Effectiveness of Odor-Baited Trap Trees for Plum Curculio (Coleoptera: Curculionidae) Monitoring in Commercial Apple Orchards in the Northeast

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ABSTRACT The plum curculio, *Conotrachelus nenuphar* (Herbst), is a key pest of pome and stone fruit in eastern and central North America. For effective management of this insect pest in commercial apple (*Malus* spp.) orchards in the northeastern United States and Canada, one of the greatest challenges has been to determine the need for and timing of insecticide applications that will protect apple fruit from injury by adults. In a 2004–2005 study, we assessed the efficacy and economic viability of a reduced-risk integrated pest management strategy involving an odor-baited trap tree approach to determine need for and timing of insecticide use against plum curculio based on appearance of fresh egg-laying scars. Evaluations took place in commercial apple orchards in seven northeastern U.S. states. More specifically, we compared the trap-tree approach with three calendar-driven whole-block sprays and with heat-unit accumulation models that predict how long insecticide should be applied to orchard trees to prevent injury by plum curculio late in the season. Trap tree plots received a whole-plot insecticide spray by the time of petal fall, and succeeding sprays (if needed) were applied to peripheral-row trees only, depending on a threshold of one fresh plum curculio egg-laying scar out of 25 fruit sampled from a single trap tree. In both years, level of plum curculio injury to fruit sampled from perimeter-row, the most interior-row trees and whole-plot injury in trap tree plots did not differ significantly from that recorded in plots subject to conventional management or in plots managed using the heat-unit accumulation approach. The amount of insecticide used in trap tree plots was reduced at least by 43% compared with plots managed with the conventional approach. Advantages and potential pitfalls of the bio-based trap tree approach to plum curculio monitoring in apple orchards are discussed.

KEY WORDS monitoring, integrated pest management, reduced-risk, aggregation, semiochemicals

Apples (*Malus* spp.), the most valuable and widely grown tree crop in northeastern United States, are susceptible to numerous arthropod pests and diseases, but only a few species account for most of the pesticide applied in orchards (Cooley and Coli 2009). Among all insect pests associated with apple the plum curculio, *Conotrachelus nenuphar* (Herbst) (Coleoptera: Curculionidae), stands as one of the most devastating in eastern North America (Racette et al. 1992). Plum curculio is native to North America where before the introduction of cultivated fruit trees, it presumably reproduced mainly on wild plum species such as *Prunus americana* Marsh., *Prunus nigra* Aiton, and *Prunus mexicana* S.Watson (Whitcomb 1929, Leskey et al. 2009). Currently, the plum curculio attacks nearly all stone and pome fruit (Rosaceae) with plum, apple, cherry, pear, peach, nectarine, and apricot as its preferred hosts (Racette et al. 1992). High-bush blueberry, *Vaccinium corymbosum* L., and deerberry, *Vaccinium stamineum* L. (both Ericaceae), also have been reported as being attacked by plum curculio (Polavarapu et al. 2004, Jenkins et al. 2006). Damage to fruit by plum curculio may be initiated as soon as fruit reach a diameter of 6–7 mm (shortly after petal fall) and results from feeding and oviposition scars produced by adult females and from burrows by larvae (Vincent et al. 1999).

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A critical aspect of managing plum curculio populations adequately is determining the need for and timing of insecticide applications that will protect fruit from injury (Racette et al. 1992, Vincent et al. 1999, Prokopy et al. 2004). For many decades, apple growers in the northeastern United States faced the problem of accurately monitoring plum curculio; consequently, populations were commonly managed through an average of three calendar-based sprays of insecticide in May and June (Prokopy et al. 1996, Reissig et al. 1998). Recent studies have focused on the development of monitoring systems to provide an early warning of plum curculio population presence, abundance, and activity level in an attempt to accurately determine the need for and timing of insecticide treatments. Approaches that have received considerable attention for monitoring plum curculio include 1) cumulative heat-unit models designed in New York to predict the termination of oviposition (Reissig et al. 1998), 2) odor-baited traps deployed near woods to monitor timing and extent of plum curculio immigration (Piñero et al. 2001, Piñero and Prokopy 2006), and 3) odor-baited trap trees to monitor the seasonal course of egg-laying activity (Prokopy et al. 2003a, 2004). Approaches 2 and 3 are based on a semiochemical approach that uses a synergistic lure consisting of the plum curculio aggregation pheromone grandisoic acid, and the synthetic host-plant volatile benzaldehyde (Piñero and Prokopy 2003). Even though traps baited with benzaldehyde and grandisoic acid have proven effective in monitoring the timing and magnitude of plum curculio immigration into orchard blocks and also could aid in predicting initiation of adult immigration using thermal constants (Piñero and Prokopy 2006), odor-baited traps have repeatedly failed to reliably monitor the course of plum curculio injury to fruit in commercial apple orchards, both in the northeastern United States (Prokopy et al. 2003a) and in the Mid-Atlantic (Leskey and Wright 2004). This renders the trap tree and the heat-unit accumulation approaches as the best candidates developed thus far for monitoring egg-laying activity by plum curculio in commercial apple orchards.

