application dates were as follows: CB, NAA, CB + NAA (30 May 2018), Metamitron (2 June 2018).

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Table 9. Influence of various rates and combinations of metamitron, carbaryl (CB), and naphthaleneacetic acid (NAA), on harvest parameters in 2018 of Honeycrisp/M.26 apple trees planted in 2008.

Treatment (mg/L)[a]	Total fruit yield (kg per tree)	Total number of fruit (no. per tree)	Percent marketable fruit (%)	Adjusted average fruit weight (g)	Crop load (no. fruit per TCSA)[b]
Untreated control	26.4a	130a	52.4cd	226cd	4.8a
Hand-thinned control	18.7c	86de	61.4bc	218d	3.1de
1500 CB	18.3c	69e	62.9abc	266a	2.8de
10 NAA	19.0c	76e	68.2ab	245bc	2.5e
1500 CB + 10 NAA	7.6d	25f	72.6a	262ab	0.8f
165 Metamitron	24.1ab	116ab	50.4d	227cd	4.5ab
248 Metamitron	24.9ab	114ab	60.6bcd	236cd	4.1abc
330 Metamitron	21.3bc	94cd	60.8bcd	230cd	3.3cde
413 Metamitron	24.6ab	108bc	63.2ab	234cd	3.6bcd
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Rate of Metamitron	L**	L***, Q*	L***	NS	L***, Q*

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. TCSA, trunk cross-sectional area. NS, *, **, ***, indicates not significant, and significant differences at $P = 0.05$, $P = 0.01$, and $P = 0.001$, respectively. L, Q refer to linear and quadratic relationships.

[a]Treatment application dates were as follows: CB, NAA, CB + NAA (30 May 2018), Metamitron (2 June 2018).

[b]Crop load determined by dividing the total number of fruit harvested with the TCSA measured in fall.

loads than the untreated control trees, as did the hand-thinned control, carbaryl, NAA, and carbaryl and NAA applications. There was minimal effect of MET on leaf phytotoxicity (data not shown).

Honeycrisp fruit were large because of relatively light crop loads. Thinning treatments had a significant effect on fruit size distribution in all size categories except the smaller 150, 163, 198, and 216 categories (Table 10). The untreated trees had the greatest number of small fruit, but only 3% of the fruit (by weight) were smaller than the 138 size category. Trees that were hand-thinned had the greatest number of large fruit where most were distributed in the 64 to 100 count size. All trees treated with MET had similar amounts of fruit in each of the size categories ranging from 56 through 125 compared with the untreated control trees.

Experiment 6 — Ambrosia/M.9 (2019)

Thinning treatments had a significant effect on Ambrosia fruit set ($P < 0.0001$), the percentage of flowering spurs with zero, one, two, and three fruits, and return bloom ($P < 0.0001$) but had no effect on TCSA (Table 11). Fruit set decreased with increasing rate of MET in a highly significant linear fashion (P = 0.001). Trees treated with 1500 mg L^{-1} carbaryl or 1500 mg L^{-1} carbaryl combined 75 mg L^{-1} 6-BA had similar fruit set as trees treated with 351 and 438 mg L^{-1} MET. Trees that were left untreated or hand-thinned had the highest fruit set. Whereas applications of 263 mg L^{-1} MET at 8–11 or 16–20 mm fruitlet diameter reduced fruit set more than the petal fall application, and the 12–14 mm timing was the most efficacious. Regardless of treatment, most trees had flowers set as either zero or one fruit per spur. For example, trees left untreated had only 8% fruit with more than one fruit per flower cluster. With increasing rates of MET, the percentage of spurs with no fruit increased in a linear fashion while the percentage of spurs with one fruit decreased in a linear fashion.

Thinning treatments also had a highly significant effect on Ambrosia total yield ($P < 0.0001$), number of fruit per tree ($P < 0.0001$), percent marketable fruit ($P < 0.0001$), adjusted average fruit weight ($P < 0.0001$), and crop load ($P < 0.0001$) (Table 12). Increasing rates of MET had an inverse linear relationship with yield, number of fruit per tree, percent marketable fruit, average fruit weight and crop load. Applications of 263 mg L^{-1} MET made after the petal fall timing were more effective in reducing the total number of fruit per tree and crop load. Trees spayed with 263, 351, and 438 mg L^{-1} MET at 12–14 mmm were equally effective as 1500 mg L^{-1} carbaryl and 1500 mg L^{-1} carbaryl combined with 75 mg L^{-1} 6-BA at the same timing. Percent marketable fruit increased in a linear fashion with MET, with 438 mg L^{-1} MET treatment resulting in 92% marketable fruit. The untreated control trees had only 23% fruit that were marketable, owing largely to poor colour (data not shown) rather than small fruit size. Petal fall and 8–11 mm fruit diameter applications of 263 mg L^{-1} MET had a similar percentage of marketable fruit as the untreated control, while applications made at 12–14 and 16–20 mm had 89% and 62% percent marketable fruit, respectively. The two grower control applications of carbaryl and carbaryl combined with 6-BA had 85% and 86% marketable fruit, respectively. In comparison with

Table 10. Influence of various rates and combinations of metamitron, carbaryl (CB), and naphthaleneacetic acid (NAA), on the amount of fruit in each size category in 2018 of Honeycrisp/M.26 apples planted in 2008.

