# Direct Sampling of Resting Codling Moth (Lepidoptera: Tortricidae) Adults in Apple Tree Canopies and Surrounding Habitats

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**ABSTRACT** Field investigations were conducted to determine the resting locations of codling moth (*Cydia pomonella* [L.]) (Lepidoptera: Tortricidae) males and females in mating disrupted and nondisrupted apple (*Malus domestica* Borkh.) orchard plots. A custom-made sampling device, consisting of a leaf blower converted into a powerful vacuum, yielded 20–24% success in recovering marked moths, released in the tree canopy in orchards. Four collections each were made between 0900 and 1800 hours and 1800 and 2200 hours in 2005. Ninety-four moths were collected during the 1800–2200 hours samples. In mating disruption plots, 42% of females and 22% of males were found in the top third of the tree canopy (3.0–4.5m), 46% females and 43% males in the middle third (1.5–3.0m), and 12% female and 35% male in the lower third (0–1.5m). In nondisrupted plots 36.4% of females and 40% of males were in the top third of the canopy, 36.4% females and 52% males in the middle third, and 27.2% females and 8% males in the lower third of the tree canopy. Daylight vacuum sampling recovered only one female and two male moths from the top, four males from the middle and one male from the lower third of the tree canopy. Release-recapture studies of marked adult codling moths were conducted in 2006–2007 in screened tents to determine within orchard habitats for adult moths during 0900–1800 hours. Of moths recaptured, 14.6% of females and 13.5% of males were from the ground (herbicide strip and drive-row grass) and 32.9% of females and 24.6% of males were captured in the tree canopy 16-h post release, 17.4% of females and 3.4% of males from the ground and 26.5% of females and 38.2% of males in the tree 40-h post release, and 15.1% of females and 18.6% of males from the ground and 15.7 of females and 25.5% of males in the tree 64-h post release. Application of pyrethrum + PBO by using an orchard blast sprayer in 2007 resulted in the recapture of 28% and 37% of laboratory reared male and female moths, respectively, from trees during 0900–1800 h. Our results suggest that distributing pheromone dispensers throughout the tree canopy may be more effective than placing them in one location, such as near the tree crown.

**KEY WORDS** codling moth, adult distribution, mating disruption, vacuum, diel behavior

Mating disruption of codling moth (*Cydia pomonella* [L].) by using various hand-applied dispensers has become an accepted practice. Approximately 162,000 ha of apple (*Malus domestica* Borkh.) and pear (*Pyrus* spp.) are treated throughout the world (Witzgal et al. 2008). Sampling methods that depend on measuring moth flight activity have resulted in the standard recommendation that mating disruption pheromone dispensers be applied within the top meter of the tree canopy. Research with pheromone-baited and passive traps indicates that moth activity is greater in the upper than lower portion of the tree canopy (McNally and Barnes 1980, Barret 1995, Weissling and Knight 1995, Knight 2000). Witzgall et al. (1998) observed male moths flying and searching in branches of the upper half of tree crowns. Other researchers report increased levels of codling moth larval infestation of fruit in the upper tree canopy as evidence of greater moth presence in the treetops (Richardson, C. H. and F. R. Du Chanois 1950).

In addition, it is widely understood that codling moth is behaviorally active during evening twilight hours, ≈1900–2200 hours (Geier 1963, Castrovillo and Cardé 1979, Witzgall et al. 1998). Very little is known about codling moth resting site locations during periods of behavioral inactivity. It is assumed that adult moths confine themselves within the tree canopy during inactive periods (Geier 1963).

The studies reported here determined the location of resting codling moth males and females in apple orchards during daylight and twilight hours. To directly measure moth spatial distribution within the tree canopy and surrounding habitats, a vacuum-sampling technique was developed. The long-term aim of this work is to improve the effectiveness of codling moth mating disruption through understanding of

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adult distribution within the canopy, and of moth habitat selection during daylight resting periods.

## Materials and Methods

**Vacuum.** Several three horsepower or smaller backpack vacuums were evaluated and found inefficient for sampling resting codling moth from potted apple trees. Instead, a 10 horsepower (Briggs & Stratton Intek engine) leaf blower (MacKissic Inc., Parker Ford, PA) with a 34-cm-diameter impeller and 322KPH air velocity, was converted into a vacuum sufficiently powerful to remove codling moth adults from sampled surfaces. A 2 m length of 15-cm-diameter reinforced rubber air hose (Cathey Co, Lansing, MI) was attached to the leaf blower air intake opening. The open end of the rubber hose was attached to a 2-m-long wand constructed of 15-cm-diameter heat duct sheet metal. A handle constructed of 1-m-long, 2.5-cm-diameter metal was attached to the wand with hose clamps. Four 3.5-cm-long bolts were attached at 90-degree spacing 2.5 cm from the end of the sheet metal wand. Moths were collected from trees into a 19-liter nylon mesh paint strainer bag (Master Craft, El Monte, CA) inserted into the wand, folded back over the bolts, and secured with rubber bands to prevent the bag from being drawn into the impeller. A 90-degree sheet metal register box was attached to the wand end for vacuuming ground surfaces. The paint strainer bag used for tree canopy sampling was replaced with collection bags constructed from fiberglass window screening tapered to 10 cm at the closed end to avoid clogging airflow through the wand (15 cm in diameter) because of accumulation of particulate matter (soil, rocks, grass, and weeds) when sampling ground surfaces.