The heat-unit accumulation model developed by Reissig et al. (1998) relates cumulative fruit injury to cumulative heat units (degree-days base 10°C [DD_{10}]) after petal fall. It indicates that the last spray against plum curculio should have sufficient residual activity for effective control until 171 DD_{10} have accumulated since petal fall. This model has proven useful under some (but not all) conditions for predicting how long insecticide protection should be maintained on orchard trees to prevent late-season plum curculio injury. One shortcoming of using this model involves uncertainty of the extent to which insecticide residue truly remains effective, because it assumes sufficient insecticide protection to fruit for ≈14 d after insecticide sprays.

The trap-tree approach was developed by Prokopy et al. (2003a) and operates by aggregating adult plum curculios and subsequently egg-laying injury in the canopies of select baited perimeter-row apple trees. The need for and timing of subsequent insecticide sprays made against plum curculio in trap tree-monitored blocks can be based on a treatment threshold of one fresh egg-laying scar out of 50 fruit sampled per trap tree (Prokopy et al. 2004). Using this threshold, not only were economically acceptable low levels (0.77% on average) of orchard-wide injury to fruit by plum curculio recorded at harvest in Massachusetts commercial orchard blocks but also important reductions in insecticide use were achieved when compared with the conventional approach in Massachusetts orchards involving three whole-block sprays (Prokopy et al. 2004). Because trap trees also are sprayed with insecticide, they serve as excellent indicators of the extent to which insecticide residue remains effective against plum curculio, thereby complementing the use of cumulative heat unit models developed by Reissig et al. (1998).

Here, we report results of a study aimed at validating the efficacy and economic viability of the trap-tree monitoring approach over a broader geographic area. We compared the trap-tree approach with calendar-driven sprays and use of heat-unit-accumulation models for determining the need for and timing of insecticide treatments against plum curculio in blocks of apple trees throughout New England and New York in 2004 and 2005.

Materials and Methods

Study Sites. This study was conducted in 2004 and 2005 in apple orchard blocks located in seven northeastern U.S. states: Massachusetts (14 blocks in 2004 and 11 blocks in 2005); New Hampshire, Vermont, New York, and Rhode Island (two blocks each); and Connecticut and Maine (one block each), for a total of 24 and 21 experimental blocks in 2004 and 2005, respectively. Each orchard block was ≈1.2 ha, with at least 210 m of perimeter-row. The perimeter row of each block bordered open field, hedgerow, or woods. Each block was divided into three similar-sized plots with at least 70 m of perimeter-row. All three plots within a block had trees of similar size and similar border habitat adjacent to the perimeter row. Of the 24 orchard blocks evaluated in 2004, five had large trees (M.7 rootstock), 12 had medium-sized trees (M.26 rootstock) and seven had small trees (M.9 rootstock). In 2005, the number of blocks with large, medium, and small trees was three, 11, and seven, respectively. The majority of blocks with large trees had nine rows of trees whereas the number of rows in blocks with medium- and small-sized trees ranged between 11 and 17, depending on the inter-row distance.

Cultivar type may have varied among rows within a plot, but the relative cultivar composition was the same for all three plots within a block. The cultivars most commonly present in the test blocks were 'McIntosh' (57% in 2004, 53% in 2005), followed by 'Empire' (10% in 2004, 11% in 2005) and 'Cortland' (7% in 2004, 12% in 2005).

Insecticides used against plum curculio included azinphosmethyl (Guthion), carbaryl (Sevin XLR+), phosmet (Imidan), indoxacarb (Avaunt), thiacloprid (Calypso), and lambda-cyhalothrin (Warrior). Even though the materials used may have had a slightly different toxicity profile and residual activity against plum curculio, we accommodated our test design to existing grower practices. Decisions regarding insecticides used and application rates were made by individual growers and in general were as recommended by the New England Apple Pest Management Guide (Loss 2003) or the Cornell guidelines (Agnello et al. 2004, 2005). In those blocks that received thinning sprays before the initiation of the study or fungicide during the plum curculio season, all plots within a block received the same spray. Within a block, each of the three plots received a particular management approach (described below) that was assigned randomly.

Conventional Approach. This management tactic involved three calendar-driven sprays of organophosphate insecticide applied to all trees within the plot. The first spray was applied within a few days after petal fall. Two additional whole-plot sprays were applied 10–14 and 20–28 d after petal fall. The length of these intervals depended primarily on the amount of rainfall. This approach is considered to be the standard in Massachusetts orchards (Prokopy et al. 1996).