	Amount of fruit in each size category (kg per tree)[b]														
Treatment (mg/L)[a]	48	56	64	72	80	88	100	113	125	138	150	163	175	198	216
Untreated control	0.0b	0.3c	2.4ab	5.3ab	4.0ab	4.1ab	3.5ab	2.8a	1.7a	1.4a	0.4	0.1	0.2a	0.0	0.2
Hand-thinned control	0.1b	0.7bc	2.4ab	4.8ab	4.2ab	2.4a–d	2.1abc	1.1ab	0.3ab	0.2b	0.1	0.1	0.0b	0.0	0.1
1500 CB	1.0ab	3.5a	6.0a	3.4ab	1.8bc	1.4cd	0.8bc	0.2b	0.3ab	0.0b	0.1	0.0	0.0b	0.0	0.0
10 NAA	0.7ab	2.2abc	4.9ab	4.4ab	3.1abc	1.7bcd	1.4abc	0.3b	0.1b	0.1b	0.1	0.0	0.0b	0.0	0.1
1500 CB + 10 NAA	1.4a	3.0ab	1.5b	1.1b	0.3c	0.2d	0.1c	0.0b	0.0b	0.0b	0.0	0.0	0.0b	0.0	0.0
165 Metamitron	0.0b	0.6bc	1.7b	4.7ab	5.2ab	4.5a	3.1ab	2.8a	0.9ab	0.2b	0.1	0.0	0.0b	0.0	0.2
248 Metamitron	0.0b	0.6bc	3.9ab	4.8ab	5.3a	3.7abc	3.6a	1.7ab	0.6ab	0.4ab	0.0	0.1	0.1ab	0.0	0.1
330 Metamitron	0.0b	0.5bc	3.2ab	4.9ab	4.2ab	3.6abc	3.0ab	1.0ab	0.6ab	0.0b	0.0	0.1	0.0b	0.0	0.1
413 Metamitron	0.0b	0.8bc	2.4ab	7.4a	4.6ab	4.7a	2.5abc	1.3ab	0.4ab	0.2b	0.1	0.0	0.0b	0.0	0.2
P	0.0004	0.0002	0.0024	0.0291	0.0003	<0.0001	0.0005	<0.0001	0.0356	0.0025	0.2069	0.7276	0.0046	0.6087	0.0747
Rate of Metamitron	NS	NS	NS	NS	NS	NS	NS	L**	L**	L***, Q*	L*	NS	L***, Q*	NS	NS

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. NS, *, **, ***, indicates not significant, and significant differences at $P = 0.05$, $P = 0.01$, and $P = 0.001$, respectively. L, Q refer to linear and quadratic relationships.

[a]Treatment application dates were as follows: CB, NAA, CB + NAA (30 May 2018), metamitron (2 June 2018).

[b]Fruit diameter equivalents for each count size: 48 = >98 mm, 56 = 95–98 mm, 64 = 92–95 mm, 72 = 89–92 mm, 80 = 84.5–89 mm, 88 = 83–84.5 mm, 100 = 79–83 mm, 113 = 76–79 mm, 125 = 73–76 mm, 138 = 70–73 mm, 150 = 67–70 mm, 163 = 64–67 mm, 175 = 60–64 mm, 198 = 57–60 mm, 216 = <57 mm.

Table 11. Influence of various rates, combinations, and application timings of metamitron, carbaryl (CB), and 6-benzyladenine (6-BA), on fruit set in 2019 of Ambrosia/M.9 apples planted in 2012.

Treatment (mg/L)[a]	Application timings/fruitlet diameter	TCSA fall 2019 (cm^2)	Fruit set (no. fruit per 100 flower clusters)	Percentage of flower clusters with indicated number of fruit				Return bloom 2020 (% of spurs with flowers)
				0	1	2	3	
Untreated control		10.8	67.6a	39.9de	51.8ab	6.7a	1.6a	47.8f
Hand-thinned control	June drop	11.1	74.7a	34.1e	58.4a	6.6a	0.9ab	74.8cd
1500 CB	12–14 mm	12.1	27.3d	70.9a	28.8c	0.3c	0.0b	96.7a
1500 CB + 75 6-BA	12–14 mm	11.9	24.0d	75.0a	24.8c	0.2c	0.0b	93.2ab
175 Metamitron	12–14 mm	11.8	51.0b	51.3bcd	45.9b	2.8abc	0.0b	64.6de
263 Metamitron	12–14 mm	11.1	23.2d	76.0a	23.9c	0.1c	0.0b	90.1ab
351 Metamitron	12–14 mm	10.5	31.7cd	70.5a	27.9c	1.2c	0.4ab	84.2bc
438 Metamitron	12–14 mm	11.4	20.0d	79.1a	20.5c	0.3c	0.0b	91.4ab
263 Metamitron	Petal fall	9.8	58.5ab	41.9cde	52.9ab	5.2ab	0.0b	59.8e
263 Metamitron	8–11 mm	10.9	49.0b	53.7bc	43.9b	2.4bc	0.0b	76.4c
263 Metamitron	16–20 mm	10.5	46.8bc	54.5b	42.2b	2.9abc	0.3ab	74.6cd
P		0.2355	<0.0001	<0.0001	<0.0001	<0.0001	0.0016	<0.0001
Rate of Metamitron		NS	L***	L***	L***, C*	L***, Q*	L***, Q*	L***, Q**, C*

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. TCSA, trunk cross-sectional area. NS, *, ***, indicates not significant, and significant differences at $P = 0.05$ and $P = 0.001$, respectively. L, Q, C refer to linear, quadratic, and cubic relationships.

[a]Treatment application dates were as follows: petal fall (31 May 2019), 8–11 mm (7 June 2019), 12–14 mm (9 June 2019), 16–20 mm (18 June 2019).

Table 12. Influence of various rates and combinations of metamitron, carbaryl (CB), and 6-benzyladenine (6-BA) on harvest parameters in 2019 of Ambrosia/M.9 apples planted in 2012.

Treatment (mg/L)[a]	Application timings/fruitlet diameter	Total fruit yield (kg per tree)	Total number of fruit (no. per tree)	Percent marketable fruit (%)	Adjusted average fruit weight (g)	Crop load (no. fruit per TCSA)[b]
Untreated control		18.4a	138a	22.7d	168abcb	13.2a
Hand-thinned control	June drop	12.4cd	68def	84.8ab	173abc	6.5cde
1500 CB	12–14 mm	13.0bcd	64ef	85.5ab	191ab	5.5de
1500 CB + 75 6-BA	12–14 mm	13.4bcd	67ef	81.6ab	191ab	5.6de
175 Metamitron	12–14 mm	16.5ab	108abc	44.3cd	164c	9.3bcd
263 Metamitron	12–14 mm	12.2cd	61ef	88.6a	193a	5.5de
351 Metamitron	12–14 mm	13.0bcd	78c–f	54.6bc	176abc	8.2b–e
438 Metamitron	12–14 mm	10.6d	51f	92.1a	191ab	4.5e
263 Metamitron	Petal fall	15.6abc	114ab	31.6cd	166bc	12.0ab
263 Metamitron	8–11 mm	14.7abc	98bcd	43.3d	169abc	9.5abc
263 Metamitron	16–20 mm	13.3bcd	84b–e	62.3abc	165c	8.6bcd
P		<0.0001	<0.0001	<0.0001	0.0001	<0.0001
Rate of Metamitron		L***	L***	L***	L**	L***

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. TCSA, trunk cross-sectional area. NS, **, ***, indicates not significant, and significant differences at $P = 0.01$ and $P = 0.001$, respectively. L refers to a linear relationship.

