Impact of a glossy collard trap crop on diamondback moth adult movement, oviposition, and larval survival

Fred R. Musser[1,2]*, Brian A. Nault[1], Jan P. Nyrop[1] & Anthony M. Shelton[1]

[1]*Department of Entomology, Cornell University, New York State Agricultural Experiment Station, 630 W. North St. Geneva, New York 14456, USA,* [2]*Department of Entomology and Plant Pathology, Mississippi State University PO Box 9775, MS 39762*

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Abstract

One component of developing a systematic approach for deployment of trap crops is to understand how the trap crop modifies pest behavior. Glossy-leafed collards, *Brassica oleracea* L. var. *acephala* (Brassicaceae), were evaluated as a potential trap crop for diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae), because they are attractive to *P. xylostella* adults and are a poor host for *P. xylostella* larvae compared to cabbage, *Brassica oleracea* L. var. *capitata*. We used large field plots to measure the changes in adult, egg, and larval *P. xylostella* densities in cabbage when the trap crop was planted in the field. Furthermore, we planted the trap crop in dispersed and concentrated spatial arrangements to determine the impact of trap crop arrangement on the behavior of *P. xylostella*. In 2002, results showed that the presence of collards within a cabbage field reduced larval density on cabbage. In 2003, neither trap crop arrangement had a significant impact on *P. xylostella* larval density on cabbage. Adult moths aggregated in proximity to collards in 2002, but not in 2003. Egg and larval data in both years in all treatments showed that total oviposition was highest near a central release point, indicating that females lay many eggs before dispersing very far when suitable host plants are available. The mean direction of *P. xylostella* movement and oviposition from a central release point was not consistent or correlated to wind direction. Plant size of the trap crop in relation to the main crop and environmental factors may have been responsible for the inconsistent effectiveness of the trap crop.

Introduction

Diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae), is the most damaging insect pest of crucifers (Brassicaceae) worldwide (Talekar & Shelton, 1993). One of the factors that have enabled *P. xylostella* to cause so much damage is its ability to rapidly develop resistance to many classes of insecticides (Talekar & Shelton, 1993). To manage this pest in a more sustainable manner, multiple management practices that include non-chemical techniques should be developed. Trap cropping, the planting of a highly preferred plant in proximity to the main crop to reduce damage to the main crop (Hokkanen, 1991), is one technique that has shown some potential to reduce damage by *P. xylostella* in crucifers (Srinivasan & Moorthy, 1991; Charleston & Kfir, 2000; Mitchell et al., 2000). However, success has not been consistent (Silva-Krott et al., 1995; Luther et al., 1996; Shelton & Nault, 2004), possibly due to a lack of understanding of the mechanisms by which the trap crop influences oviposition behavior for this insect.

The first requirement of an effective trap cropping system is that the target pest prefers to oviposit in the trap crop rather than in the main crop (Hokkanen, 1991; Banks & Ekbom, 1999). For *P. xylostella*, glossy leaves (Eckenrode et al., 1986; Justus et al., 2000) and high concentrations of glucosinolates (Reed et al., 1989) are preferred leaf traits for oviposition. An additional desirable trap crop trait for

*Correspondence: Fred R. Musser, Department of Entomology & Plant Pathology, Mississippi State University, PO Box 9775, Mississippi State, MS 39762. E-mail: fm61@msstate.edu

pests like *P. xylostella*, which have a short generation cycle, is low larval survival. This trait reduces the buildup of large pest concentrations on the trap crop that could migrate into the main crop (McPherson & Newsom, 1984; Todd & Schumann, 1988). In laboratory and screenhouse studies in New York, (Badenes-Perez et al., 2004) showed that *P. xylostella* prefer to oviposit on glossy varieties of collards (*Brassica oleracea* L. var. *acephala*) up to 300 times more than on cabbage. Because *P. xylostella* larval survival is also low on glossy varieties of collards (Stoner, 1990) and because collard production is compatible with the agronomic practices of cabbage production, we selected a glossy variety of collards for our trials.

The placement and quantity of the trap crop in the field are other aspects of trap cropping that need to be understood to maximize oviposition on the trap crop. The primary factors to consider when placing the trap crop in relation to the main crop are the anticipated source of pests and their movement patterns for oviposition. The source of pests could lead to placing the trap crop on one side of the field if pests are expected to come from one direction. For *P. xylostella*, the initial source of moths has been difficult to predict based on long-distance and field-to-field migration studies (Shirai & Nakamura, 1994; Chapman et al., 2002). Furthermore, in studies of directional movement, no relation to wind or other directional forces have been documented (Shirai & Nakamura, 1994; Mo et al., 2003). However, directional movement in a homogeneous environment merits further investigation because none of these studies were conducted in a single field of uniform crop maturity. Banks & Ekbom (1999) showed that less damage occurred on the main crop as the proportion of the trap crop increased. However, the benefits incurred from a large trap crop area must be balanced with the economic pressure to produce a marketable crop on as much land as possible. In general, trap crops occupy less than 10% of the land area (Hokkanen, 1991).