Heat-Unit Accumulation Approach. This management tactic is the current integrated pest management (IPM) approach recommended by Cornell University for managing plum curculio in New York. The first, second and third (if needed) whole-plot sprays against plum curculio were the same as for the first treatment, except that the need and timing of the last (third) spray was determined on the basis of the heat accumulation model developed by Reissig et al. (1998). According to this model, the last spray against plum curculio should have sufficient residual activity for effective control until 171 DD_{10} have accumulated since petal fall. Thus, the third full-plot spray against plum curculio took place only if rainfall and cool temperatures suggested that the second application would lose efficacy before 171 DD_{10} accumulated since petal fall. To gather day-degree information, Skybit, Orchard Radar (or equivalent), or Hi-Low thermometers were used in each orchard block.

Trap-Tree Approach. This tactic involved a whole-plot insecticide spray by the time of petal fall to kill any plum curculios that may have either overwintered within the plot or immigrated from overwintering sites into the plot. Subsequent sprays (if needed) were applied to perimeter-row trees only, a practice adopted in some orchards in Quebec, Canada (Chouinard et al. 1992, Vincent et al. 1997) and Massachusetts (Prokopy et al. 2001, 2003b), depending on the appearance of fresh plum curculio egg-laying scars to fruit sampled from a single trap tree, baited with attractive odor, located midway along the length of the perimeter row of a plot. Efforts were made to restrict the spray to both sides of the perimeter row and the perimeter-facing side of trees in row two for those plots where rows ran parallel to the border habitat. For plots where rows ran perpendicular to border habitat, applications targeted the perimeter-facing side of trees. The perimeter trees on both lateral sides of the plot and the outer-facing side of back-row trees were also sprayed to prevent penetration of the block from the side or rear.

Trap trees were baited during full bloom; each trap tree was baited with four 15-ml low-density white polyethylene vials containing 8 ml of a 9:1 mixture of benzaldehyde and 1, 2, 4-trichlorobenzene (Sigma-Aldrich Inc., St. Louis, MO) (wt:wt) as a stabilizing agent (Leskey et al. 2005) for a total estimated release rate of ≈40 mg/d (Piñero and Prokopy 2003). Each vial was hung by its neck from a wire and placed inside an inverted green 266-ml plastic cup (CVS, Woonsocket, RI) to provide additional protection against heat and UV light. Vials were distributed evenly at head-height within the tree canopy. Dispensers releasing grandisoic acid (ChemTica International, San Jose, Costa Rica) were deployed at the center of each trap tree. Pheromone dispensers were replaced four weeks after deployment whereas vials releasing benzaldehyde were left in place for the entire plum curculio season.

Beginning when fruit reached 6 mm in diameter (i.e., ≈1 wk after petal fall), 35 fruit clusters were designated on each trap tree using flagging tape and numbered using a nontoxic, water-resistant marking pen (Sharpie, Sanford L.P., Oak Brook, IL). Each king fruit (i.e., the biggest fruit within a cluster) was selected as the fruit to be inspected for occurrence of fresh plum curculio egg-laying scars throughout the season. Only king fruit in clusters 1–25 were used for making a threshold decision. King fruit in clusters 26–35 were checked on each visit and the damage circled, but they were not counted toward the threshold, because they were considered as potential replacements in the event a designated king fruit fell off. Fruit sampling on the trap tree took place twice per week (e.g., Mondays and Thursdays in Massachusetts orchards in 2004) for ≈6 wk. During sampling, a tight circle was drawn around each fresh plum curculio scar detected and data for each labeled fruit were recorded.

Prokopy et al. (2004) evaluated various candidate thresholds for insecticide application with the expectation that orchard-wide damage would remain below a preset economic injury level of 1%. Because in that study one or two freshly-injured fruit out of 50 fruit sampled on a trap tree offered similar results, then for the current study we selected a threshold of one scarred fruit out of 25 fruit sampled because it was considered to be equivalent to a threshold of two scarred fruit out of 50 fruit reported in the above paper. If the threshold was reached, the grower was advised to spray, within 24 h, all perimeter row trees including the trap tree. Fruit sampling resumed 3–4 d after an insecticide spray took place. Table 1 presents, for the 2004 season, the specific sampling dates and the frequency with which fresh egg-laying scars by plum

Table 1. For each sampling date in 2004, frequency with which fresh egg-laying scars by plum curculio were found in 25 designated fruits sampled from a perimeter-row single trap tree on each of 14 participant orchard blocks in Massachusetts

Orchard	20 May	24 May	27 May	31 May	3 June	7 June	10 June	14 June	17 June	21 June	24 June	28 June	No. alerts	Season-long no. injured fruit
A	0	0	0	0	0	0	**1**	*1*	0	0	0	0	1	1
B	0	0	0	0	0	**1**	0	**2**	0	**2**	0	0	3	5
C	0	**1**	0	**1**	0	0	0	0	0	0	0	0	2	2
D	0	**1**	*1*	**3**	*2*	0	0	**2**	*1*	**1**	0	0	4	7
E	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
F	**1**	*1*	0	0	0	0	0	0	0	**1**	0	0	2	2
G	0	**1**	0	0	0	**1**	*1*	0	0	0	0	0	2	2
H	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
I	**1**	0	0	0	0	0	**5**	*2*	0	0	**1**	0	3	7
J	0	0	0	0	0	0	0	0	0	0	**1**	0	1	1
K	0	0	0	**1**	0	0	0	0	**1**	0	0	0	2	2
L	0	**2**	0	**1**	0	0	0	0	0	0	0	0	2	3
M	0	**1**	0	0	0	0	0	**2**	0	0	0	0	2	3
N	—	—	—	—	0	0	**1**	0	0	0	0	0	1	1

