Evaluating Trap Crops for Diamondback Moth, *Plutella xylostella* (Lepidoptera: Plutellidae)

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ABSTRACT Potential trap crops for the diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae), were evaluated through a series of ovipositional preference and larval survival experiments in outdoor screenhouses in 2002 and 2003. Hosts examined as trap crops were glossy and waxy collards, *Brassica oleracea* L. variety *acephala*; Indian mustard, *Brassica juncea* (L.) Czern; and yellow rocket, *Barbarea vulgaris* (R. Br.) variety *arcuata*. More eggs were laid on the potential trap crops, with the exception of waxy collards, than on cabbage. When *P. xylostella* was offered multiple hosts at the same time, numbers of eggs laid on glossy collards, Indian mustard, and yellow rocket were 3, 18, and 12 times greater than on cabbage, respectively. Similarly, when *P. xylostella* was offered a single trap crop host and cabbage, numbers of eggs laid on glossy collards, Indian mustard, and yellow rocket were 300, 19, and 110 times greater than on cabbage, respectively. Our studies suggest differences in oviposition between the potential trap crops and cabbage were likely due to host volatiles, leaf morphology and color, or a combination of these factors, rather than to total leaf areas, leaf shape, or plant architecture. Two-choice tests with a Y-tube olfactometer indicated that plant volatiles were major factors in *P. xylostella* host preference. The percentage larval survival from egg to pupation was 22.2% on cabbage, 18.9% on waxy collards, and 24.4% on Indian mustard, whereas survival was significantly lower on glossy collards (6.7%) and yellow rocket (0%). Based on our tests, it seems that yellow rocket may be the best candidate for use as a trap crop for *P. xylostella* because it is highly attractive for oviposition, but larvae do not survive on it.

KEY WORDS *Plutella xylostella*, trap crop, glossy and waxy collards, Indian mustard, yellow rocket

THE DIAMONDBACK MOTH, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae), is the most destructive insect pest of crucifers throughout the world (Talekar 1992) and has a history of becoming resistant to most insecticides used to control it (Talekar and Shelton 1993). Insecticide resistance and environmental and health concerns have triggered a growing interest in alternative management techniques such as trap crops (Talekar and Shelton 1993, Hooks and Johnson 2003). Despite having been used for decades (Talekar and Shelton 1993), trap crops proposed for *P. xylostella* control still remain unreliable, preventing growers from being more open to trying this cultural technique (Banks and Ekbom 1999). For example, the two most commonly proposed trap crops for *P. xylostella,* Indian mustard, *Brassica juncea* (L.) Czern and collards, *Brassica oleracea* L. variety *acephalla,* have been proclaimed as successful (Srinivasan and Krishna Moorthy 1992, Mitchell et al. 2000, Åsman 2002) as well as unsuccessful trap crops (Silva-Krott et al. 1995, Luther et al. 1996, Bender et al. 1999, Shelton and Nault 2004). These contradictory results may be due to different deployment strategies, insect behavioral patterns, or other factors, but they indicate that a lack of fundamental knowledge about trap crop management for *P. xylostella* exists.

Another trap crop that has been suggested for *P. xylostella* control is yellow rocket, *Barbarea vulgaris* (R. Br.) variety *arcuata,* a biannual weed that occurs in temperate regions worldwide (MacDonald and Cavers 1991). Yellow rocket has been shown to be very attractive to *P. xylostella* despite not sustaining the development of its larvae (Idris and Grafius 1994, 1996; Shelton and Nault 2004). Yellow rocket was first suggested as a trap crop for flea beetles (Root and Tahvanainen 1969) and later for *P. xylostella* (Idris and Grafius 1994).

An important quality for a trap crop to be effective is that it must be more attractive to the pest as either a food source or oviposition site than the main crop. Unless the immature stages of the insect pest die before reaching the adult stage, insect pest movement from the trap crop to the main crop is likely to occur later in the season. In many phytophagous insects and particularly in Lepidoptera, immature stages have limited mobility, so their survival is profoundly influenced by the female decision on what host to choose for oviposition (Renwick 1989). If the trap crop were a poor host for the pest, it would serve as a sink rather than a source for subsequent generations. This situation has been termed "dead-end" trap cropping, and research has indicated that yellow rocket may fit this definition for *P. xylostella* (Shelton and Nault 2004).