[a]Treatment application dates were as follows: petal fall (31 May 2019), 8–11 mm (7 June 2019), 12–14 mm (9 June 2019), 16–20 mm (18 June 2019).

[b]Crop load determined by dividing the total number of fruit harvested by the TCSA measured in fall.

the untreated control, MET at any of the concentrations did not increase average fruit weight, nor was there any effect of MET application timing on fruit weight; however, based on orthogonal contrasts, there was a linear increase in fruit weight with increasing concentration of MET. Carbaryl and carbaryl combined with 6-BA treatments did not improve fruit weight compared with the untreated control. Despite the minor effects on fruit weight, increasing rates of MET reduced crop load in a highly linear fashion, with all rates of MET resulting in lower crop loads compared with the untreated controls. Petal fall and 8–11 mm fruit diameter applications of 263 mg L^{-1} MET were ineffective in reducing crop loads below that of the untreated control, whereas 12–14 and 16–20 mm applications reduced crop loads similar to the hand-thinned and grower control applications of carbaryl and carbaryl combined with 6-BA. There was minimal effect of MET on leaf phytotoxicity (data not shown).

Thinning treatments had a significant effect on fruit size distribution in all categories ranging from 64 through 175 (Table 13) with the exception of the 100 size category. The untreated trees had the greatest number of small fruit, but only 4% of the fruit (by weight) were smaller than the 163 size category, the minimum weight of fruit sold to the fresh/retail market. Trees that were treated with 1500 mg L^{-1} carbaryl and 1500 mg L^{-1} carbaryl combined 75 mg L^{-1} 6-BA had the greatest amount of large fruit where most fruit was distributed in the 56 to 88 size categories. The untreated control trees produced fruit primarily in the 100–175 size categories, which is a respectable number of marketable fruit given the relatively high crop loads from these trees. Trees treated with MET and the grower control fruitlet thinners had most of their fruit fall in two or three size categories larger.

Experiment 7 — Ambrosia/B.9 (2020)

There was a significant treatment effect on fruit set ($P < 0.001$) (Table 14). The untreated control treatment had the highest fruit set while trees treated with 438 mg L^{-1} MET without Agral 90 had the lowest fruit set. Trees treated with 351 mg L^{-1} or 438 mg L^{-1} MET with Agral 90 also had significantly lower fruit set compared with the untreated and hand-thinned controls. The 175 mg L^{-1} or 263 mg L^{-1} L MET treatments resulted in intermediate values, mildly affected fruit set and were statistically similar to the hand-thinned control and grower standard carbaryl and carbaryl combined with 6-BA treatments. There was a significant negative linear rate response ($P < 0.0001$) in fruit set; that is to say fruit set decreased with increasing rates of MET. The addition of a surfactant had no statistical effect on fruit set.

There was also a significant treatment effect on the number of fruit set per flower cluster (Table 14). Treatments that had the greatest number of flowering clusters where zero fruit set per cluster were the 438 mg L^{-1} MET without Agral 90 followed by the 351 and 438 mg L^{-1} MET treatments with Agral 90. Having a proportion of flowering spurs with no fruit is important because these are the spurs that will flower and fruit the following season. The untreated control treatments had the greatest percentage numerically of flower clusters with one fruit, but this was similar to the hand-thinned controls and grower standard carbaryl and carbaryl combined with 6-BA treatments as shown by the means separation. Applications of 438 mg L^{-1} MET without Agral 90 resulted in the lowest percentage of clusters with one fruit. The 175 mg L^{-1} or 263 mg L^{-1} rates of MET were similar to the hand-thinned control and grower standard treatments. The untreated control trees had the highest percent of clusters with two fruit per cluster while the 438 mg L^{-1} MET without Agral 90 and 351 to 438 mg L^{-1} MET with Agral 90 treatments had the lowest percent of clusters with two fruit. The untreated control also had the highest percentage of flowering clusters with three fruit. Few flowering clusters had four fruit per cluster and consequently there was not treatment effect. The percentage of clusters with zero fruit increased while the percentage of clusters with one to three fruits decreased in a linear fashion with increasing rates of MET ($P < 0.0001$). The addition of a surfactant did not affect the number of fruit per cluster.

The thinning treatments did not significantly affect total yield per tree, total number of fruits per tree, fruit weight, or crop load (Table 15). There was a significant treatment effect on percent marketable fruit, which was highest in trees treated with 438 mg L^{-1} MET without Agral 90. Although the ANOVA generally showed no significant treatment effects at $P = 0.05$, the orthogonal contrasts of the various MET rates indicated that total yield, total number of fruit, and crop load decreased, while percent marketable fruit increased, in a linear fashion with increasing rates of MET. There was a significant linear and quadratic effect of rate of MET without Agral 90 on the percentage of flowering spurs and a significant linear effect of rate of MET with Agral 90 on percentage of flower spurs. That is to say that as the rate of MET increased, the percentage of flowering spurs increased in a curvilinear (quadratic) fashion when Agral 90 was excluded, and decreased in a linear fashion when Agral 90 was included.

Overall, thinning treatments did not have a marked effect on the size distribution of fruit (Table 16), with the exception of the 125, 163, and 175 size categories, which had significant treatment effects according to the ANOVA but no treatment differences shown by the lsmeans separation. Within these size categories, increasing rates of MET generally had an inverse linear effect on the amount of fruit within each category. The addition of a surfactant with MET had no measurable

Table 13. Influence of various rates and combinations of metamitron, carbaryl (CB), and 6-benzyladenine (6-BA) on the weight of fruit per count size in 2019 of Ambrosia/M.9 apples planted in 2012.