Numbers indicate the actual number of fruit with fresh egg-laying scars. Boxes with bold values indicate occasions when the grower was advised to spray in trap-tree plots. Boxes with italic values indicate presence of fresh egg-laying scars that probably occurred between the time the grower was alerted and the actual spray, and thus the grower was not advised to spray again. The number of alerts and season-long number of injured fruit does not include boxes with italic values. Orchard N is at higher elevation thus sampling started later than the other orchards.

curculio were found in 25 fruit sampled from a trap tree for the 14 Massachusetts orchard blocks.

Efficacy Assessment. The efficacy of each management tactic was assessed twice, first in July (6–7 wk after petal fall), to monitor the buildup of plum curculio injury to fruit at the end of the egg-laying period, and again ≈1 wk before harvest to estimate actual amounts of fruit rendered unmarketable due to plum curculio injury. For each of these two time periods and for each of the three plots within a block, 10 random fruit were inspected for egg-laying scars on each of 10 trees in nine rows (=900 fruit per treatment plot, 2,700 fruit per orchard block). Rows selected for sampling depended on the number of rows included in a plot. If the block had large (M.7 rootstock) trees, all nine rows were sampled. If trees were on M.26 or M.9 rootstocks, the nine rows sampled were distributed as evenly as possible among all the rows in the plot, and always included the perimeter and the most interior rows. An additional 50 fruit (excluding the 25 designated fruit that were used to drive the decision of whether or not to spray the perimeter-row trees of trap tree plots) were sampled on the odor-baited trap tree in that treatment plot to determine the extent of aggregation of plum curculio damage on trap trees. In all, 115,800 fruit (combining the first survey and the harvest survey) were inspected for plum curculio injury in 2004 and 96,400 fruit in 2005.

Injury by another key early-season pest, tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois) (Heteroptera: Miridae), was recorded (in Massachusetts orchards only) during the surveys to determine whether insecticide application to only perimeter-row trees after the whole-block spray that targeted plum curculio would result in increased tarnished plant bug populations in the trap-tree plots compared with the other two approaches that involved whole-plot sprays.

Insecticide Use. Data for 2004 are expressed in terms of number of insecticide sprays against plum curculio per plot, including the petal fall spray. For the 2005 study, actual amounts used per plot were calculated and expressed in terms of dosage-equivalents by dividing the actual rate used by the manufacturer's recommended field rate, to adjust for the wide range of field rates used by growers. Actual costs of insecticide applied per hectare also were estimated based on dosage equivalent values obtained for 14 (eight in Massachusetts; two in New York; and one each in Connecticut, Maine, New Hampshire, and Vermont) of the 21 blocks that were evaluated in 2005. For the computation we assigned a value of one to whole-plot sprays, indicating the amount of insecticide used per application for the petal fall sprays in the conventional, heat-unit accumulation and trap tree plots and the subsequent whole-block spray covers applied only in the conventional and heat-unit accumulation plots. A value of 0.25 was assigned to perimeter-row sprays in the trap-tree plots. This was done in an attempt to reflect the relative amounts of insecticide applied to the front and back perimeter-row trees) as well as to the lateral sides of blocks. Consequently, dosage-equivalent values are a conservative estimate because in blocks with small-sized trees, a value <0.25 would have been used due to the comparatively lesser number of perimeter-row trees that were sprayed in trap tree plots compared with the higher density of interior trees.

Statistical Analysis. For each of the two years and for each of the two fruit samplings conducted (6 wk after petal fall and 1 wk before harvest), one-way analysis of variance (ANOVA) were conducted to compare, for each year and for each sampling date (i.e., first sampling and harvest sampling) level of injury (expressed as proportions) to fruit sampled from 1) perimeter row, 2) the most interior row, and 3) for whole-plot injury, across the three management tactics. Under this approach, 12 different ANOVAs were conducted after arcsine transformation of the data. ANOVAs also were used to test for differences among plots in whole-plot level of injury to fruit caused by

Table 2. Incidence of infestation (mean percentage of infested fruit ± SEM) by plum curculio to apple fruit sampled from perimeter-row or most-interior-row trees, and for whole-plot injury, according to management tactic