Understanding why trap crops work requires identifying the basic mechanisms by which insects prefer them to other possible hosts. Insects are particularly attracted to certain plants because of chemical (olfactory/gustatory) and/or physical (tactile/visual) stimuli (Thompson and Pellmyr 1991, Bernays and Chapman 1994). In *P. xylostella* and other crucifer specialists, glucosinolates and their volatile hydrolysis products seem to be the main attractants and oviposition stimulants (Reed et al. 1989, Pivnick et al. 1994, Renwick 2002). Besides plant volatiles, *P. xylostella* also seems to rely on vision and mechanoreception for host recognition and oviposition (Gupta and Thorsteinson 1960, Tabashnik 1985, Spencer et al. 1999). *P. xylostella* also has been shown to prefer ovipositing on glossy (shiny green with reduced surface wax) compared with waxy (lighter in color and with more wax bloom) cultivars of cabbage, canola, and rapeseed (Eigenbrode et al. 1991, Justus et al. 2000, Ulmer et al. 2002). Besides a higher ovipositional preference for glossy over waxy cultivars, little is known about the main factors involved in ovipositional preference across acceptable hosts. For host recognition, *P. xylostella* most likely uses chemical and physical cues to segregate between the hosts it encounters and then ranks them regarding ovipositional preference. Knowing the main factors involved in ovipositional preference across hosts may help to determine the most promising trap crop.

The principal focus of this study was to compare *P. xylostella* ovipositional preference and larval survival between cabbage and four of its most commonly proposed trap crops: glossy and waxy collards, Indian mustard, and yellow rocket. Ovipositional preference comparisons were made between the potential trap crop host and cabbage to simulate a scenario that would occur if trap crops were deployed in cabbage fields. These comparisons were made in a multiple-choice manner, where potential trap crops were ranked by *P. xylostella* according to its ovipositional preference. We hypothesize that plant cues, including total leaf area, leaf shape, plant architecture, and plant volatiles, may be used by *P. xylostella* to discriminate and establish a hierarchical ovipositional preference among possible hosts, so these factors also were examined.

Materials and Methods

Experiments were conducted at the New York State Agricultural Experiment Station in Geneva, NY. *P. xylostella* used in all experiments originated from a colony collected in 2002 from a cabbage field in Camilla, GA, and maintained on a wheat germ-casein artificial diet (Shelton et al. 1991). For the olfactometer experiment, an additional *P. xylostella* population collected in 1988 in Geneva and maintained on the same diet was used. For the cabbage and trap crops tested, the following cultivars were used: 'Bobcat' cabbage (Reed's Seeds, Cortland, NY), 'Green Glaze' collards (Pennington Seed, Madison, GA), 'Green Wave' Indian mustard (Johnny's Seeds, Albion, ME), and G-type yellow rocket whose seeds were obtained from wild plants growing near Ithaca, NY. Seeds from 'Green Glaze' collards produced both the glossy and waxy phenotypes used in our experiments. Glossy and waxy collards and cabbage had similar leaf shape and plant architecture, whereas Indian mustard had a more erect plant architecture with very crinkly leaves and yellow rocket had pinnate leaves growing as a rosette. Yellow rocket, with its slower growth as a rosette, was seeded 2 wk before cabbage and collards to compensate for its smaller size. A uniform plant size is highly desired when using a mechanical transplanter, because it allows simultaneous transplanting of both cabbage and the trap crop. All plants were grown in 15-cm pots, first in the greenhouse and later outdoors (for at least 2 wk before starting the experiment). Plants were moved to screenhouses 24 h before releasing the moths. At the time *P. xylostella* adults were released, yellow rocket plants were 12 wk old, cabbage and collards plants were 10 wk old, and Indian mustard plants were 6 wk old (Indian mustard has a 6- to 7-wk crop cycle from seeding to blossom). Indian mustard plants were fertilized one time, 4 wk after seeding, whereas cabbage, collards, and yellow rocket plants were fertilized twice, 4 and 8 wk after seeding. Plants were fertilized with an all-purpose 15–30-15 fertilizer (Wilson Laboratories Inc., Springdale, CT).