Local movement patterns have been studied for some crucifer herbivores, but to our knowledge, not for *P. xylostella*. Root & Kareiva (1984) found that *Pieris rapae* (L.) (Lepidoptera: Pieridae) females lay a single egg on a plant and then typically fly over four or more host plants before ovipositing again. Furthermore, they tend to fly in a rather linear fashion and show no change in flight behavior when they encounter a field edge. Therefore, an effective trap crop arrangement for *P. rapae* may be to plant trap crop plants throughout the field. In contrast, Hokkanen et al. (1986) showed that *Meligethes aeneus* F. (Coleoptera: Nitidulidae) damage in cauliflower was minimized by arranging the trap crop as a series of concentrated patches between the main crop and a known source location, effectively preventing the insect from reaching the main crop. In this case, the trap crops were planted outside the cauliflower field. The movement and oviposition behavior of *P. xylostella* will determine which spatial arrangement of the trap crop will be most effective. If *P. xylostella* behaves as *P. rapae*, the ideal arrangement of trap crops may be uniformly dispersed throughout the field. However, if *P. xylostella* behaves more like *M. aenus*, a concentrated patch or border of trap crops between the cabbage field and the source of *P. xylostella* may be the best arrangement.

The objectives of this study were to evaluate the effectiveness of various spatial arrangements of glossy collards as a trap crop for *P. xylostella* in cabbage, and to better understand the local movement of *P. xylostella* in these arrangements so that an appropriate spatial arrangement of trap crops in a cabbage field could be identified.

Materials and methods

Field trials were conducted in 2002 and 2003 on Cornell's New York State Agricultural Experiment Station Fruit and Vegetable Research Farm in Geneva, NY. A circular plot design was used both years with different arrangements of the trap crop to collect data on *P. xylostella* adult, egg, and larval distributions. In both years, plots were conventionally tilled, with fertilizer and herbicides applied according to current recommendations (Reiners et al., 2003). Cabbage and collards were transplanted in 76 cm rows with 76 cm spacing between plants within a row. This spacing was used to eliminate any bias of row-to-row movement vs. movement within a row. At least 50 m separated each plot from other crucifers.

Plot design in 2002

There was one trap crop treatment and a control in a randomized complete block design replicated three times. All plants within each treatment were transplanted in circular plots (radius 24.4 m) around a central release point in fields that were 0.24 ha. The trap crop treatment consisted of three concentric rings of glossy 'Green Glaze' collards, while the remainder of the field was 'Bobcat' cabbage (Figure 1A). The control was 'Bobcat' cabbage only. The trap crop was arranged in circles so that directional dispersal could be monitored without any bias due to the placement of the trap crops. Each ring of collards was 2.3 m wide (three rows) with 6.9 m (nine rows) of cabbage between the rings of collards, so the trap crop represented 26% of the plants in the plot. Adult *P. xylostella* were released from the center of the plot, which was surrounded by an area (3-m radius) of bare ground. The nearest plants to the release point in the trap crop treatment were collards in the inner trap crop ring. Plots were transplanted between June 20 and July 10, 2002,

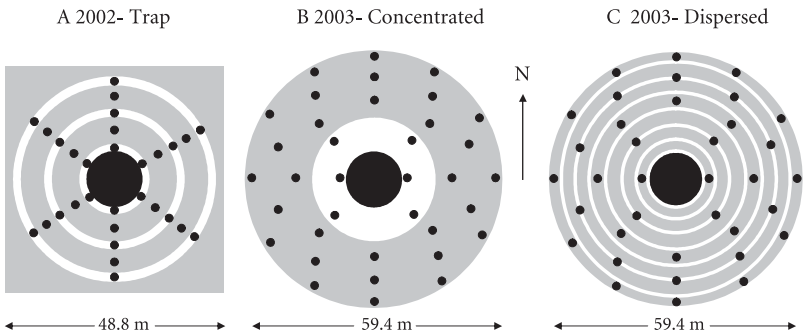

Figure 1 Layout of trap crop plots and adult traps. Gray and white areas represent cabbage and collards, respectively. The black area in the center of each plot represents bare ground where *Plutella xylostella* moths were released. Small black dots are the locations of the adult sticky traps. Control plots (not shown) were similarly designed, but contained only cabbage. Sticky traps were placed in the same arrangement in the control as in the trap crop plots both years.

blocked by replicate. The cabbage seedlings had been grown outside for 7 weeks prior to transplanting. Collards were seeded in a greenhouse on April 2, transplanted into 15 cm plastic pots, and then grown outside until transplanting. As a result, the collards were larger than the cabbage when transplanted and remained larger than the cabbage throughout the growing season. Both cabbage and collards were free of *P. xylostella* before transplanting.

Plot design in 2003

Because the trap crop arrangement appeared successful in 2002, we decided to explore the mechanism at work more thoroughly in 2003 by using two different trap crop arrangements. Two trap crop arrangements ('concentrated' and 'dispersed') were evaluated in 2003 following a similar experimental approach used in 2002, planting trap crops in circles around a central release point. However, plot size was increased in 2003 because *P. xylostella* readily reached the edge of our plots in 2002. Each plot was 0.37 ha with a radius of 29.7 m from the release point to the edge of the plots. The trap crop was the same glossy 'Green Glaze' variety as used in 2002, but the cabbage variety was changed to 'Huron' because 'Bobcat' seed was unavailable. In 2003 there were two trap crop treatments and a control arranged in a randomized complete block design with three replicates. In both trap crop treatments, 18% of the total plants in the field were collards, a percentage that previous work indicated would allow for treatment effects to be manifest if treatments were to have any effect at all. The 'concentrated' treatment (Figure 1B) had one 9.9-m-wide ring of collards (13 rows) around a central release point within a cabbage field. This arrangement was chosen to mimic placing the trap crop as a border around the field when moths arrive from outside the field. In contrast, the 'dispersed' treatment (Figure 1C) had seven 0.8-m-wide concentric rings (one row each) around a central release point with 3.8 m of cabbage (five rows) between the collard rings. The control plot was cabbage only around a central release point. Plots were transplanted between May 21 and June 18, 2003, blocked by replicate. Cabbage and collard seedlings had been grown in a greenhouse for 6–7 weeks prior to transplanting and were free of *P. xylostella*. Unlike in 2002 when collards were larger than cabbage at transplanting, both cabbage and collards were the same age and approximately the same size at transplanting in 2003. This modification substantially reduced the labor requirement of transplanting large plants and was a more commercially feasible method of transplanting trap crops.