**Recovery Efficacy of Vacuum.** The efficiency of the vacuum was tested by mark–release–recapture trials. An initial test of whether adult codling moths could be effectively collected with the vacuum was conducted using 2-m-tall potted 'Red Delicious' trees in a greenhouse at Michigan State University. Three individual releases of 20 laboratory-reared moths each were made onto four trees, then immediately vacuumed to recover moths. Two additional release–recapture trials were performed in the field in 2005 with the 10-hp leaf blower vacuum. Moths were marked by placing them in a 19 liter plastic pail and spraying 0.5 g dry fluorescent dust dye (Dayglo Color Division, Switzer, Cleveland, OH) dissolved in 75 ml of acetone (99.9%) through cheesecloth covering the top opening of the pail. Forty laboratory-reared moths were marked and released on two occasions onto individual 16-yr-old 'Red Delicious' trees grown on a 3- by 6-m spacing and 4–5m in height at the Trevor Nichols Research Complex (TNRC) in Fennville MI (42° 35′ 38.10″N, 86° 06′ 05.92″W). Immediately after moth release, trees were vacuumed to recover moths.

**Effect of Canopy Height and Pheromone Treatment on Capture of Feral Moths.** All orchard vacuum collections (day and evening twilight) were conducted in six 0.4-ha apple plots at the TNRC. Four plots were 16-yr-old Red Delicious (3- by 6-m planting), 4–5 m in height, and two plots were 23-yr-old 'Macspur', (5.5 m by 6 m), 5 m in height. All orchards are uniformly fruit bearing on central leader trained trees. Two of the Red Delicious plots and one Macspur plot were treated with Isomate C+ (Shin-Etsu Chemical Co., Tokyo, Japan) at the full label rate of 1,000 dispensers per ha. The remaining three plots were not treated with pheromone. Daytime samples were collected between the hours of 900 and 1600 and twilight collections occurred between 1800 and 2200 hours. Twelve trees from each of the six plots were sampled on four dates for both daytime and twilight samples in 2005. Six of the 12 sample trees were located on plot perimeters and six trees were located in plot middles. Thirty-second samples were collected from the top third (3–4.5 m), middle third (1.5–3 m), and lower third (0–1.5 m), of each tree. The lower third of the tree sample included the trunk to the soil surface, and weeds growing within 0.5 m of the tree trunk. Sample contents were transferred from the nylon mesh collection bag located in the vacuum wand into 4-liter freezer bags, and identified in the laboratory. Only adult codling moths were counted in these collections, even though the vacuum was powerful enough to remove cocooned larvae (five individuals) and pupae (seven individuals) from the trunks and scaffold branches of the trees. One trap (LPD Scenturian Guardpost, Suterra, Bend, OR) baited with 1 mg of (*E,E*)-8,10-dodecadien-1-ol (codlemone) loaded onto a rubber septum (The West Co., Lionville, PA) was placed in the upper third of the tree canopy in each nondisrupted plot (four traps total) to monitor codling moth flight.

**Daytime Sampling of Feral Moths by Tree Fogging.** Twelve trees were fogged with pyrethroid insecticides on two separate dates in 2005 to test this method for sampling codling moth adults in the tree canopy. Aerosol foggers containing 142 g of 0.20% tetramethrin, 0.40% sumithrin, and 99.4% inert ingredients (Accuity Brands Enforcer Four Hour Fogger, Cartersville, GA) were attached to the trunks of each tree. Trees were covered with 4-ml plastic, and the foggers were activated until empty. After 10 min, the plastic covers were removed, and trees shaken to dislodge codling moth adults, as well as other insects, onto tarps placed on the ground under each tree. All arthropods were collected from tarps and taken to the laboratory for later processing. The fogging was conducted in plots with populations of codling moth as estimated by monitoring of male moths in pheromone traps as described above.