Treatment (mg/L)[a]	Application timings/fruitlet diameter	Amount of fruit in each size category (kg per tree)[b]													
		56	64	72	80	88	100	113	125	138	150	163	175	198	216
Untreated control		0.0	0.0b	0.0b	0.0e	0.1d	1.4b	3.9ab	5.4a	3.5a	1.8a	1.4a	0.6a[c]	0.2a	0.00
Hand-thinned control	June drop	0.0	0.1b	0.3b	1.1a–e	1.6a–d	3.5ab	3.5ab	1.5bcd	0.5cd	0.2b	0.1b	0.0a	0.0a	0.00
1500 CB	12–14 mm	0.1	0.5ab	1.7a	2.4ab	2.9a	2.6ab	2.2ab	0.5d	0.2d	0.0b	0.0b	0.0a	0.0a	0.00
1500 CB + 75 6-BA	12–14 mm	0.0	0.9a	1.8a	2.6a	2.2abc	3.1ab	1.8b	0.8cd	0.1d	0.0b	0.0b	0.0a	0.0a	0.00
175 Metamitron	12–14 mm	0.0	0.0b	0.1b	0.4de	0.9bcd	3.0ab	5.0a	4.2a	2.2abc	0.4ab	0.1b	0.1a	0.0a	0.00
263 Metamitron	12–14 mm	0.1	0.4ab	1.1ab	2.0abc	2.5ab	3.0ab	2.0b	0.8cd	0.2d	0.1b	0.0b	0.0a	0.0a	0.00
351 Metamitron	12–14 mm	0.0	0.1b	0.4b	1.0b–e	1.8abc	4.5a	3.5ab	1.2cd	0.3d	0.0b	0.0b	0.0a	0.0a	0.00
438 Metamitron	12–14 mm	0.0	0.2ab	1.2ab	1.6a–d	2.3abc	2.9ab	1.5b	0.6d	0.1d	0.0b	0.0b	0.0a	0.0a	0.00
263 Metamitron	Petal fall	0.0	0.0b	0.1b	0.2de	1.1bcd	2.3ab	3.9ab	4.1ab	2.5ab	1.2a	0.4b	0.4a	0.0a	0.02
263 Metamitron	8–11 mm	0.0	0.1b	0.4b	0.8cde	0.7cd	2.1ab	3.9ab	3.9ab	2.0a–d	0.8ab	0.1b	0.0a	0.0a	0.00
263 Metamitron	16–20 mm	0.0	0.0b	0.2b	0.4de	0.9bcd	3.2ab	3.6ab	3.1abc	1.6bcd	0.2b	0.0b	0.1a	0.0a	0.00
P		0.6041	<0.0001	<0.0001	<0.0001	<0.0001	0.0784	0.0029	<0.0001	<0.0001	<0.0001	<0.0001	0.0236	0.0488	0.2080
Rate of Metamitron		NS	NS	L**	L***	L***	L**	L*	L***	L***	L***, Q*	L***, Q***	L***	L**, Q*	NS

Note: Mean values with the same letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. NS, *, **, ***, indicates not significant, and significant differences at $P = 0.05$, $P = 0.01$, and $P = 0.001$, respectively. L, Q refer to linear and quadratic relationships.

[a]Treatment application dates were as follows: petal fall (31 May 2019), 8–11 mm (7 June 2019), 12–14 mm (9 June 2019), 16–20 mm (18 June 2019).

[b]Fruit diameter equivalents for each count size: 56 = >95 mm, 64 = 92–95 mm, 72 = 89–92 mm, 88 = 82–89 mm, 100 = 79–82 mm, 113 = 76–79 mm, 125 = 73–76 mm, 138 = 70–73 mm, 150 = 67–70 mm, 163 = 64–67 mm, 175 = <64 mm, 198 = 57–60 mm, 216 = <57 mm.

[c]The means separation does not reflect all significant comparisons. The following additional treatments are significantly different: (untreated control, 263 metamitron/8–11 mm), (untreated control, 1500 CB + 75 6-BA), (untreated control, 1500 CB), (untreated control, 438 Metamitron/12–14 mm).

Table 14. Influence of carbaryl (CB), 6-benzyladenine (6-BA), and various rates of metamitron with or without Agral 90 surfactant on fruit set in 2020 of Ambrosia/B.9 apple trees.

Treatment (mg/L)[a]	Application timings/fruitlet diameter	Fruit set (no. fruit/100 flower clusters)	Percentage of flowering spurs with indicated number of fruit				
			0	1	2	3	4
Untreated control		88.5ab	36.4e	44.2a	14.3a	4.7a	0.4
Hand-thinned control	June Drop	76.3ab	43.6de	42.2ab	12.0ab	2.2ab	0.2
1500 CB	12–14 mm	61.0a–d	50.2cde	38.9ab	10.5abc	0.4b	0.0
1500 CB + 75 6-BA	12–14 mm	65.1a–d	50.0cde	39.3ab	9.6abc	1.4b	0.0
175 Metamitron	6–7 mm, 12–14 mm	65.7abc	51.5bcde	38.4ab	8.0abc	2.9ab	0.0
263 Metamitron	6–7 mm, 12–14 mm	51.3bcd	58.5a–d	33.2abc	7.0abc	1.1b	0.2
351 Metamitron	6–7 mm, 12–14 mm	49.2bcd	60.3a–d	33.3abc	6.6abc	0.0b	0.0
438 Metamitron	6–7 mm, 12–14 mm	29.9d	74.6a	21.1c	4.0bc	0.2b	0.0
175 Metamitron + Agral 90	6–7 mm, 12–14 mm	52.6bcd	56.1a–e	35.6abc	7.9abc	0.4b	0.0
263 Metamitron + Agral 90	6–7 mm, 12–14 mm	50.9bcd	59.1a–d	34.7abc	5.8abc	0.6b	0.0
351 Metamitron + Agral 90	6–7 mm, 12–14 mm	36.1cd	70.3ab	26.8bc	2.8bc	0.3b	0.0
438 Metamitron + Agral 90	6–7 mm, 12–14 mm	36.4cd	68.5abc	29.7abc	2.1c	0.0b	0.0
P		<0.0001	<0.0001	<0.0001	0.0002	<0.0001	0.5415
Contrasts							
Rate of Metamitron (without Agral 90)		L***	L***	L***	L***	L***	L*
Rate of Metamitron (with Agral 90)		L***	L***	L***	L***	L***, Q*	L*
Surfactant vs. no surfactant		NS	NS	NS	NS	NS	NS

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. NS, *, **, ***, indicates not significant, and significant differences at $P = 0.05$, $P = 0.01$, and $P = 0.001$, respectively. L, Q refer to linear and quadratic relationships.

[a]Metamitron sprays were applied on 1 June (petal fall, 6–7 mm), 9 June (12–14 mm). Carbaryl and 6-BA were applied on 9 June only.

effect on fruit size distribution for any of the 15 size categories.