Plutella xylostella releases

A population of *P. xylostella* was created by crossing field populations obtained from Georgia in the early spring of 2002 and 2003 with a laboratory colony (Geneva 88) and rearing them on artificial diet in 473 ml styrofoam cups with lids (Shelton et al., 1991). After pupation, lids containing the pupae were removed and placed in a clear plastic bin ($26 \times 32 \times 10$ cm) so that each bin contained approximately 2000 pupae. A 5% sugar solution in a flask with a dental wick was also placed in the bin as a food source. After most moths had emerged, the bin was placed at the central release point of each plot and opened 1–4 h before sunset. Release dates in both years were blocked by replicate. In 2002 the first insect release was between July 1 and July 16, the second release was between August 5 and 12, and the third release was on September 9. In 2003 the first insect release was between June 19 and July 9, and the second release was between July 30 and August 13. Periodically, up to 600 larvae were reared to adulthood to estimate the sex ratio of the released population; the ratio was always approximately 1 : 1. Fields were sprayed with insecticides approximately 7 days before the second and third insect releases to reduce *P. xylostella* and other pest populations in these fields. In 2002, *Bacillus thuringiensis*, var. *kurstaki* (Dipel 2X) and esfenvalerate (Asana XL) were sprayed at labeled rates before the second and third releases, respectively. In 2003, esfenvalerate was sprayed before the second release. There were no phytotoxic effects from these sprays, nor is there any reason to suspect any

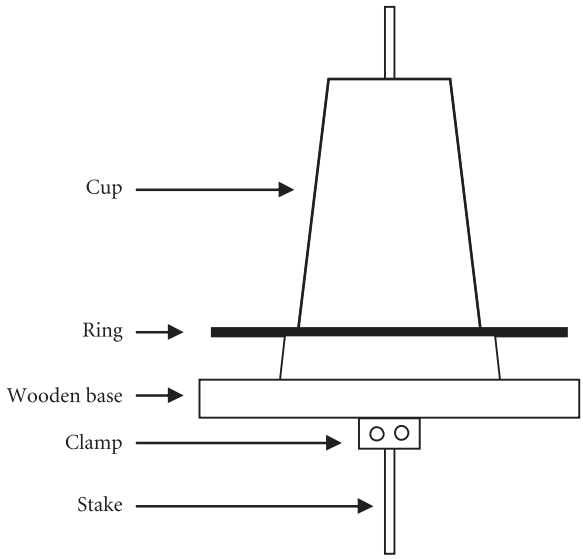

Figure 2 Diagram of adult sticky trap. The outside of the cup above the ring and the upper side of the ring were covered with Tangle-Trap Insect Trap Coating (Tanglefoot Company, Grand Rapids, MI). Trap height was adjusted with the clamp so that the wooden base was always approximately 5 cm above the top of the plant canopy.

sublethal effects from insecticide residues on the subsequent moth releases.

Adult movement assessment

Adult movement was monitored after the September release in 2002 and after both releases in 2003 to understand the rate and direction of movement in a way that could not be determined from the larval monitoring. Adults were monitored using a sticky trap made from a 473 ml white styrofoam drinking cup turned upside down (Figure 2). A white plastic ring, 14 cm outside diameter and 8.5 cm inside diameter, was placed over the cup so that it rested on the thickest part of the cup near the lip. Both the outside of the cup and the upper side of the plastic ring were coated with Tangle-Trap Insect Trap Coating (Tanglefoot Company, Grand Rapids, MI). These traps, modified from the design described by Mo et al. (2003), were placed on fiberglass stakes containing a 10×10 cm wooden platform. Trap height was controlled by a clamp under the wood and adjusted so that the bottom of the trap was approximately 5 cm above the top of the plant canopy. Traps were placed in the field 1–2 days before the insect releases to monitor background populations of *P. xylostella* and then were changed at the time of release and 1, 3, and 5 days after the moths were released. Traps were returned to the laboratory where the number of *P. xylostella* on each trap was recorded. In 2003, the sex of each captured adult was also determined.

In 2002 traps were placed at five distances (3.8, 8.4, 13.0, 17.5, and 22.1 m) in six directions (0, 60, 120, 180, 240, and 300° from north) from the central release point (Figure 1A). Traps at 3.8, 13.0, and 22.1 m were placed over collards in the trap crop treatment while the other traps were placed over cabbage. In 2003, traps were placed at five distances from the release point (5.3, 11.0, 16.8, 22.5, and 28.2 m) as shown in Figure 1B,C during both releases. In both the concentrated and dispersed treatments, traps at two distances were over collards and three distances were over cabbage.

Egg density assessment

Egg densities were assessed in 2003, but not in 2002. Cabbage and collard plants were sampled for *P. xylostella* eggs 7 days after moths were released. Plants were cut at ground level and both surfaces of each leaf were examined for *P. xylostella* eggs using a low-power magnifying lens in the laboratory. After the first release, a total of 68 plants per plot were examined from plants at eight distances from the release point, collected in proportion to the total number of plants at each distance (e.g., two plants were collected 3.8 m from the release point and 15 plants were sampled 28.2 m from the release point). After the second release, 35 plants per plot were examined from the same eight distances, again in proportion to the total number of plants at each distance. In all sampling, individual plants at each distance were chosen at specific locations so that the direction of insect movement could be analyzed.