Yr and type of injury	% infested fruit		
	Conventional	Heat-unit accumulation	Trap tree
2004—First sampling[a]			
Perimeter row	2.43 ± 1.32a	3.33 ± 1.50a	5.95 ± 1.89a
Most interior row	0.95 ± 0.43a	0.76 ± 0.30b	1.71 ± 0.90b
Whole-plot injury	1.15 ± 0.44	1.26 ± 0.35	3.01 ± 1.19
2004—harvest sampling[b]			
Perimeter row	1.83 ± 0.63a	3.74 ± 0.69a	3.91 ± 0.91a
Most interior row	1.27 ± 0.60a	1.14 ± 0.55b	1.95 ± 0.52a
Whole-plot injury	1.18 ± 0.33	1.61 ± 0.33	2.68 ± 0.88
2005—first sampling			
Perimeter row	1.11 ± 0.25a	0.94 ± 0.35a	1.83 ± 0.41a
Most interior row	0.50 ± 0.28b	1.05 ± 0.55a	0.98 ± 0.73b
Whole-plot injury	0.59 ± 0.12	0.59 ± 0.11	1.03 ± 0.31
2005—harvest sampling			
Perimeter row	0.99 ± 0.20a	1.05 ± 0.39a	1.87 ± 0.49a
Most interior row	0.77 ± 0.31a	0.25 ± 0.10a	0.93 ± 0.40b
Whole-plot injury	0.71 ± 0.16	0.70 ± 0.16	1.56 ± 0.55

Data were collected in 24 (in 2004) and 21 (in 2005) orchard blocks in seven northeastern U.S. states. All values within each row are not significantly different at the 0.05 significance level according to one-way ANOVAs that were conducted separately for each year, for each sampling date and for each type of injury. Values within each column followed by the same letters are not significantly different at the 0.05 significance level according to non-parametric Mann–Whitney tests that compared perimeter-row versus most-interior row injury by plum curculio for each year and for each type of management.

[a] In July, ≈5–6 wk after petal fall.

[b] Approximately 1 wk before harvest.

tarnished plant bug and for differences among plots in number of insecticide applications, as well as for estimated amounts of insecticide applied in terms of dosage equivalent values and insecticide costs per ha per plot. Nonparametric Mann–Whitney tests were used to compare, for each year, for each sampling date and for each plot type, incidence of fruit infestation recorded in perimeter-row versus the most-interior-row trees. All tables show untransformed data. Statistical analyses were conducted using STATISTICA (StatSoft 2001).

Results

In 2004, no significant differences in the proportion of perimeter-row or most-interior-row fruit with plum curculio injury were detected among the three management strategies for the first survey, conducted 6 wk after petal fall, (ANOVA: $F_{2,\ 66} = 2.35$; $P = 0.103$ and $F_{2,\ 60} = 0.70$; $P = 0.498$ for perimeter-row and most-interior-row trees, respectively) and for the second survey conducted at harvest (ANOVA: $F_{2,\ 51} = 1.79$; $P = 0.176$ and $F_{2,\ 63} = 0.61$; $P = 0.547$ for perimeter-row and most-interior-row trees, respectively) (Table 2). The level of whole-plot injury by plum curculio did not vary across management tactics, either for the first (ANOVA: $F_{2,\ 63} = 1.88$; $P = 0.162$) or second (ANOVA: $F_{2,\ 66} = 1.83$; $P = 0.168$) assessments. The amount of whole-plot injury (i.e., perimeter plus all interior trees combined) to fruit recorded at harvest was ≤1% in 71% (17/24) of the plots subject to conventional management, in 46% (11/24) of the heat-unit accumulation plots, and in 33% (8/24) trap-tree plots. For the first sampling date (i.e., 6 wk after petal fall), incidence of infestation by plum curculio to fruit sampled from perimeter-row trees was significantly greater than that recorded in the most-interior-row trees for plots managed using the heat-unit accumulation (Mann–Whitney, Z-adjusted = 1.98; $P = 0.046$) and the trap-tree (Mann–Whitney, Z-adjusted = 1.91; $P = 0.049$) approach. For the conventional plots, incidence of infestation to fruit sampled from perimeter-row did not differ significantly from that recorded in most-interior-row trees (Mann–Whitney, Z-adjusted = 1.19; $P = 0.233$) (Table 2). For the second sampling date, conducted 1 wk before harvest, significantly greater fruit infestation was recorded in perimeter-row trees than in most-interior-row trees for heat-unit accumulation plots (Mann-Whitney, Z-adjusted = 3.40; $P < 0.001$) but not for conventional (Mann–Whitney, Z-adjusted = 1.32; $P = 0.186$) or trap-tree plots (Mann–Whitney, Z-adjusted = 1.70; $P = 0.088$) (Table 2).