Severity of leaf phytotoxicity, as measured by the Brevis rating scale, on the Ambrosia trees was low (<4 rating) but was significantly affected by the MET treatments (Table 17). Phytotoxicity was most severe in trees treated with 438 mg L^{-1} MET without Agral 90. The 263 and 438 mg L^{-1} rates of MET with Agral 90 also resulted in significantly greater phytotoxicity compared with the untreated control, as shown by the lsmean separation. The percent of leaves affected was very low (<2%) but was significantly higher following applications of 438 mg L^{-1} MET without Agral 90 and 263 and 438 mg L^{-1} rates of MET with Agral 90 compared with the untreated control. Albeit low, the orthogonal contrasts indicated that the severity and incidence of phytotoxicity increased in a linear fashion with increasing rates of MET. The addition of Agral 90 surfactant did not affect the severity of phytotoxicity but had a mild effect on the incidence of phytotoxicity, which increased on average from 1.1% to 1.4% ($P = 0.05$). Overall, this would have an inconsequential effect on the orchard commercially.

Discussion

This study investigated various application rates and timings of MET as post-bloom thinners for Gala, Ambrosia, and Honeycrisp apples over four growing seasons. As with many thinning studies of this nature, response to MET varied by cultivar and season. In six of the seven experiments MET reduced fruit set, but in only four (57%) of the studies, which included one study on each of Honeycrisp and Gala and two on Ambrosia, did MET significantly reduce the number of fruit per tree or the crop load compared with the untreated control trees. Fruit per tree and crop load metrics were better indicators for documenting the thinning response than using select limbs to determine fruit set. It is apparent in this study that despite taking care to select suitable branches from which to measure fruit set, selecting multiple branches is not a valid method to indicate the overall tree response to thinners because they represent only a small portion of the tree canopy. Variation in fruit set in the tree canopy is likely associated with spatial differences in light interception, shading, spray penetration, and flowering within the tree canopy. Consequently, measuring the total number and weight of fruit per tree will provide a more precise measurement of thinning efficacy.

Effect of fruit development — fruitlet diameter

In three of the four experiments where we investigated different times of application, applications between 8 and 20 mm fruitlet diameter were most effective, while petal fall applications, which represents fruitlets approximately 5 to 6 mm diameter, were least

Table 15. Influence of carbaryl (CB), 6-benzyladenine (6-BA), and various rates of metamitron with or without Agral 90 surfactant on harvest parameters of Ambrosia/B.9 apple in 2020.

Treatment (mg/L)[a]	Application timings/fruitlet diameter	Total fruit yield (kg/tree)	Total number of fruit (no/tree)	Percent marketable fruit (%)	Adjusted average fruit weight (g)	Crop load fall 2020 (no/TCSA)[b]	Return bloom 2021 (% of spurs with flowers)
Untreated Control		39.9	225	75.9ab	208	6.2	44c
Hand-thinned control	June Drop	30.5	157	93.8ab	190	4.3	46c
1500 CB	12–14 mm	31.7	183	76.7ab	170	4.1	69ab
1500 CB + 75 6-BA	12–14 mm	35.4	210	75.3ab	197	5.5	59bc
175 Metamitron	6–7 mm, 12–14 mm	32.6	208	73.9ab	182	5.1	51bc
263 Metamitron	6–7 mm, 12–14 mm	36.8	183	88.4ab	202	4.3	52bc
351 Metamitron	6–7 mm, 12–14 mm	29.1	165	86.1ab	180	4.4	63abc
438 Metamitron	6–7 mm, 12–14 mm	25.8	122	95.2a	199	3.7	84a
175 Metamitron + Agral 90	6–7 mm, 12–14 mm	35.0	213	65.1b	188	5.7	55bc
263 Metamitron + Agral 90	6–7 mm, 12–14 mm	32.5	165	87.2ab	203	4.3	57bc
351 Metamitron + Agral 90	6–7 mm, 12–14 mm	30.1	138	91.1ab	209	3.6	73ab
438 Metamitron + Agral 90	6–7 mm, 12–14 mm	26.5	128	94.0ab	201	4.0	72ab
P		0.4047	0.0702	0.0111	0.2043	0.3940	<0.001
Contrasts							
Rate of Metamitron (without Agral 90)		L*	L**	L*	NS	L*	L***, Q**
Rate of Metamitron (with Agral 90)		L**	L***	L**	NS	L**	L***
Surfactant vs. no surfactant		NS	NS	NS	NS	NS	NS

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. NS, *, **, ***, indicates not significant, and significant differences at $P = 0.05$, $P = 0.01$, and $P = 0.001$, respectively. L, Q refer to linear and quadratic relationships.

[a]Metamitron sprays were applied on 1 June (petal fall, 6–7 mm), 9 June (12–14 mm). Carbaryl and 6-BA were applied on 9 June only.

[b]Crop load determined by dividing the total number of fruit harvested by the TCSA measured in fall.

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Table 16. Influence of carbaryl (CB), 6-benzyladenine (6-BA), and various rates of metamitron with or without Agral 90 surfactant on the weight of fruit per count size of Ambrosia/B.9 apples in 2020.