Larval density assessment

Plutella xylostella larvae and young pupae (hereafter collectively called larvae) were counted 14–20 days after the first and second releases in both years. After the first release in both years, larvae were counted on 20% of the plants found at specified distances from the release point. After the second release in both years, 20% of the plants were sampled at the shortest distances from the release point, while 10% of the plants were sampled at the remaining distances due to time limitations. In 2002, collards were sampled from the inner and outer edge of each ring (six distances total) and cabbage was sampled from the inner, middle, and outer parts of each ring (six distances total). Cabbage plants at the same distances from the release point were sampled in the cabbage control (12 distances total). In 2003 samples were collected at 10 distances from the release point. All samples were collected in cabbage with the exception of the shortest three of the 10 distances in the concentrated treatment, which were in collards. Sampling after the first release in both years consisted of a non-destructive visual examination of the entire plant, recording the number of *P. xylostella* larvae. Sampling

after the second release was a destructive examination of each leaf of the plant in the field, recording the same information as after the first release. In all sampling, individual plants at each distance were chosen at specific locations so that the direction of insect movement could be analyzed.

Data analysis

The primary objective in our analysis was to determine the impact of the trap crop treatments on the density of *P. xylostella*. A second objective was to examine the rate and distance at which *P. xylostella* adults oviposit and disperse from a central release point. The impacts of the trap crop treatment and distance from the release point on total eggs and larvae were assessed using PROC MIXED (SAS Institute, 1999). In this model, an autoregressive covariance structure grouped over the treatment was used to analyze the counts collected at different distances (repeated measures) within the same plot. Each release in each year was analyzed separately. Only distances that had common plant species in a treatment were used within an analysis (e.g., comparing the overall impact of treatments on adult trap capture in cabbage, only 2002 counts from traps placed 16.8 m and 28.2 m from the release point were used as these were the only distances to have cabbage in both treatments). The sum of all *P. xylostella* collected at a common distance from the release point was used as the sample unit. This was possible because the same percentage of plants was sampled at each distance, enabling us to estimate the total number of *P. xylostella* at each distance.

The significance of treatment, days after release, and distance from the release point on the number of moths captured on sticky traps also were estimated using PROC MIXED (SAS Institute, 1999). Both days after release and distance from the release point were repeated measures. However, the model seldom converged using a compound covariance structure, so an autoregressive covariance structure grouped over treatment on each day was used. The sample unit was the sum of all samples collected at a common distance in a day. In all analyses, logarithms of the sample unit were used to equalize variance, and a factor was considered significant when it had a P-value <0.05.

Although individual insects do not passively diffuse into an environment, the dispersal of many insect populations can be adequately described with the equations developed to describe diffusion (Kareiva, 1982, 1983; Rudd & Gandour, 1985; Firle et al., 1998; Turchin, 1998; Hannunen & Ekbom, 2001). Insect dispersal of active flyers is best modeled by diffusion when the environment is relatively homogeneous (Turchin, 1998). Because flight behavior of males and females are known to differ for *P. xylostella* (Goodwin & Danthanarayana, 1984; Begum et al., 1996), diffusion was modeled separately for males and females for the control plots only. Diffusion rates were calculated according to the equation

$$u(r,t) = N_0/(4\pi Dt)\exp[-r^2/(4Dt)]$$

where u is the density at distance r in meters from the release point at time t in days. D is the diffusion rate and N_0 is the number of released insects (Kareiva, 1982; Turchin, 1998). $N_0 = 1000$ was used to calculate diffusion rates for each gender. A higher diffusion rate indicates more rapid dispersal from the release point. The diffusion rate (D) for each gender in each replicate in each release was estimated using PROC NLIN (SAS Institute, 1999). PROC GLM (SAS Institute, 1999) was then used to determine if the estimated diffusion rates varied by gender, replicate, or release. Diffusion rates were log transformed to equalize variance.

To test if *P. xylostella* adults disperse and oviposit equally in all directions from the release point, the Rayleigh test (Batschelet, 1981; Zar, 1996) was used on adult, egg, and larval data. Trap crop treatments were placed in concentric rings around the release point so that they would not influence dispersal direction. Therefore, all treatments from the same replicate were pooled for directional analysis. Because replicates were blocked by the time moths were released, each replicate was analyzed separately. Wind data from a weather station within 2 km of all the plots were used to test for any correlation between insect movement and wind direction. Because *P. xylostella* are known to be most active between sunset and midnight (Harcourt, 1957; Goodwin & Danthanarayana, 1984), mean wind direction from these hours only were used in the analysis. Egg, larva, and adult data from all replicates in both years were analyzed together to test for a circular–circular correlation between wind direction and *P. xylostella* dispersal using rank correlation (Batschelet, 1981).

Results

Trap crop effectiveness

Fewer moths were captured above cabbage plants in the trap crop treatment than on the respective traps in the control in 2002 ($F_{2,4} = 12.1$, $P = 0.025$) (Figure 3A). However, this trend did not occur in 2003 (first release: $F_{2,4} = 0.57$, $P = 0.606$; second release: $F_{2,4} = 1.80$, $P = 0.277$) (Figure 3B). Similarly, more moths were captured over collards than on the respective traps in the control in 2002 ($F_{1,2} = 49.3$, $P = 0.020$) (Figure 3C), but not in 2003 (first release: $F_{2,4} = 1.15$, $P = 0.403$; second release: $F_{2,4} = 1.96$, $P = 0.255$) (Figure 3D).