In 2005, the level of plum curculio control achieved based on percent fruit injury in trap tree plots did not differ significantly from that recorded in the other two plot types for any of the two sampling dates (first sampling ANOVA: $F_{2,\ 51} = 1.92$; $P = 0.157$ and $F_{2,\ 54} = 0.31$; $P = 0.736$ for perimeter- and most-interior-row trees, respectively; second sampling ANOVA: $F_{2,\ 51} = 1.64$; $P = 0.205$ and $F_{2,\ 54} = 1.43$; $P = 0.248$ for perimeter- and most-interior-row trees, respectively). Furthermore, mean percentages of fruit with plum curculio injury recorded for the first surveys (ANOVA: $F_{2,\ 57} = 1.60$; $P = 0.211$) and second (ANOVA: $F_{2,\ 57} = 2.01$; $P = 0.143$) surveys were not significantly different among the three management tactics when fruit from all sampled trees (perimeter- and all interior-row trees) were combined (Table 2). The level of whole-plot injury to fruit recorded at harvest did not exceed

Table 3. Incidence of whole-plot fruit infestation (mean percentage of infested fruit ± SEM) by tarnished plant bug, another early-season pest of apple, according to management tactic used against plum curculio

Yr	% infested fruit		
	Conventional	Heat-unit accumulation	Trap tree
2004	3.16 ± 0.53b	6.89 ± 1.18a	6.51 ± 1.36a
2005	0.96 ± 0.21a	1.46 ± 0.30a	1.22 ± 0.24a

Values within each row followed by the same letters are not significantly different according to ANOVA and Fisher's protected LSD tests at the 0.05 level.

1% in 75% (15/20) of the plots assigned to conventional and heat-unit accumulation management, and in 60% (12/20) of the plots managed with trap-trees. For the first sampling date, incidence of infestation in perimeter-row trees was significantly greater than that recorded in the most-interior-row trees in the conventional (Mann–Whitney, Z-adjusted = 2.05; P = 0.040) and trap-tree plots (Mann-Whitney, Z-adjusted = 3.03; P = 0.002), but not in plots managed with the heat-unit accumulation method (Mann-Whitney, Z-adjusted = 0.89; P = 0.374). Same type of result was found for the second sampling date in trap-tree plots only (Mann–Whitney, Z-adjusted = 1.96; P = 0.049). Fruit sampled from perimeter-row and most-interior-row trees in plots managed using the conventional approach and the heath-unit-accumulation method injury received similar amounts of damage at harvest (Mann–Whitney, Z-adjusted = 1.63; P = 0.102 and Mann–Whitney, Z-adjusted = 1.71; P = 0.085, respectively) (Table 2).

Incidence of injury by plum curculio recorded on 50 fruit sampled from trap trees (excluding the designated sampled fruit) was 21.2 ± 0.05% (range, 2–96%; n = 18) in 2004 and 14.3 ± 2.5% (range, 0–42%; n = 12) in 2005. This amount of injury recorded in trap trees was nearly 5 and 4 times greater (for 2004 and 2005, respectively) than the overall amount of injury recorded on fruit sampled from perimeter-row trees in trap-tree plots (excluding trap trees) in the harvest survey, as shown in Table 2.

Injury by Tarnished Plant Bug. In 2004 in Massachusetts orchards, the level of whole-plot injury to fruit by this early-season pest was significantly greater in trap tree plots than in plots subject to conventional and heat unit accumulation plots (ANOVA: $F_{2,\ 39}$ = 3.57; P = 0.038). In 2005, no significant differences in level of whole-plot injury by this insect were detected among the three plum curculio management tactics (ANOVA: $F_{2,\ 30}$ = 0.98; P = 0.387) (Table 3).

Insecticide Use. In practice, there was some variability concerning the compliance with protocols by particular growers, depending, in part, on the perceived level of plum curculio pressure and on rain events. Our 2004 data indicate that, in terms of number of insecticide applications by growers, the trap-tree plots received significantly (ANOVA: $F_{2,\ 39}$ = 4.13; P = 0.025) fewer sprays (2.21, on average, ±0.19 SEM) than the other two management tactics (3.21 ± 0.24 and 2.71 ± 0.30 for the conventional and heat-unit accumulation approaches, respectively) for eight orchard blocks in Massachusetts. In at least four orchard plots (two in New York and two in Massachusetts [Table 1]), no additional insecticide sprays were advised beyond the petal fall application, owing to the absence of oviposition damage on any of the designated fruit on the trap trees for the entire period (>5 wk) of fruit inspection after petal fall.

Table 4. Number of insecticide applications made in 2005 against plum curculio from petal fall until the end of the plum curculio season (≈6 wk after petal fall), according to compound type (trade names are shown in parentheses)

Compound	CT	MA	ME	NH	NY	VT	Total
	1	8	1	1	2	1	14
Azinphosmethyl (Guthion)	0	40	0	6	0	0	46
Carbaryl (Sevin XLR+)	3	27	3	3	3	0	39
Phosmet (Imidan)	7	11	8	0	9	7	42
Indoxacarb (Avaunt)	0	7	0	0	0	0	7
Thiacloprid (Calypso)	0	4	0	0	0	0	4
Lambda-cyhalothrin (Warrior)	0	0	0	0	1	0	1

Data shown are for all orchard blocks combined. For each participating state, the number of orchard blocks for which this type of data was obtained is shown below state abbreviation. Insecticide data from RI, a participant state, were not obtained.