Treatment[a]	Application timings/fruitlet diameter	kg fruit per tree in each size category[b]														
		48	56	64	72	80	88	100	113	125	138	150	163	175	198	216
Untreated Control		0.00	0.00	0.95	1.42	4.57	5.03	8.26	7.93	5.16ac	3.28	1.70	0.81a	0.39a	0.35	0.00
Hand-thinned control	June Drop	0.00	0.00	0.35	2.04	4.53	6.50	6.17	6.46	3.16a	0.92	0.25	0.00a	0.08a	0.00	0.00
1500 CB	12–14 mm	0.00	0.00	2.13	3.09	3.81	2.84	4.69	4.71	3.89a	3.51	1.32	1.01a	0.42a	0.32	0.00
1500 CB + 75 6-BA	12–14 mm	0.00	0.13	1.00	1.67	1.68	2.10	5.46	8.06	6.28a	4.29	2.81	1.17a	0.51a	0.22	0.00
175 Metamitron	6–7 mm, 12–14 mm	0.00	0.00	0.00	1.23	2.87	2.59	5.71	3.46	3.76a	3.93	3.26	1.83a	1.66a	1.53	0.78
263 Metamitron	6–7 mm, 12–14 mm	0.30	0.89	1.66	3.58	3.77	5.17	9.69	8.05	1.49a	1.93	0.16	0.07a	0.00a	0.06	0.00
351 Metamitron	6–7 mm, 12–14 mm	0.00	0.30	1.67	1.54	3.54	2.10	5.81	3.87	4.30a	3.35	1.25	0.68a	0.11a	0.46	0.09
438 Metamitron	6–7 mm, 12–14 mm	0.00	0.65	1.57	3.04	3.88	4.64	5.81	4.27	1.14a	0.61	0.12	0.06a	0.06a	0.00	0.00
175 Metamitron + Agral 90	6–7 mm, 12–14 mm	0.00	0.40	0.00	0.00	0.80	3.33	5.20	7.34	6.95a	4.61	2.93	1.72a	1.05a	0.30	0.35
263 Metamitron + Agral 90	6–7 mm, 12–14 mm	0.00	0.90	1.40	3.44	3.73	3.37	7.74	7.56	2.24a	1.29	0.43	0.31a	0.05a	0.00	0.00
351 Metamitron + Agral 90	6–7 mm, 12–14 mm	0.15	0.91	3.30	5.34	4.99	3.54	5.53	3.29	1.29a	1.55	0.07	0.10a	0.00a	0.00	0.00
438 Metamitron + Agral 90	6–7 mm, 12–14 mm	0.00	0.42	1.88	3.16	3.24	6.02	5.08	3.96	1.23a	0.70	0.53	0.05a	0.19a	0.00	0.00
P		0.4671	0.7992	0.6461	0.3340	0.8539	0.4756	0.9160	0.4690	0.0175	0.1240	0.1241	0.0231	0.0485	0.5934	0.4516
Contrasts																
Rate of Metamitron (without Agral 90)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	C*	NS	NS
Rate of Metamitron (with Agral 90)		NS	NS	NS	NS	NS	NS	NS	NS	L**	L*	NS	L*, C*	C**	NS	NS
Surfactant vs. no surfactant		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at $P = 0.05$. NS, *, **, ***, indicates not significant, and significant differences at $P = 0.05$, P = 0.01, and P = 0.001, respectively. L, Q refer to linear and quadratic relationships.

[a]Metamitron sprays were applied on 1 June (petal fall, 6–7 mm), 9 June (12–14 mm). Carbaryl and 6-BA were applied on 9 June only

[b]Fruit diameter equivalents for each count size: 56 = >95 mm, 64 = 92–95 mm, 72 = 89–92 mm, 88 = 82–89 mm, 100 = 79–82 mm, 113 = 76–79 mm, 125 = 73–76 mm, 138 = 70–73 mm, 150 = 67–70 mm, 163 = 64–67 mm, 175 = <64 mm, 198 = 57–60 mm, 216 = <57 mm.

Table 17. Severity of phytotoxicity following applications of carbaryl (CB), 6-benzyladenine (6-BA), and various rates of metamitron with or without Agral 90 surfactant in 2020 on Ambrosia/B.9 apple trees.

Treatment[a]	Application timings/fruitlet diameter	Rating (Brevis Scale 1 [unaffected]; -9 [entire leaf necrosis])	% of leaves affected
Untreated control		1.3c	0.3c
Hand-thinned control	June Drop	1.5bc	0.5bc
1500 CB	12–14 mm	1.5bc	0.5bc
1500 CB + 75 6-BA	12–14 mm	2.0abc	0.8abc
175 Metamitron	6–7 mm, 12–14 mm	2.0abc	1.0abc
263 Metamitron	6–7 mm, 12–14 mm	2.8abc	1.0abc
351 Metamitron	6–7 mm, 12–14 mm	2.8abc	1.0abc
438 Metamitron	6–7 mm, 12–14 mm	3.5a	1.5ab
175 Metamitron + Agral 90	6–7 mm, 12–14 mm	2.0abc	1.0abc
263 Metamitron + Agral 90	6–7 mm, 12–14 mm	3.0ab	1.8a
351 Metamitron + Agral 90	6–7 mm, 12–14 mm	2.5abc	1.3abc
438 Metamitron + Agral 90	6–7 mm, 12–14 mm	3.0ab	1.7a
P		0.0001	0.0002
Contrasts			
Rate of Metamitron (without Agral 90)		L***	L***
Rate of Metamitron (with Agral 90)		L***	L***
Surfactant vs. no surfactant		NS	*

Note: Mean values with the same lowercase letter within a given column are not significantly different according to Tukey's highly significant difference test at *P* = 0.05. NS, *, **, ***, indicates not significant, and significant differences at P = 0.05, *P* = 0.01, and *P* = 0.001, respectively. L, Q refer to linear and quadratic relationships.

[a]Metamitron sprays were applied on 1 June (petal fall, 6–7 mm), 9 June (12–14 mm). Carbaryl and 6-BA were applied on 9 June only.

[b]Metamitron sprays were applied on 1 June (petal fall, 6–7 mm), 9 June (12–14 mm). Carbaryl and 6-BA were applied on 9 June only.

effective. Brunner (2014) found the highest abscission rates when MET was applied to Fuji and Golden Delicious around 12 mm fruitlet diameter; for Fuji specifically, MET was less effective when applied at petal fall and at 16 mm fruitlet fruit diameter, whereas for Golden Delicious good thinning with MET occurred at petal fall and at 16 mm fruit fruitlet diameter. Gabardo et al. (2017) found MET was effective when applied at petal fall to Baronesa and Fuji apple trees. Greene (2014) found MET application at 16 mm and 20 mm were effective in thinning CandyCrisp apple trees. Lafer (2010) found strong overthinning when 350 mg L^{-1} MET was applied to Elstar at 6–8 mm one year but not the next. Furthermore, when MET was applied at 12–14 mm fruitlet diameter, it only thinned in one of three years. The authors found optimal fruit size was obtained by the repeated application of MET at 6–8 mm and 12–14 mm fruit diameter. In a 3-yr study, McArtney and Obermiller (2014) observed that 350 mg L^{-1} MET applied at petal fall to Morgan Spur Delicious did not reduce fruit set over 3 yr but found applications at 10 mm fruitlet diameter exhibited strong thinning activity. The authors concluded that yearly variation in thinning efficacy of chemical thinning sprays applied at 10 mm fruit diameter could not be explained by a thinning index based on the average daily carbon balance for 4 d beginning on the day of thinner application. In another study on Gale Gala, McArtney and Obermiller (2012) observed that 350 mg L^{-1} MET reduced fruit set when applied at 18 mm fruitlet diameter. Radivojevic et al. (2020) observed that application of 250 mg L^{-1} MET to Golden Delicious at 16–18 mm fruit diameter was very effective in reducing fruit set. In a Chilean study, Reginato et al (2017) found that 450 g MET ha^{-1}, applied between 4 mm (petal fall) and 28 mm fruit diameter, effectively thinned Brookfield Gala trees, even when the trees were predicted to have a strong carbohydrate balance, especially during the later application timings. Collectively, these studies indicate a wide variation in thinning response when MET is applied to fruitlets of different diameters during fruit set. This is because timing effects can be confounded by environmental factors, fruit, and tree physiological factors, and genetic differences among rootstocks and scions. There is unlikely one specific fruitlet size at which the thinning response is consistently effective.