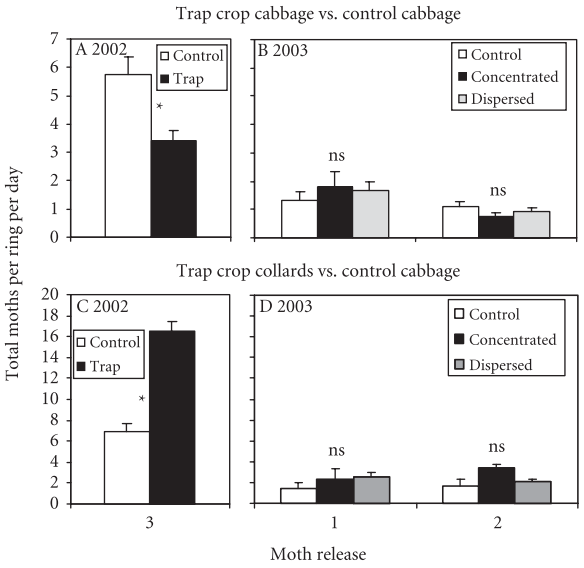

Figure 3 Comparison of back-transformed least squared means (+SEM) of *Plutella xylostella* adults on traps placed over: cabbage in the trap crop treatments vs. similarly placed traps in the control in (A) 2002 and (B) 2003; collards in the trap crop treatments vs. similarly placed traps in the control in (C) 2002 and (D) 2003. ns: P>0.10, *P<0.05.

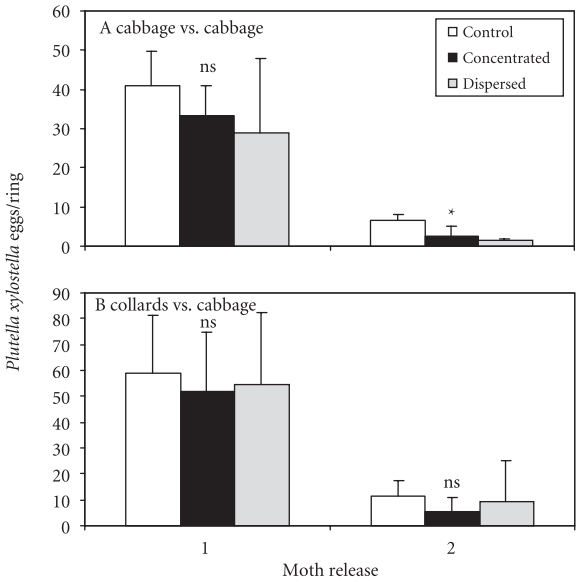

Figure 4 Comparison of back-transformed least squared means (+SEM) of *Plutella xylostella* eggs in 2003 on (A) cabbage in the trap crop treatments vs. similarly placed cabbage in the control, and (B) collards in the trap crop treatments vs. similarly placed cabbage in the control. ns: P>0.10, *P<0.05.

Plutella xylostella egg densities were significantly lower on the cabbage in the dispersed treatment than on the equivalent plants in the control only after the second release in 2003 ($t_4 = 4.10$, P = 0.015) (Figure 4A). No other treatment differences in cabbage were observed for egg densities after either release. Surprisingly, there was no evidence of increased oviposition on the collards within the dispersed or concentrated treatments after either release compared to the equivalent cabbage plants in the control (first release: $F_{2,4} = 0.04$, P = 0.964; second release: $F_{2,6} = 0.43$, P = 0.669) (Figure 4B).

In 2002, the number of *P. xylostella* larvae found on cabbage in the trap crop treatment was marginally lower than the number found on the equivalent cabbage plants in the control after the first ($F_{1,2} = 5.26$, P = 0.149) and second ($F_{1,2} = 12.83$, P = 0.070) releases (Figure 5A). In 2003, larval densities on cabbage did not vary between the treatments after either release (first release: $F_{2,4} = 0.77$, P = 0.522; second release: $F_{2,2} = 2.01$, P = 0.333) (Figure 5B). Larval densities on collards were significantly or marginally lower than densities on the equivalent cabbage in the control after three of the four releases (2002 first release: $F_{1,2} = 13.54$, P = 0.067; 2002 second release: $F_{1,2} = 21.25$, P = 0.044; 2003 first release: $F_{1,2} = 8.51$, P = 0.100; 2003 second release: $F_{1,1} = 5.83$, P = 0.250) (Figures 5C,D).

Spatial and temporal patterns of *Plutella xylostella* activity

In both years, adult *P. xylostella* were caught in higher numbers near the release point than at further distances after 24 h, but catches became more uniform over distance after 3 and 5 days (Figures 6 and 7). The impact of collards on trap catches was similar over all days. Males were more likely to be captured on sticky traps than females, especially near the release point (Figure 7). While males comprised about half of the released insects, 76% of the adults caught on sticky traps were male, suggesting that male behavior makes them more likely to be captured on sticky traps. However, estimated male and female diffusion rates show that females (D = 57.4) have a higher dispersal rate than males (D = 18.3) ($F_{1,5} = 9.90$, P = 0.026).