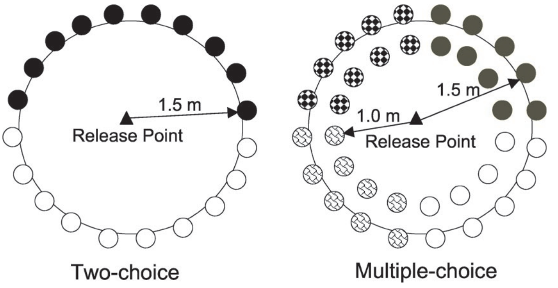

Fig. 1. Diagram of two-choice and multiple-choice experimental arenas to test ovipositional preference.

Ovipositional Preference Experiments Conducted in Screenhouses. Ovipositional preference experiments were conducted with *P. xylostella* in both a two-choice and a multiple-choice manner in outdoor screenhouses that were 3.2 m in width by 4.7 m in length and 2.5 m in height. Multiple screenhouses were used in these experiments, each of which was considered a replicate or block. All plants were positioned equidistantly around the center of the screenhouse arranging them in either two concentric circles of 1.0- and 1.5-m radii (multiple-choice test) or one circle of 1.5-m radius (two-choice test) (Fig. 1). For the multiple-choice test, nine plants of the same host were positioned in each of four 90° arcs of the two concentric circles; this arena was replicated six times. For the two-choice tests, 10 cabbage plants were positioned in one half of the circle and 10 trap crop plants in the other half; this arena was replicated four times for each comparison (cabbage versus glossy collards, cabbage versus waxy collards, cabbage versus Indian mustard, and cabbage versus yellow rocket).

A total of 30 and 54 *P. xylostella* adults (1.5 per plant) were released for each replicate in the two-choice and in the multiple-choice tests, respectively. Adults of *P. xylostella* were always <2 d old and were released in a 1:1 sex ratio from a plastic container placed on top of two cinder blocks (80 cm above ground) located in the middle of the screenhouse. A 50-ml Erlenmeyer flask with a 10% sugar solution and dental wick (Absorbal, Wheat Ridge, CO) was placed on top of the cinder blocks in each screenhouse for adult feeding. Two days after releasing the moths, all eggs on each plant were counted in the laboratory by using a microscope.

Relationship between Total Leaf Area and Number of Eggs Laid on Cabbage, Glossy and Waxy Collards, Indian Mustard, and Yellow Rocket. To determine whether a host's total leaf area was correlated with ovipositional preference, five plants of cabbage, glossy collards, waxy collards, Indian mustard, and yellow rocket were randomly selected from the multiple-choice oviposition experiment, and the total leaf area of each of these plants was measured by using a color image analysis system (model WinDIAS, Delta-T-Devices Ltd., Cambridge, England).

Ovipositional Preference Experiment Conducted in Plexiglas Tubes. To eliminate the influence that total leaf area may have on *P. xylostella* ovipositional preference for certain hosts, two-choice ovipositional preference tests were conducted by keeping leaf area constant among the hosts. Moths were offered only a 6.4-cm^2 circular disk of the lower side of one leaf of the host. Ovipositional preference was studied in eight pair comparisons: cabbage versus the four potential trap crops (glossy and waxy collards, Indian mustard, and yellow rocket), glossy versus waxy collards, glossy collards versus Indian mustard, glossy collards versus yellow rocket, and Indian mustard versus yellow rocket.