**Daytime Sampling of Feral and Laboratory Moths by Orchard Blast Spraying.** Three adjacent rows of 21 trees (≈60m) were sprayed with an orchard airblast sprayer (Orchardmaster CD 3400, Washington Tractor, Inc., Quincy, WA) with pyrethrum insecticides on four separate dates in 2007 at the Washington State University Tree Fruit Research and Extension Center in Wenatchee, WA to test this method for sampling codling moth adults in the tree canopy. The spray trials were conducted between 1030 and 1300 hours on each

date. An airblast sprayer was used with a spray volume of 936 liters per ha and a tank mix of 114 liters of water mixed with 237 ml of Pyronyl (6.0% pyrethrins and 60% Piperonyl Butoxide) and 296 ml of Sylgard (76% Siloxylated Polyether and 24% surfactant Mixture) as a surfactant. Before spraying, the soil surface beneath the tree canopies was covered by using 6-ml plastic covering the drip line of the trees. Also before spraying, 20 laboratory reared codling moth males and 30 laboratory-reared codling moth females were placed within the tree canopy of each row. Laboratory moths were internally marked through the addition of Calico red oil to their diet (Charmillot 1979). Laboratory moths were allowed ≈30 min to settle, at which point the rows were sprayed with a single pass of the tank mix. Immediately after spraying, the trees were gently shaken and moths that fell to the plastic covering were collected. Moths were individually placed in vials and returned to the laboratory for identification to sex and origin (wild or lab).

**Mark–Release–Recapture Studies.** Release–recapture studies of marked moths were conducted in 2006 and 2007 in screened tents to identify daytime (0900–1800) resting habitats for adult moths within the orchard. Four tents measuring 3 m high, 5.5 m wide, and 6.5 m long were constructed at the TNRC. The walls and ceiling of the tent structure were made of mosquito netting, sewn together to slip over the tent as one piece (Quality Awning Shops, Inc., Lansing, MI). Mosquito netting walls were staked into the ground with tent stakes to minimize open space where the tents met the ground. The tents were erected over single apple trees, encompassing drive row grass. Trees were 2.8-m-high Red Delicious, spaced 3 by 6 m. All trees were trained to a central leader and were uniformly fruit bearing. Data loggers (Hobo Pro series, Onset Computer Corporation, Bourne, MA) were placed in the tree and in the herbicide strip and grass at soil level to record daily temperature and relative humidity levels from 9 June to 29 August.

Moths were recaptured with the vacuum 16 h post release in 2006 (15 releases, six dates, 2-three tents on each date), and 40 h (13 releases, six dates, 2–4 tents on each date) and 64 h (17 releases, seven dates, 2–4 tents on each date) post release in 2007. Adult *C. pomonella* were reared from pupae purchased from Benzon Research Inc., Carlisle PA (Stelinski et al. 2006a). Females and males were sorted in the pupal stage and placed into 50-ml plastic cages containing 5% sucrose in plastic cups with cotton dental wick protruding from the lids. Releases with wild-type moths also were conducted in 2006 (one release, 60 males and females); and 2007 (two releases, 40 females and 20 males on 8 August, and 40 females and 25 males on 9 August). Wild-type codling moths were reared from cocooned larvae collected from orchards at the TNRC by using corrugated cardboard strips (Uline Inc., Waukegan IL) placed around tree trunks 0.5–1m above the orchard floor at the end of first codling moth generation. Cardboard bands were collected and placed in 50-ml plastic cages in the laboratory until adult emergence.

Moths were marked with luminescent powder by placing 20 male or female moths into 13 cm petri dishes coated with differing colors of 0.4-g powder (Bioquip Inc., Rancho Dominguez, CA) for easy differentiation of gender upon recapture. The moths accumulated powder after several min of movement within the dish. Moths were released into tents within 2 d of pupal emergence between 1800 and 1900 hours and recaptured at 16-, 40-, and 64-h post release, between 1000 and 1400 hours.

Release cages consisted of two 50-ml plastic containers with two 5-cm by 10-cm windows cut from each, so that the two containers could be oriented with windows nonaligned for transport, and aligned for moth release. Moths were released by placing two opened release containers, one with 20 males and one with 20 females, within the tree canopy. Male and female moths were released in equal numbers and were segregated into separate release containers before all releases. All tree, herbicide strip, and grass habitats were systematically vacuumed without time limit to recapture moths. Contents of mesh vacuum collection bags were transferred into 4-liter freezer bags for transport to the laboratory for identification.