Egg densities were highest near the release point in 2003 with slightly higher densities near the outer edge of the plot than in the middle of the plot resulting in both meters and meters squared being significant factors (meters: $F_{1,40} = 27.49$, P<0.001; meters^2: $F_{1,40} = 30.22$, P<0.001) (Figure 8). Larval densities showed a similar trend in 2002 (meters: $F_{1,46} = 17.87$, P<0.001; meters^2: = 12.41, P = 0.001) (Figure 9A). In 2003 this trend appeared in the control and dispersed treatments, but not in the con-

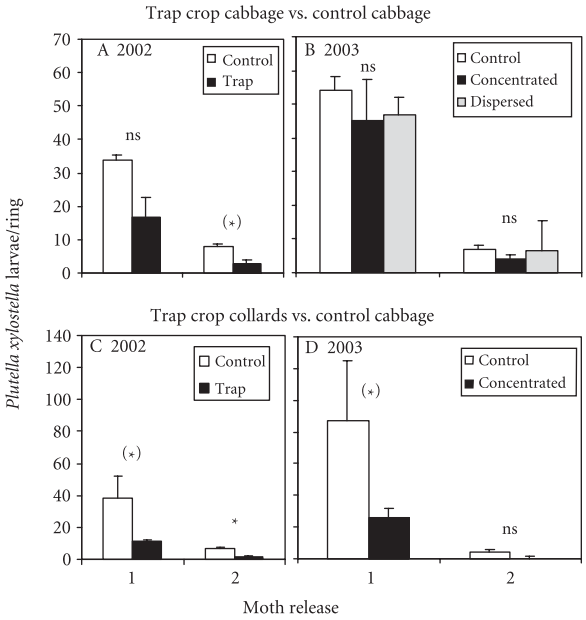

Figure 5 Comparison of back-transformed least squared means (+SEM) of *Plutella xylostella* larvae on: cabbage in the trap crop treatments vs. similarly placed cabbage in the control in (A) 2002 and (B) 2003; collards in the trap crop treatments vs. similarly placed cabbage in the control in (C) 2002 and (D) 2003. ns: >0.10, (*)0.10≥P≥0.05, *P<0.05. Note: No collards were evaluated in the dispersed treatments.

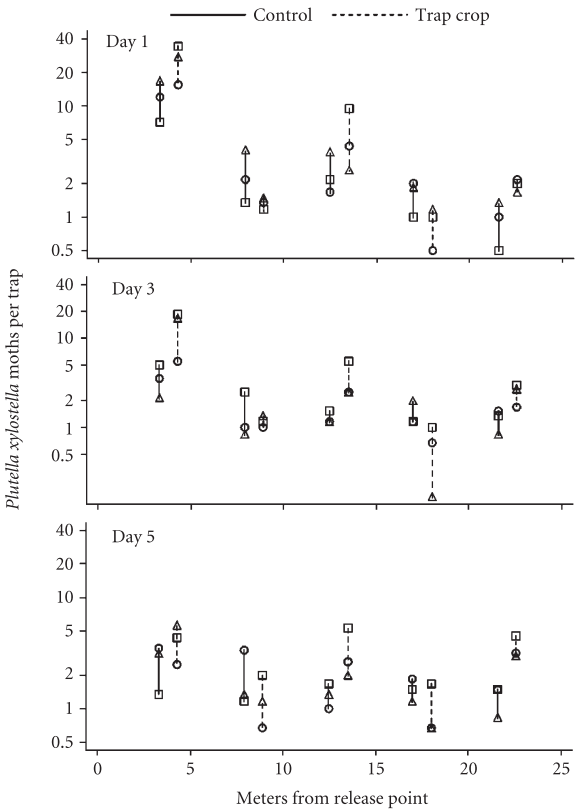

Figure 6 Adult *Plutella xylostella* caught on sticky traps 1, 3, and 5 days after the third release in 2002. Data for control and trap crop treatments are joined by lines that, for clarity, are offset ±0.5 m along the x-axis. Symbols represent replicates. Traps at 3.8, 13.0, and 22.1 m were over collards in the trap crop treatment. All other traps were over cabbage.

centrated treatment, resulting in a significant interaction between treatment and distance from the release point (treatment*meters: $F_{2,48} = 5.02, P = 0.011$; treatment*meters^2: $F_{2,48} = 4.79, P = 0.013$) (Figure 9B). Treatment-by-distance interactions were not significant for larvae in 2002 or for eggs in 2003. Because several adult *P. xylostella* were found on traps prior to the second releases that may have laid eggs, the distribution of eggs and larvae after the second release was used to compare treatment impacts, but not to estimate the distribution of *P. xylostella* over distance from the release point.

Due to the high power obtained from many counts of adults, eggs, and larvae, the Rayleigh test, which was used to determine if dispersal was uniform in all directions, was often statistically significant (P<0.05). However r, a measure from zero to one (0 = uniform dispersal in all directions, 1 = all insects disperse in one direction) that indicates the strength of the directionality was never higher than 0.34 and was generally less than 0.2, indicating that *P. xylostella* dispersal was not strongly oriented in any direction (data not shown). Wind is the most likely factor to influence adult directional movement as it influences the direction from which the moths perceive plant volatiles (Banks et al., 1988; Evans & Allen, 1994). Mean wind speed was 8.4 km h^{-1}. However, there was no correlation between the mean angle of insect movement and mean wind direction (r = 0.07).