In 2005, no significant differences in the number of spray applications were recorded among treatment plots (ANOVA: $F_{2,\ 39}$ = 0.69; P = 0.506). Numbers (mean ± SEM) of applications were 3.3 ± 0.29, 2.86 ± 0.25, and 2.93 ± 0.29 (N = 14) for conventional, heat-unit accumulation, and trap tree plots, respectively. Table 4 shows that Guthion (azinphosmethyl) (33.1% of all applications for all plots combined), followed by Imidan (phosmet) (30.2%) and Sevin XLR+ (carbaryl) (28.1%) accounted for 91.4% of the insecticide sprays applied against plum curculio in 2005 in six participant northeastern U.S. states. In terms of actual amounts of insecticide against plum curculio used per plot, the average dosage equivalents were significantly lower in trap tree plots (0.76 ± 0.09; N = 14) than in plots managed through the conventional (1.09 ± 0.07; N = 14) or heat-unit accumulation (1.05 ± 0.07; N = 14) approaches (ANOVA: $F_{2,\ 137}$ = 7.64; P < 0.001). The last two approaches did not differ significantly from each other. Overall, the amount of insecticide used in trap-tree plots in 2005 was reduced by 43% compared with plots managed with the conventional approach and by 28% compared with the heat-unit accumulation plots. Estimated insecticide costs (per hectare) at actual application rates calculated for 2005 also varied significantly across management strategies (ANOVA: $F_{2,\ 137}$ = 9.15; P < 0.001). The average costs of insecticide applied per hectare were $35.3, $31.9, and $20.8 per application for conventional, heat-unit accumulation, and trap tree plots, respectively.

Discussion

This work was conducted as part of a multistate project aimed at validating and demonstrating the efficacy of a recently developed bio-based method that uses a perimeter-row, odor-baited trap-tree (Prokopy et al. 2003a) to monitor egg-laying activity by plum curculio in commercial apple orchards throughout New England and New York. In both years, level of plum curculio injury to fruit sampled from perimeter or from the most-interior-row trees in trap-tree plots did not differ significantly from that recorded in plots subject to conventional management or in plots managed using the heat-unit accumulation approach with a concomitant reduction in pesticide use in trap-tree plots compared with the other two approaches.

The efficacy of the three management strategies evaluated can be affected by different factors, such as weather conditions during the period of plum curculio egg-laying activity, by level of plum curculio pressure, and by the timing of the sprays. In 2004, mean percentages of whole-plot injury by plum curculio recorded at harvest exceeded 1% (an unacceptable economical injury level in New England orchards) in 29% (7/24) of the plots managed with the conventional approach, in 54% (13/24) of the heat-unit accumulation plots, and in 67% (16/24) of the trap tree plots. The weather during May and June 2004 was cool and rainy and resulted in a prolonged egg-laying period, with some injury still occurring through late June in some orchards. Under these conditions, managing plum curculio successfully was particularly challenging for growers, and in some instances they were not able to enter their orchards to apply an insecticide treatment against plum curculio due to extremely wet conditions. In 2005, May and June temperatures were lower than in 2004 in the Massachusetts orchards, and there was also more rainfall compared with 2004. This resulted in some plum curculio injury in early July in some Massachusetts orchard blocks (data not shown) and the resulting mean percentages of whole-plot injury by plum curculio recorded at harvest in 2005 exceeded 1% in 40% of the trap tree plots. Thus, a critical aspect for the successful implementation of the trap tree approach as a monitoring tool is the timing of insecticide treatments after fresh injury is detected. In addition, more powerful lures are needed to increase the attractiveness of trap trees to plum curculios during fruit development (Leskey et al. 2005). For example, the synergistic lure used in this and previous studies in Massachusetts orchards (Piñero et al. 2001; Piñero and Prokopy 2003, 2006) is less attractive after petal fall due to olfactory competition with developing fruit (Leskey and Wright 2004).

Several studies have confirmed that a petal fall insecticide application covering all trees in a block is necessary to kill plum curculios that have either penetrated into orchard blocks by petal fall (Vincent et al. 1999, Prokopy et al. 2003b) or may have overwintered inside the blocks (Piñero et al. 2004). This prepetal fall population represents the majority of the immigrating population (Piñero and Prokopy 2006). After the petal-fall spray, subsequent insecticide applications can be confined exclusively to perimeter-row trees based on the documented tendency of plum curculios to stay on perimeter-row trees (Rings 1952; Chouinard et al. 1992). Findings from the current study indicating consistently greater incidence of infestation to fruit sampled from perimeter-row trees compared with fruit sampled from the most-interior-row trees validate the recommendations made by Chouinard et al. (1992) and Vincent et al. (1997) in Quebec, and by Prokopy et al. (2003b, 2004) in Massachusetts orchards concerning the postpetal fall applications of insecticide to perimeter-row trees only.