Table 18. Year, cultivar, king fruitlet diameter, date of application of metamitron treatments, BreviSmart predicted thinning efficacy, average nighttime temperature, percent of time temperature was above 14°C, and solar radiation accumulated from the time of application to 4 d after application.

					BreviSmart predicted efficacy of using Brevis (Metamitron) days following application[b]				From date of application to 4 d after		
Year	Cultivar	King fruitlet diameter (mm)	Date of application	Reduction in fruit per tree compared with untreated trees (%)[a]	1	2	3	4	Average night time temperature (°C)[c]	The percentage of time the night temperature was above 14 °C from 2100 to 0700 (%)	Sum total solar radiation (MJ m^{-2})
2017	Gala	8.8	30-May	−43	low	average	average	average	13.2	27%	99
		17.3	07-Jun	+43	average	average	average	average	16.9	82%	95
		22.3	12-Jun	+46	NA	NA	NA	NA	19.2	100%	86
2017	Ambrosia	7.6	30-May	+14	low	average	average	average	13.2	27%	99
		14.6	07-Jun	+40	average	high	high	high	16.9	82%	95
		18.6	12-Jun	+12	high	high	NA	NA	19.2	100%	86
2017	Honeycrisp	10.6	30-May	−112	low	average	average	average	13.2	27%	99
		22.5	12-Jun	+38	NA	NA	NA	NA	19.2	100%	86
2018	Gala	11.5	02-Jun	+28	high	high	high	high	15.8	73%	65
2018	Honeycrisp	12.0	02-Jun	+36	high	high	high	high	15.8	73%	65
2019	Ambrosia	NA	31-May	+17	low	low	average	average	12.7	50%	77
		9.2	07-Jun	+29	average	average	average	average	16.1	75%	80
		12.4	09-Jun	+43	average	average	average	average	15.3	57%	78
		17.7	18-Jun	+39	average	average	average	average	16.3	84%	75
2020	Ambrosia	5.0	01-Jun	+26	NA	average	average	average	18.8	91%	87
		12.5	9-Jun	+33	average	high	high	high	15.6	48%	69

Note: University of Guelph, Simcoe Research Station, Simcoe, ON. NA, not applicable.

[a]actual reduction in crop load (number of fruit per tree) from trees treated with a standard rate of 330–350 mg L^{-1} metamitron compared to the untreated control. Data determined from experiments 1 to experiment 7. For the 2019 Ambrosia experiment, data from trees treated with 263 mg L^{-1} metamitron was used for calculating the reduction in crop load.

[b]determined by the BreviSmart proprietary software (https://brevismart.adama.com).

[c]nighttime temperatures calculated from 2100–0700.

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Rate effect of MET

All seven experiments evaluated two or more MET rates at single or multiple application timings. Thinning increased with higher rates in four of the seven studies, all of which occurred in 2018, 2019, and 2020 but not in 2017. In all instances, there was a linear reduction in crop load, number of fruit per tree, and fruit set with increasing rates of MET. In Honeycrisp (2018), rates above 248 mg L^{-1} MET were required to mount an effective thinning response. For Ambrosia (2019) 175 mg L^{-1} MET was effective in reducing fruit set and crop load, but rates at or above 263 mg L^{-1} MET were required to reduce the total number of fruit per tree. For Gala (2018), 248 mg L^{-1} MET reduced fruit set and number of fruit per tree, but 413 mg L^{-1} MET was required to reduce crop loads below the untreated control. The higher concentration of MET needed to thin Gala may be an indication of its greater difficultly to thin compared with Ambrosia and Honeycrisp (Ontario Ministry of Agriculture, Food and Rural Affairs 2021). Brunner (2014) found that MET increased fruit abscission of Golden Delicious in a concentration dependent manner and thinning occurred with MET (Brevis, 15% MET) when applied between 1–2.5 kg ha^{-1}. Lower rates of Brevis (0.825 kg ha^{-1}) did not sufficiently reduce fruit set, whereas over-thinning occurred with concentrations exceeding 2.5 kg ha^{-1}. Gabardo et al. (2017) found when MET was applied between 350 to 1750 mg L^{-1}, there were linear reductions in crop load, number of fruit per tree, and yield and a linear increase in fruit size. At high rates, the authors observed over-thinning and pre-harvest fruit drop at harvest with no improvement in return flowering the following year. As with the current study, Brunner (2014) found differences in thinning responses with the same amounts of MET applied in different years. As none of the higher rates of MET caused extensive overthinning in the present study, using increasing concentration of MET sprays, in addition to using multiple sprays in sequence, and combining MET with 6-BA or carbaryl, are all effective strategies of increase fruitlet abscission and improving thinning efficacy.

Effect on MET on fruit weight

In only one of the seven studies did MET increase adjusted fruit weight above that of the untreated control trees, even though MET increased fruit abscission and decreased crop load. In the 2018 Gala experiment, when 413 and 480 mg L^{-1} MET was applied when king fruitlets were 11.5 mm, fruit weight was increased by 7% and 8%, respectively, but total yield per tree was reduced by 47% and 45%, respectively. In the same experiment, the hand-thinned and grower control spray of 1500 mg L^{-1} carbaryl combined with 75 mg L^{-1} 6-BA had higher fruit weights in comparison, but even lower crop loads. In the 2019 Ambrosia experiment, MET was very effective in reducing crop load, but crop load adjusted fruit weight was similar to the untreated control trees. These data collectively indicate that MET induced increases in fruit weight can be explained by MET's ability to reduce crop load rather than a direct effect on fruit weight.