Discussion

The use of glossy collards as a trap crop within a cabbage field reduced the larval infestation of *P. xylostella* in cabbage in 2002. Moreover, unlike some trap crops that harbor large pest populations that can potentially later infest the main crop (Hokkanen, 1991), *P. xylostella* larval populations were smaller on glossy collards than on cabbage, resulting in reduced total *P. xylostella* larval populations in the trap crop treatment than in the control. While collards showed potential as a pest management option in 2002, this trap crop did not reduce *P. xylostella* larval populations in 2003. This lack of reliability is consistent with the

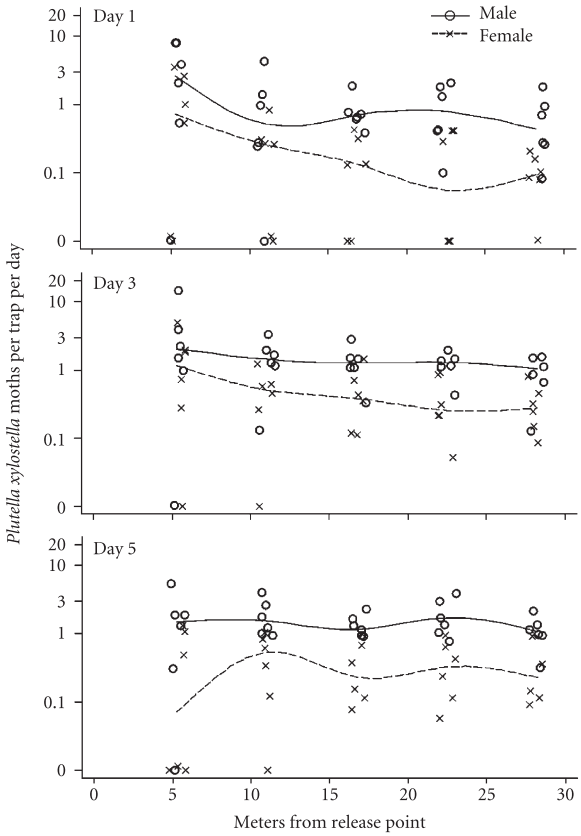

Figure 7 Male and female *Plutella xylostella* caught on sticky traps 1, 3, and 5 days after both releases in 2003 in cabbage alone (control) plots. Data were jittered (2%) for clarity. Lines are median-bands connected using cubic splines.

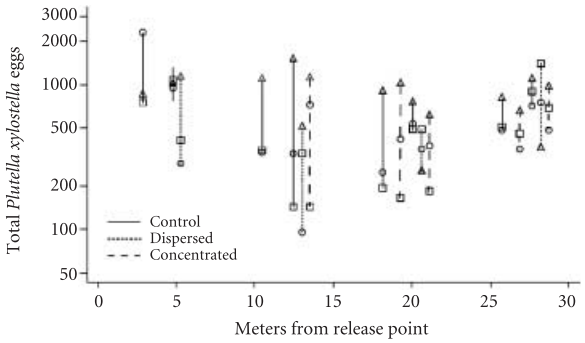

Figure 8 Total estimated *Plutella xylostella* eggs on cabbage in relation to distance from the release point after the first release in 2003. Each symbol represents a replicate and replicates of the same treatment are joined by vertical lines. Control and concentrated treatment groups are offset by 0.25 m along the *x*-axis. There are fewer points shown for the concentrated and dispersed treatments compared with the control as eggs counted on collards are not shown. Note: Total eggs are estimated from the number of eggs per plant at each distance times the number of plants at each distance (one plant in width).

variable results of trap cropping for *P. xylostella* in the literature (Srinivasan & Moorthy, 1991; Silva-Krott et al., 1995; Luther et al., 1996; Charleston & Kfir, 2000; Mitchell et al., 2000; Shelton & Nault, 2004) and points to the need for a better understanding of *P. xylostella* movement and oviposition site selection.

There were several differences in the experimental design between the 2002 and 2003 experiments that may have contributed to the variable effectiveness of the collard trap crop. In 2002, the collards were larger than the cabbage (collard plant diameter/cabbage plant diameter = 1.4 after release 1 and 1.3 after release 2) while in 2003 the collards were approximately the same size as the cabbage (collard plant diameter/cabbage plant diameter = 0.8 after release 1 and 1.0 after release 2). *Plutella xylostella* tend to lay more eggs on larger plants than on smaller plants of the same species (Pilson, 1996; Badenes-Perez et al., 2005), so the larger size of the trap crop plants used in 2002 may have made them more effective than those used in 2003. Additionally, the percentage of the field planted in trap crop was reduced from 26% in 2002 to 18% in 2003 and this may have influenced our results. While Banks & Ekbom (1999) showed that a lower percent will reduce the effectiveness of the trap crop, it should be noted that both percentages we used were far above the typical 10% of area devoted to trap crops (Hokkanen, 1991).

In addition to the planned changes between years, there were several unplanned differences between 2002 and 2003. Flea beetles [*Phyllotreta cruciferae* (Goeze) (Coleoptera: Chrysomelidae)] were not a problem in 2002, but immediately after transplanting in 2003, the leaf area of collards, and possibly the attractiveness of the collards to *P. xylostella*, were reduced by a large infestation of flea beetles that preferentially fed on the collards, while causing little damage to the adjacent cabbage. Flea beetles are known to preferentially feed on glossy leaves over waxy leaves (Stoner, 1990; Eigenbrode et al., 2000). While Pilson (1996) showed that flea beetle feeding did not alter *P. xylostella* behavior, flea beetles consumed <22% of the leaf area in her study, while we estimate consumed collard leaf area at the time of the first release in our study to have been >50% in some replicates. Plant volatiles were not measured, but insect feeding often induces plant defenses, which can alter the volatile profile of a plant (Alborn et al., 1997; Karban & Baldwin, 1997). Therefore, it is possible that the substantial feeding damage to the trap crop in 2003 made it less attractive to *P. xylostella* moths after the first release, thereby reducing ovipositional preference for collards over cabbage. Rainfall during the