It can be argued that lack of whole-orchard sprays after the petal fall spray in trap tree plots could invite buildup of other insect pests. Spraying only perimeter-row trees after the whole-plot petal-fall spray has not resulted in such buildups over 4 yr of study (1991–1994) in several Massachusetts orchards (Prokopy et al. 1996) or over a 20-yr period (1981–2000) in R.J.P.'s own commercial orchard (Prokopy 2003). In the current study, significantly greater injury by tarnished plant bug was documented in 2004 in trap tree plots and in the heat-unit accumulation plots than in plots subject to conventional management, but even so, the level of injury in plots subject to conventional plum curculio management was >3%. When population densities of tarnished plant bug were low, as in the 2005 study, no differences in level of whole-plot injury by this insect were recorded among the three plum curculio management tactics.

In this study, two organophosphate (azinphosmethyl and phosmet) and one carbamate (carbaryl) insecticides accounted for 91.4% of the total number of applications made in 2005 in 14 orchard blocks located in six northeastern U.S. states, and the same three products accounted for 87.6% of the total applications in eight Massachusetts orchards (Table 4). Azinphosmethyl, the most widely used insecticide against plum curculio and apple maggot, *Rhagoletis pomonella* (Walsh), is restricted to two applications or 2.24 kg (AI)/ha in 2010, and only 1–1.5 applications or 1.68 kg (AI)/ha per year in 2011–2012, after which it is expected to be phased out. If other insecticide compounds with shorter residual activity than that of azinphosmethyl are used to control plum curculio, then trap trees would serve as excellent indicators of the extent to which insecticide residue truly remains effective against plum curculio (Prokopy et al. 2004). More research is needed aimed at evaluating the effectiveness of trap trees in combination with reduced-risk compounds such as thiacloprid (a neonicotinoid), which was used in only one orchard in Massachusetts in 2005. Based on our estimates of amount (and cost) of insecticide applied in 2005, the trap tree plots were as effective at managing plum curculio as the other two management tactics with a substantial reduction in insecticide used: ≈43% compared with the conventional approach and ≈28% compared with the heat-unit accumulation method. Our estimation of cost savings does not take into account additional savings in application costs (e.g., labor, gasoline). A recent study by Leskey et al. (2008) demonstrated that additional reductions in insecticide can be achieved when odor-baited trap trees are used a control strategy in New England orchards. These authors showed that treating only the trap trees and ends of rows in trap tree plots after petal fall resulted in a level of plum curculio control that was comparable with that achieved by perimeter-row sprays. The trap tree control strategy resulted in a reduction of ≈70% total trees being treated with insecticide compared with perimeter row sprays, and 93% compared with standard full block sprays.

Determining an economic threshold for spraying orchard trees against plum curculio by using injury to fruit on trap trees as the basis for making a treatment decision ought to be feasible to be conducted by actual growers. Previous work by Prokopy et al. (2004) compared various candidate thresholds and determined that a preset injury threshold of one or two fresh egg-laying scars out of 50 fruit sampled resulted in similar level of whole-plot injury. For the current study, one scarred fruit out of 25 fruit sampled was considered to be equivalent to the two scarred fruit out of 50 fruit reported in the above paper. As shown here, the establishment of odor-baited trap trees on perimeter rows of apple orchards to determine need and timing of postpetal-fall insecticide applications against plum curculio by using a threshold of one fresh plum curculio egg-laying scar out of 25 fruit sampled from a trap tree is an efficient, inexpensive and practical method of preventing economic injury to apple fruit. For example, the costs of materials needed to deploy a trap-tree are ≈$ 4.00 for all benzaldehyde dispensers combined (formulated by us) and ≈$ 9.00 for the one grandisoic acid dispenser. In terms of time, setting up a trap tree involves lure (i.e., benzaldehyde and grandisoic acid) deployment, flagging 25 fruit clusters around the trap tree, and marking the king fruit within each cluster using a marking pen, a process that can be completed in 30 min. At each subsequent inspection the amount of time it took for a project participant to inspect 25 fruit on a trap tree was <10 min. Even though for this study the above practices were conducted by experienced consultants/technicians, we are confident that with some training concerning lure deployment, selection of designated fruit, and identification of fresh egg-laying scars, a grower should also be able to inspect 25 fruits in <10 min. In this study, the 25 designated fruit were inspected twice a week for incidence of fresh plum curculio injury and this decision was made based on the large number of apple orchards that needed to be visited by project participants (growers were not involved in the sampling). Because injury to fruit as a result of oviposition activity can take place very rapidly once fruit is unprotected, more frequent monitoring (e.g., three times per week) as done in a previous study of Prokopy et al. (2004), would be advisable for more precise timing of insecticide applications.

Overall, this multistate study corroborates previous findings by Prokopy et al. (2003, 2004) indicating that the establishment of odor-baited trap trees on perimeter rows of apple orchards to serve as sentinels according to principles derived from this and the aforementioned studies is, from a grower's perspective, an effective, inexpensive, expeditious, and practical method of monitoring plum curculio oviposition activity. This grower-friendly approach allows for accurate determination of the need for and timing of insecticide applications to perimeter-row trees only after a whole-plot petal fall spray. In addition, trap trees are excellent indicators of insecticide residue durability, thus complementing the use of cumulative heat unit models for this purpose, as developed by Reissig et al. (1998).

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