**Statistical Analysis.** To compare between the numbers of resting codling moth adults collected by vacuum during daylight versus twilight hours or at various heights, $\chi^2$ goodness-of-fit tests at alpha = 0.05 (Preacher 2001) were conducted. Binary $\chi^2$ comparisons were chosen for comparison of moth captures in the tree crowns versus mid and lower canopy heights to directly address previous reports indicating that codling moth primarily inhabits the upper tree canopy in apple. For the orchard blast sprayer trial the numbers of male and female wild moths captured or percentage laboratory moths recovered were analyzed by using a two-sample *t*-test. We computed a variance/mean ratio for the total number of wild moths captured over all four dates by location (tree) to assess the level of spatial contagion of wild moths captured in the blast sprayer trial addition. For mark–release–recapture trials, analyses were performed using version 2.10.0 of the R computing language (R Development Core Team 2009, R Foundation for Statistical Computing, Vienna, Austria, [http://www.R-project.org]). Spearman's rank correlation tests were performed to assess the level of correlation between percent moth recapture, after nonrecovered moths were removed, in each possible habitat category (tree, drive-row grass, herbicide strip) by either Julian date, hours between release and recapture, and by average daily temperature, respectively. Furthermore, a 4 + 4 analysis of variance (ANOVA) modeling proportion recapture, after nonrecovered moths were removed, by block and habitat was performed with posthoc multiple comparisons made by using the Tukey Honest Significant Difference method. For the latter analysis, proportion recapture was normalized by using the arcsine transformation.

**Table 1. Total numbers of resting moths collected by vacuum sampling in 2005 during daylight (0900–1600) and twilight (1800–2130) hours**

| Gender | Top 1/3 canopy | | Middle 1/3 canopy | | Low 1/3 canopy | | Total | |
|---|---|---|---|---|---|---|---|---|
| | Day[a] | Twi.[b] | Day | Twi. | Day | Twi. | Day | Twi. |
| Male | 1 | 15 | 4 | 23 | 1 | 10 | 6 | 48 |
| Female | 2 | 18 | 0 | 19 | 0 | 9 | 2 | 46 |

[a] Day = daytime captures.
[b] Twi. = evening twilight captures.

## Results

**Recovery Efficacy of Vacuum.** The leaf blower vacuum recovered 70–80% of moths released onto potted trees, 24% of moths released in field trees at the TNRC orchards, and 22% of moths from the orchard herbicide strip and drive-row grass.

**Effect of Canopy Height and Pheromone Treatment on Capture of Feral Moths.** Mean captures from the four monitoring traps placed in nondisrupted plots were 68 moths per week, 9 June to 23 August. Eight codling moth adults in total (six males and two females) were collected during 864 individual daylight samples in 2005 (Table 1). Twilight samples (864 individual vacuum samples) yielded 94 codling moth adults distributed throughout the tree canopies (Table 1). Moth captures were significantly higher in the evening hours versus daytime hours for all tree canopy heights sampled (Table 2).

The number of codling moth adults collected during twilight hours was similar between the top and middle third of the tree canopy; however, more moths were collected in both the top and middle thirds than the bottom third of the canopy (Table 3). Also more adults were found in the combined lower two-thirds of the tree canopy than the top third (Table 3). No differences were observed either by gender or time of evening sampled.

Moths were distributed evenly between plot perimeters and plot centers in both pheromone-disrupted and nondisrupted plots (Fig. 1). In pheromone-disrupted plots, significantly more males were found in the combined lower two-thirds of tree canopy than the top third of canopy (Table 4). No significant differences were observed in male capture when comparing high versus middle, high versus low, or middle versus low positions within the tree canopy

**Table 2. Vacuum samples of codling moth adults during daytime (0900–1600) and twilight (1800–2130) hours (576 samples collected) (Numbers within row with same letter not significant at $P < 0.05$)**

| 2005 d vs Night total moths (w/in height) | | | |
|---|---|---|---|
| Canopy height | Daytime captures | Twilight captures | $\chi^2$ statistics |
| Total-all heights | 8b | 94a | $\chi^2 = 72.5$, df = 1, $P < 0.0000$ |
| Top third | 3b | 33a | $\chi^2 = 25$, df = 1, $P < 0.0000$ |
| Middle third | 4b | 42a | $\chi^2 = 31.4$, df = 1, $P < 0.0000$ |
| Bottom third | 1b | 19a | $\chi^2 = 16.2$, df = 1, $P < 0.0001$ |

**Table 3. Captures of resting codling moth adults collected by vacuum sampling in 2005 during twilight (18:00–21:30) hours (Numbers within row with same letter not significant at $P < 0.05$)**

| 2005 evening (w/in height) | | | |
|---|---|---|---|
| Height comparison | Total captures | Total captures | $\chi^2$ statistics |
| High vs mid | High: 33a | Mid: 42a | $\chi^2 = 1.1$. df = 1, $P < 0.2987$ |
| High vs low | High: 33b | Low: 19a | $\chi^2 = 3.8$, df = 1, $P < 0.0522$ |
| Middle vs low | Mid: 42b | Low: 19a | $\chi^2 = 8.7$, df = 1, $P < 0.0032$ |
| High vs lower 2/3 | High: 33b | Mid + low: 61a | $\chi^2 = 8.3$, df = 1, $P < 0.0039$ |

(Table 4). In disrupted plots, 46% of female moths and 43% of male moths were collected from the middle third of the tree canopies, while 42% of females and 22% of males were in the top third of the tree canopies (Tables 4 and 5). An equal percentage of females were collected from the top (36%) and middle (36%) thirds of the tree canopies in nondisrupted plots. Male distribution in plots not treated with pheromone was skewed toward the top two thirds of the tree canopies; 52% were collected from the middle and 40% from the top (Tables 4 and 5). Thirty-five percent of males were collected from the bottom third of the tree canopies in disrupted plots, while only 8% were vacuum-collected in the lower canopy in nondisrupted plots.