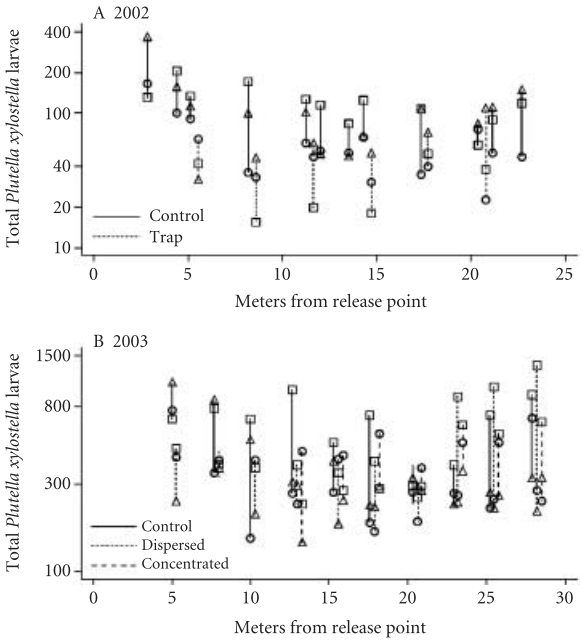

Figure 9 Total estimated *Plutella xylostella* larvae on cabbage in relation to distance from the release point after the first releases in (A) 2002 and (B) 2003. Each symbol represents a replicate and replicates of the same treatment are joined by vertical lines. Control and concentrated treatment groups are offset by 0.25 m along the *x*-axis. There are fewer points shown for some trap crop treatments compared with the control as larvae counted on collards are not shown. Note: Total larvae are estimated from the number of larvae per plant at each distance times the number of plants at each distance (one plant in width).

2002 trial was below average to normal, but above average in 2003. During the second release in 2003, daily rainfall caused some fields in the study to be partially flooded for several days. Rain can reduce adult movement and oviposition (Talekar et al., 1986; Holyoak et al., 1997). Furthermore, plant volatile expression levels vary and have been shown to be higher when plants are under stress (Schmelz et al., 2003). Because environmental conditions in the 2 years were different, the relative levels of plant volatile expression between cabbage and collards may have also varied, making the collards more attractive than cabbage to *P. xylostella* in 2002 but not in 2003. The flooding was not uniform in all fields, so this uncontrolled factor may have biased the egg and larval data during this release. More specifically, the field containing the dispersed treatment was better drained than the fields containing the concentrated and control treatments in two of the three replicates. As rainfall and associated drowning have been shown to be major mortality factors for *P. xylostella* (Harcourt, 1986; Wakisaka et al., 1992), there may have been higher egg and larval survival rates in the dispersed treatment than in the other treatments after this release, thereby reducing the measured effectiveness of the dispersed treatment after the second release.

One of the objectives of this study was to determine whether higher oviposition rates in collards could be achieved by arranging the trap crop as a concentrated patch or as a series of dispersed patches. Because the trap crop did not significantly alter *P. xylostella* infestation levels in either arrangement, we have no evidence that one arrangement was more effective than the other. However, it is unlikely that a trap crop placed only around the perimeter of commercial cabbage fields will provide season-long control of *P. xylostella* because moths were not permanently arrested in the inner ring of collards in 2002 nor were they arrested in the concentrated arrangement in 2003.

Field plots in our study were larger than those in other replicated trap cropping studies (Luther et al., 1996; Charleston & Kfir, 2000; Asman, 2002) and may have influenced ovipositional patterns. Some adults rapidly dispersed to all distances within the field, but uniform distribution over the entire plot was not attained until 4–5 days after their release. While males were more likely to be captured on the sticky traps, females tended to disperse at a higher rate. This may indicate a higher level of plant-to-plant movement by males searching for females, while female movement is comprised of fewer longer-distance flights. Some females are able to oviposit within 1 day after adult emergence (Pivnick et al., 1990), as evidenced by the large number of eggs that were laid within a few meters of the release point in our study. A concentration of eggs near the emergence site would indicate minimal genetic mixing of the population, but there is enough long-distance dispersal by *P. xylostella* to minimize the development of localized populations (Caprio & Tabashnik, 1992).

While our plot sizes were adequate for monitoring adult dispersal for a few days, they were not adequate for measuring the total trivial flight distance during the entire oviposition period. The higher egg and larval densities observed near the edge of the plots (Figures 8 and 9) likely indicate that *P. xylostella* dispersed to the edge of the plot and then tended to accumulate there. It is also possible that part of this 'edge effect' was from wild-type *P. xylostella* that immigrated into our plots. However, the wild populations during the first releases were nearly absent, so it is likely that most of the edge effect was from the retention of released insects.

While this study was conducted with glossy collards, it appears that *Barbarea vulgaris* is even more attractive to *P. xylostella* than glossy collards (Badenes-Perez et al., 2004). In small-scale screenhouse studies, Badenes-Perez et al. (2004) found that while both crucifer species were more attractive to *P. xylostella* than cabbage, moths preferred

B. vulgaris to glossy collards in a multichoice test. Other advantages of *B. vulgaris* are that *P. xylostella* larvae do not survive on it (Badenes-Perez et al., 2004; Shelton & Nault, 2004) and flea beetles do not feed on it (Nielsen, 1997; Renwick, 2002). Deploying *B. vulgaris* as a trap crop may be problematic, however, because there is more potential for it to become a weed and there is no potential to market it, unlike collard greens. Therefore, further work is needed to compare the entomological, horticultural, and economical costs and benefits of these two trap cropping alternatives.

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