Effect of surfactants

Surfactants are often added to plant growth regulator sprays in increase plant uptake vis-à-vis the leaf or fruit (Stover and Greene, 2005). Greene (2014) found that when Regulaid, a non-ionic surfactant, was included in all treatments on Candy Crisp apple, extensive thinning and phytotoxicity was observed in one year. Yet when the same surfactant was included with a spray of 150 mg L^{-1} MET the following year, there was neither increased thinning activity nor an enhancement of phytotoxicity. When McArtney and Obermiller (2012) included the organosilicone surfactant, Silwett L-77 with 350 mg L^{-1} MET sprays to Cameo apple, it resulted in a greater reduction in Fv/Fm and fruit set. Effects on thinning were not reported. Based on limited research, further studies are required to fully evaluate the effects of surfactants when combined with MET for thinning apples.

Effect of MET on leaf phytotoxicity

In the present experiments inconsequential leaf phytotoxicity was observed when applied to Ambrosia, Gala, and Honeycrisp over the 4-yr study period. There are few reports in the scientific literature that report on leaf phytotoxicity of MET for thinning apples. Lafer (2010) reported that 350 mg L^{-1} MET applied to Elstar apples over two seasons did not cause any leaf phytotoxicity, pygmy fruit formation, or fruit russeting. Antidotal reports from the Pacific Northwest have raised concern of higher rates of MET or of surfactants incorporated with MET sprays (S. Eskelsen, Adama US, personal communication). These are likely associated with environmental conditions at or immediately following applications, pre-treatment leaf cuticle development (Stover and Greene 2005), or concentrations effects of MET.

Effect of night temperature

Botton et al. (2011) suggests that fruitlet abscission is triggered by a critical level of carbohydrates within the fruit. If this is indeed the case, then the performance of MET as a fruit thinner will be dependent on several factors, including carbohydrate balance in the tree at the time of application. Solar radiation and temperature are the primary drivers of carbohydrate source, while sinks include structural wood, roots, leaves, fruit, and respiration. Competition between developing fruitlets in the corymb play an important role in abscission (Greene et al 2013), and when devoid of sufficient carbohydrate, likely initiate the abscission process. Temperature effects on dark respiration would therefore be a primary factor in determining the magnitude of this sink within developing fruitlets (Jackson 2003; Lakso et al. 2006). Indeed, Gonzalez et al. (2019, 2020) determined that the degree of fruit abscission with MET is highly dependent on night temperature, rate of application and cultivar, and suggests these are all explanations for the high variability that can exist in thinning efficacy among different trials. Gonzalez et al (2020) observed that when average night temperature exceeds 14 °C the day of and 4 d after a single application of MET, thinning efficacy is approximately 10%–25% higher in comparison with average night temperatures below 14 °C. This is corroborated by Byers (2002), who found low light conditions and periods of high night temperatures favour the abscission of fruitlets. Penzel and Kröling (2020) observed that a single application of MET at a relatively low rate (165 g ha^{-1}) effectively thinned RoHo 3615 apple trees under conditions of high night temperatures and low solar radiation. MET also appears more efficacious in warmer climates such as Israel (Stern 2014, 2015).

For comparison with the Gonzalez et al. (2020) study, key environmental conditions were summarized for the present study. Average nighttime air temperature between 2100 and 0700, cumulative solar radiation, and the percentage of time of hourly air temperatures above 14 °C were calculated for 0 to 4 d following each application of MET for each experiment using on-site research weather data (Table 18). In addition, the predicted thinning efficacy of MET based on proprietary web-based thinning software specifically designed for use with Brevis (15% MET; BreviSmart 2021; Adama Agricultural Solutions Ltd.), was included 1–4 d following application of MET (BreviSmart 2021). Briefly, the model predicts low, average, or high thinning efficacy based on cultivar, fruitlet size, solar radiation, and night temperatures based on studies done in Spain and MET trials from other European countries (Ton Besseling, Adama Agricultural Solutions Ltd., personal communication). The reduction in fruit per tree on trees treated with 330 to 350 mg L^{-1} MET compared with the untreated trees (expressed as %) was calculated to provide an indication of thinning efficacy for each experiment. Overall, average nighttime temperature and accumulated solar radiation 4 d post treatment do not appear to be a good predictor of the thinning response to MET in this 4-yr study. When average nighttime air temperatures fell below 14 °C (30 May 2017, 31 May 2019), thinning on Gala and Honeycrisp was poor, but moderate on Ambrosia. The BreviSmart model predicted lower efficacy when applied on these days. On 31 May 2019, when nighttime temperature was on average 12.7 °C, predicted thinning efficacy was low, yet there was a 17% reduction in fruit on Ambrosia trees. When higher nighttime temperatures were experienced on 12 June 2017, MET was more effective in thinning Gala (22 mm fruitlet diameter) than Ambrosia (18.6 mm fruitlet diameter). Clearly, cultivars differ in their response to MET under similar environment conditions which cannot be explained by nighttime temperature and solar radiation levels and the BrevisSmart model. This study demonstrates stage of fruit development (fruitlet diameter) and concentration influence the thinning response to MET, but other factors including intra-fruit competition, tree carbohydrate balance, vis-à-vis differences in photoassimilate sources, and sinks, also influence the thinning response. Collectively, the interaction of these, and likely other unknown factors at this time, make it difficult to predict the overall thinning response to MET.

Future Research

Future research should investigate combining MET with 6-BA, NAA, or carbaryl (tanked mixed or as separate spays in a thinning program) to enhance the thinning effect of MET. This may also reduce the risk of leaf phytotoxicity in some regions when using higher rates of MET alone or two applications. Also, MET should be investigated for its potential to enhance late thinning of apples beyond the traditional 15 mm fruitlet diameter when MET is combined or used in conjunction with other available thinning agents such as carbaryl, NAA, or 1-aminocyclopropane carboxylic acid in apples. Greater understanding of carbon balance in apple trees and the interplay of solar radiation, nighttime temperature, and fruitlet size on thinning response are needed to improve the predictive thinning response to MET.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be interpreted as a potential conflict of interest.

Authorship contribution statement

J. Cline conceptualized and planned the experiments. A. Beneff and C. Bakker organized and conducted the orchard work. J. Cline imposed the chemical thinning treatments. A. Beneff assisted with data collection. A Beneff and C. Bakker processed the data. C. Bakker conducted the data analyses and assisted with writing the materials and methods. J. Cline reviewed the literature and wrote the original manuscript and compiled revision.

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