**Tree Fogging.** Two applications of pyrethroid insecticides applied to 12 covered trees during daylight hours did not result in the capture of any codling moth.

**Orchard Blast Spraying.** Wild and laboratory male and female codling moth were recaptured on all four dates where this technique was employed. Average (±SEM) recapture of laboratory reared male and female moths was 36.7% ± 7.3% for males and 28.1% ± 2.8% for females and did not differ significantly by sex ($t = 1.58$, df = 8, $P = 0.16$). However, marginally significantly more wild females were captured compared with wild males ($t = 2.29$, df = 8, $P = 0.06$) with 7.8 ± 1.6 and 14.3 ± 3.3 wild males and females captured, respectively (Table 6). 103 wild females and 54 wild males in total were recaptured across all four sampling events. The variance and mean ratio for total females, males, and total wild moths by tree was 2.3,

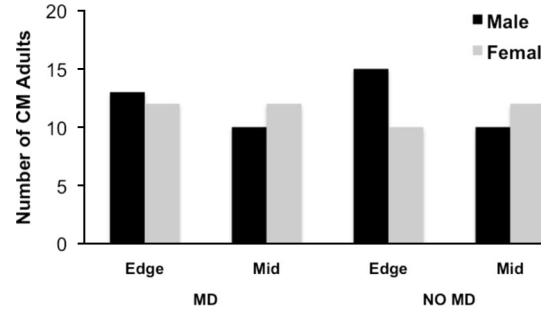


**Fig. 1.** Numbers of codling moth male and female adults vacuumed in pheromone-disrupted and nondisrupted plots.

**Table 4. Numbers of resting male codling moth adults vacuumed in plots with and without pheromone disruption. Samples were collected during twilight (1800–2130) hours in 2005 (Numbers within row with same letter not significant at $P < 0.05$)**

| 2005 Male moth captures in MD Plots vs Non-MD plots | | | |
|---|---|---|---|
| Mating disrupted plots-males | | | |
| Height | No. moths | No. moths | $\chi^2$ statistics |
| High vs Middle | High: 5a | Mid: 10a | $\chi^2 = 1.7$, df = 1, $P < 0.1966$ |
| High vs Low | High: 5a | Low: 8a | $\chi^2 = 0.692$, df = 1, $P < 0.4054$ |
| Middle vs Low | Mid: 10a | Low: 8a | $\chi^2 = 0.692$, df = 1, $P < 0.6375$ |
| High vs low 2/3 | High: 5a | Mid + Low: 18b | $\chi^2 = 7.35$, df = 1, $P < 0.0067$ |
| Nonmating disrupted plots–males | | | |
| Height | No. moths | No. moths | $\chi^2$ statistics |
| High vs middle | High: 10a | Mid: 13a | $\chi^2 = 0.391$, df = 1, $P < 0.5316$ |
| High vs low | High: 10a | Low: 2b | $\chi^2 = 5.33$, df = 1, $P < 0.0209$ |
| Middle vs low | Mid: 13a | Low: 2b | $\chi^2 = 8.07$, df = 1, $P < 0.0045$ |
| High vs low 2/3 | High: 10a | Mid + low: 15a | $\chi^2 = 1$, df = 1, $P < 0.3137$ |

1.5, and 2.6, respectively. Variance/mean ratios of >1 indicate a spatially contagious or aggregated spatial distribution.

**Mark–Release–Recapture.** Fifteen mark–release–recapture trials in screened tents resulted in the recovery of 47.7% of 596 released moths 16 h after release. Of the recovered moths, 29.2% were found in the tree, 5.3% in the grass, 8.8% in the herbicide strip, 32.4% on the tent screen surface, and 24.3% did not leave the release cage (Table 7). In 2007, 25.3% of released moths were recovered after 40 h (13 releases) and 45.7% were recovered after 64 h (17 releases) (Table 7). Significantly more moths were recovered from the tree than either the grass or the herbicide strip (Table 8). There was no statistically significant correlation between percent moth recapture in varying resting habitats and Julian date, hours between release and recapture or ambient temperature.

Although not statistically significant, higher percentages of female moths were consistently collected from drive-row grass and weeds under the trees than of male moths (14.6% of females and 13.5% of males after 16 h, 17.4% of females and 3.4% of males after 40 h, and 16.9% of females and 7.8% of males after 64 h) (Table 7). When analyzed temporally, no male moths were found in the grass or herbicide strip in June, 3.7% of males were recovered from the ground in July, and 11.7% from the ground in August (Table 9). Seven percent of female moths were recovered from ground surfaces in June, 11% in July, and 22.6% in August (Table 9).

Mean temperature was similar over a 3-mo period within the tree (22.1°C) and grass (22.1°C) microclimates. However, mean relative humidity was greater in grass (92.0%) than tree (78.7%) microclimates.

Mark–release–recapture of wild-type moths was conducted once in 2006 (Recovery 16 h post release) and on two dates in 2007 (Recovery 64 h post release). Twenty-four percent of wild-type moths released were recovered 16 h post release, and 16% of moths were recovered 64 h post release. All male moths that left the release cage in 2006 were recovered 16 h post release from the tree (43%), while a single female moth recovered was found in the grass (Table 10). Twenty-five percent of female wild-type moths recovered after 64 h were recovered from the drive-row grass, 18.8% from the tree and 6.3% from the herbicide strip (Table 10).

## Discussion

According to orchard vacuum samples, codling moth adults were distributed throughout all heights of the tree canopy during twilight hours (1800–2130) when female calling and male searching activity is occurring. More moths were captured at mid-tree canopy (1.5–3.0 m) than in either the top third (3.0–4.5 m) or lower third (0–1.5 m) of the canopy. However, the majority were found in the combined lower two-thirds (0–3.0 m) than the top third (3.0–4.5 m) of the tree canopy (Table 3).

**Table 5. Numbers of resting female codling moth adults vacuumed in plots with and without pheromone mating disruption. Samples were collected during twilight (18:00–21:30) hours in 2005 (Numbers within row with same letter not significant at $P < 0.05$)**

| 2005 female moth captures in MD plots vs non-MD plots | | | |
|---|---|---|---|
| Mating disrupted plots–females | | | |
| Height | No. moths | No. moths | $\chi^2$ statistics |
| High vs middle | High: 10a | Mid: 11a | $\chi^2 = 0.048$, df = 1, $P < 0.8267$ |
| High vs low | High: 10a | Low: 3b | $\chi^2 = 3.77$, df = 1, $P < 0.0522$ |
| Middle vs low | Mid: 11a | Low: 3b | $\chi^2 = 4.57$, df = 1, $P < 0.0325$ |
| High vs low 2/3 | High: 10a | Mid + Low: 14a | $\chi^2 = 0.667$, df = 1, $P < 0.4141$ |
| Nonmating disrupted plots–females | | | |
| Height | No. moths | No. moths | $\chi^2$ statistics |
| High vs middle | High: 8a | Mid: 8a | $\chi^2 = 0$, df = 1, $P < 1$ |
| High vs low | High: 8a | Low: 6a | $\chi^2 = 0.29$, df = 1, $P < 0.5928$ |
| Middle vs ow | Mid: 8a | Low: 6a | $\chi^2 = 0.29$, df = 1, $P < 0.5928$ |
| High vs low 2/3 | High: 8a | Mid + low: 14a | $\chi^2 = 1.6$, df = 1, $P < 0.2009$ |

**Table 6. Numbers of wild male and female codling moth captured and percentage male and female codling moth adults recovered in the orchard blast sprayer exp**

| Date | Wild moths captured | | Percentage laboratory moths recovered | |
|---|---|---|---|---|
| | Male | Female | Male | Female |
| 7/31/2007 | 8 | 11 | 35% | 36% |
| 8:7:2007 | 6 | 10 | 22% | 22% |
| 8/14/2007 | 5 | 12 | 33% | 26% |
| 8/21/2007 | 12 | 24 | 57% | 29% |
| Mean (± SEM) | 7.7 ± 1.5 | 14.25 ± 3.3 | 36.7% ± 7.3% | 28.1% ± 2.8% |

Pheromone treatment affected the distribution of codling moth adults within the tree canopy. In plots under pheromone disruption, female moths were captured in approximately equal numbers from the top third and mid third of tree canopies; few were captured in the lower third of tree canopies (Table 5). In nonmating disrupted plots, female moths were captured relatively equally from the three strata (Table 5). Autodetection, female sensitivity to sex pheromone, has been observed among tortricids, and is thought to function either as a mechanism to: 1) advance female calling periodicity under high population densities to increase the probability of attracting males, 2) induce dispersal under high population densities to reduce competition for males or food resources, or 3) aggregate females to increase local probability of mating success. (Palanaswamy and Seabrook 1978, Stelinski et al. 2006b).

The effect of the pheromone treatment was more evident with respect to male distribution. In plots that were not treated with pheromone dispensers, the majority of collected codling moth males were found in the upper two-thirds of the tree canopy (Table 4). However, in those moths receiving pheromone dispensers deployed near the top of the tree canopy, the majority of males were found in the lower two-thirds of the tree canopy (Table 4). These results suggest that pheromone dispenser placement affected distribution of male codling moth within the tree canopy. These results are congruent with those of Weissling and Knight (1995), who also found that males shifted to a lower position within the tree canopy in the presence of pheromone treatment. However, the majority of males were collected from the middle of the tree canopy in both disrupted and nondisrupted plots (Tables 4 and 5). Future research to determine the mechanisms underlying male codling moth settling behavior under mating disruption is warranted.

Current protocols for the deployment of hand applied mating disruption dispensers state that dispensers should be placed exclusively in the top meter of tree canopies, based on investigations showing that male activity is concentrated in the top third of the tree canopy (McNally and Barnes 1980, Barret 1995, Witzgall et al. 1998, Knight 2000). Our results indicate that the majority of codling moths were located in the

**Table 8. Tukey multiple comparison of the means of percent moth recapture in varying habitats**

| Comparisons | Difference | Lower | Upper | p adj |
|---|---|---|---|---|
| H-G | 0.1697 | −0.7557 | 1.0951 | 0.5718 |
| T-G | 2.1459 | 1.2205 | 3.0712 | 0.0110[a] |
| T-H | 1.9762 | 1.0508 | 2.9015 | 0.0003[a] |

H = Herbicide Strip, G = Grass; T = Tree.
[a] indicates significant *P* value @ alpha = 0.05.

**Table 7. Percent male and female codling moth adults recovered in five habitats in release–recapture trials in 2006–2007**

| | Moth recovery 16-, 40,- and 64-h postrelease in 2006–2007 trials | | | | | |
|---|---|---|---|---|---|---|
| | Male | Female | Total | Mean % recovered | % Males recovered | % Females recovered |
| 16 h | | | | | | |
| Tree | 31 | 52 | 83 | 29.2 | 24.6 | 32.9 |
| Grass | 6 | 9 | 15 | 5.3 | 4.8 | 5.7 |
| H-strip | 11 | 14 | 25 | 8.8 | 8.7 | 8.9 |
| Screen | 49 | 43 | 92 | 32.4 | 38.9 | 27.2 |
| Rel. cage[a] | 29 | 40 | 69 | 24.3 | 23.0 | 25.3 |
| Recovered | 126 | 158 | 284 | | | |
| No. released | 297 | 299 | 596 | | | |
| 40 h | | | | | | |
| Tree | 34 | 26 | 60 | 32.1 | 38.2 | 26.5 |
| Grass | 2 | 12 | 14 | 7.5 | 2.3 | 12.3 |
| H-strip | 1 | 5 | 6 | 3.2 | 1.1 | 5.1 |
| Screen | 31 | 19 | 50 | 26.7 | 34.8 | 19.4 |
| Rel. Cage[a] | 21 | 36 | 57 | 30.5 | 23.6 | 36.7 |
| Recovered | 89 | 98 | 187 | | | |
| No. released | 370 | 370 | 740 | | | |
| 64 h | | | | | | |
| Tree | 26 | 27 | 53 | 19.3 | 25.5 | 15.7 |
| Grass | 6 | 18 | 24 | 8.8 | 5.9 | 10.5 |
| H-strip | 2 | 11 | 13 | 4.7 | 1.9 | 6.4 |
| Screen | 17 | 15 | 32 | 11.7 | 16.7 | 8.7 |
| Rel. cage[a] | 51 | 101 | 152 | 55.5 | 50.0 | 58.7 |
| Recovered | 102 | 172 | 274 | | | |
| No. released | 300 | 300 | 600 | | | |

[a] Rel. cage = release cage.

**Table 9. Percent moths recovered from grass plus herbicide strip habitats over three months of release/recapture trials in 2006–2007**

| h post release | June | | July | | Aug. | |
|---|---|---|---|---|---|---|
| | Male | Female | Male | Female | Male | Female |
| 16 | 0.0 | 0.0 | 0.0 | 0.0 | 12.5 | 14.7 |
| 40 | 0.0 | 6.3 | 0.0 | 3.7 | 8.8 | 35.9 |
| 64 | 0.0 | 7.5 | 11.1 | 29.3 | 13.9 | 17.3 |
| Mean | 0.0 | 6.9 | 3.7 | 11.0 | 11.7 | 22.6 |

mid third of the tree canopy, and are unique in determining the locations of resting adult codling moths, including females. The discrepancy between our results and those results of investigations that have employed pheromone or passive trapping to investigate codling moth distribution (McNally and Barnes 1980, Barret 1995, Knight 2000) may indicate a difference between the optimal location for trapping flying adults and actual moth distribution within the tree canopy. Furthermore, it is possible that it is easier to see male codling moths flying near the top of tree canopies than in the middle of canopies (Witzgall et al. 1998) during twilight hours. Direct sampling of resting adults with a vacuum may have addressed these potential drawbacks of determining adult codling moth location within the tree canopy. The results of this study indicate that additional research addressing placement height of pheromone dispensers within the tree for optimization of codling moth disruption is warranted.

The low number of moths captured with the vacuum during 2005 daylight collections, in concert with the lack of recovered moths during daytime fogging of tree canopies, raised the question of whether codling moth adults move to other habitats during daytime. Although it is possible that codling moth population densities were below the threshold for recovery by the fogging technique employed in this investigation, there was a clear difference in recaptures of adults between daytime and twilight hours with the vacuum sampler.

The mark–release–recapture study reported here directly addressed whether codling moth adults move away from the tree canopy during daylight hours, and provides evidence that some proportion of adult moths inhabit drive-row grass and herbicide strip vegetation in apple orchards during daytime periods of inactivity. Significantly more moths were recovered from the tree than either the grass or the herbicide strip (Table 8), but both male and female lab-reared moths were recovered from the grass and herbicide strip at all recovery time periods, 16-, 40-, and 64-h post release (Table 7). Laboratory rearing of released moths did not affect our results, as wild-type females were recovered from the grass after 16 h (6.7%), and wild-type males (25%) and females (31.3%) were recovered from ground habitats (combined grass and herbicide) after 64 h (Table 10).

Results from the airblast sprayer trial in 2007 support the data showing that codling moth are found in the tree canopy during daylight hours. However, this approach did not allow us to assess moths in the ground cover (Table 6). Furthermore, the spatial pattern of wild codling moth appeared to be aggregated, especially for female moths. The relatively high level of aggregation may suggest that the moths observed in this study originated from even smaller areas within the sampled orchard space. Differences in environmental conditions between Michigan and Washington, including humidity (higher in Michigan), temperature (higher in Washington) as well as differences in ground cover may also account for the incongruence between the earlier pyrethroid sampling of moths during daylight hours and the airblast experiments in Washington.

Although not statistically significant, a numerical trend was observed for greater recovery of female codling moths from ground habitats as the summer season progressed (6.9% in June, 11% in July, and 22.6% in August) (Table 9). Males also were recovered in higher percentages from ground habitats as the

**Table 10. Recovery of wild-type moths in five habitats 16- and 64-h postrelease in release–recapture trials in 2006–2007**

| | Male | Female | Total | Mean % recovered | % Males recovered | % Females recovered |
|---|---|---|---|---|---|---|
| 16 h | | | | | | |
| Tree | 6 | 0 | 6 | 20.7 | 42.86 | 0.00 |
| Grass | 0 | 1 | 1 | 3.4 | 0.00 | 6.67 |
| H-strip | 0 | 0 | 0 | 0.0 | 0.00 | 0.00 |
| Screen | 0 | 2 | 2 | 6.9 | 0.00 | 13.33 |
| Rel. cage[a] | 8 | 12 | 20 | 69.0 | 57.14 | 80.00 |
| Recovered | 14 | 15 | 29 | | | |
| No. released | 60 | 60 | 120 | | | |
| 64 h | | | | | | |
| Tree | 2 | 3 | 5 | 25.0 | 50.00 | 18.75 |
| Grass | 0 | 4 | 4 | 20.0 | 0.00 | 25.00 |
| H-strip | 1 | 1 | 2 | 10.0 | 25.00 | 6.25 |
| Screen | 1 | 5 | 6 | 30.0 | 25.00 | 31.25 |
| Rel. cage[a] | 0 | 3 | 3 | 15.0 | 0.00 | 18.75 |
| Recovered | 4 | 16 | 20 | | | |
| No. released | 45 | 80 | 125 | | | |

[a] Rel. cage = release cage.

summer months progressed (0% in June, 3.7% in July, and 11.7% in August) (Table 9).

Data loggers maintained for this study documented that mean relative humidity varied by 13.3% between the tree (78.7%) and the grass (92.0%) microclimates. The higher availability of moisture found in the grass could explain why moths may seek shelter in this habitat during hot, dry summer days. It is also possible that adult codling moths move away from the tree canopy (in grass or ground) or deep into the canopy during daylight hours to seek refuge from predators.

Adult codling moth behavior between 0900 and 1800 hours has received little attention previously, and is not well understood. Investigations of behavioral management tactics should consider the impact of moth behavior during periods of inactivity to better understand potential impacts of behavior modifying chemicals such as pheromones on control efficacy. For example, movement of adult moths away from the tree canopy could affect efficacy of mating disruption. If desensitization from long-term exposure to high pheromone concentrations is an operative mechanism, movement away from dispensers within the tree canopy may reduce efficacy. Furthermore, the resting location of adult codling moths may impact efficacy of mating disruption depending where dispensers of synthetic pheromone are placed. Our results suggest that distributing pheromone dispensers throughout the tree canopy may be more effective than placing them in one location, such as near the tree crown.

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