Tests were made in Plexiglas tubes 3.75 cm (interior diameter) by 12 cm (length). For each choice test, the ends of a single tube were attached to one leaf of each of two plants with rubber bands. One mated female was placed in each tube. Tubes had a 0.5-cm-diameter circular orifice in the middle, through which a 1-cm-long piece of dental wick soaked with a 10% sugar solution was inserted to feed *P. xylostella.* Although eggs were laid mainly on the leaf, some were laid on the plastic tube near the leaf, particularly for cabbage. Thus, the sum of the number of eggs laid on the leaf and the number laid on the half of the plastic tube closer to the leaf was used in the analyses. The number of eggs laid per leaf was recorded 24 h after the moth was released. Each two-choice comparison was replicated 10 times.

Preference between Cabbage and Glossy and Waxy Collards, Indian Mustard, and Yellow Rocket Volatiles. To determine whether leaf morphology and color are important cues for attracting *P. xylostella,* two-choice olfactory tests were conducted using a Y-tube olfactometer. Although we realize that attraction does not equal oviposition, this test provides insight into the choice *P. xylostella* likely makes when searching for a host. In total, 12 runs were conducted for each comparison (cabbage versus glossy collards, cabbage versus waxy collards, cabbage versus Indian mustard, and cabbage versus yellow rocket) and for each of two *P. xylostella* populations (Geneva and Camilla). In addition to these 24 runs, 12 more test runs were conducted for each *P. xylostella* population with clean air. These additional runs were made without plants in the container holding the odor source to detect potential bias of the apparatus.

The olfactometer was made of transparent glass (3.5-cm interior diameter, 15.5-cm stem, 12.0-cm arms, 140° stem-arms angle). Each arm was connected to a plastic container holding the odor source (a potted plant of either cabbage or a potential trap crop). Between each container and the end of each olfactometer arm, a screen was placed to prevent insect escape. Active-charcoal-filtered air was drawn from the containers with the odor source to the arms of the olfactometer at a speed of 600 ml/min, which was measured with a digital flowmeter (model ADM 1000, J & W Scientific, Folsom, CA). Air flow in the Y-tube was visualized initially with dry ice vapors to ensure that air flow was laminar at the chosen flow rate. The apparatus was rotated 180° after three test runs to exclude directional bias. The olfactometer and the containers were disconnected and washed with soap and water every six test runs.

A single moth was released into the stem (downwind end) of the Y-tube olfactometer and observed for 10 min. Because moths were expected to be most active during their scotophase (Goodwin and Danthanarayana 1984, AVRDC 1987), observations were conducted in the dark (from 1900 to 2400 hours) with the help of a 7.5-W red light. Observations were conducted in a room at 22 ± 1°C and 60 ± 5% RH. The first choice of the moth was recorded taking into account that responses were considered positive only when a moth penetrated >6 cm into one arm and remained there for >1 min. The Observer (Noldus Information Technology 1996) was used to record the time a moth spent in each of the arms of the olfactometer. Moths that did not make a clear choice according to our criteria within 10 min were not included in the statistical analysis of first choice and time spent in each arm of the olfactometer. In all, 120 female moths were observed (60 for each population).

Larval Survival and Development on Cabbage, Glossy and Waxy Collards, Indian Mustard, and Yellow Rocket. For each plant, 10 *P. xylostella* eggs (<2 d old) laid on aluminum foil were randomly attached with a pin to either the upper or the lower part of each of three leaves. The experiment was conducted in an outdoor screenhouse (3.0 by 4.5 m)

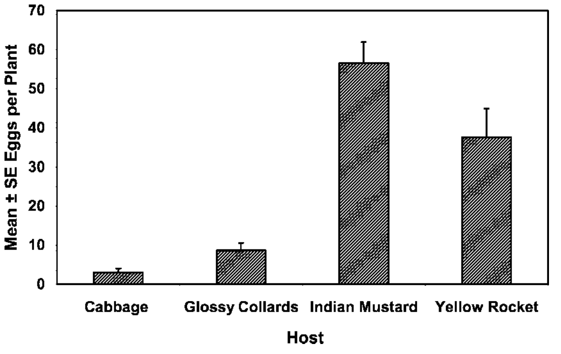

Fig. 2. *P. xylostella* ovipositional preference among cabbage, glossy collards, Indian mustard, and yellow rocket (multiple-choice test in screenhouse).

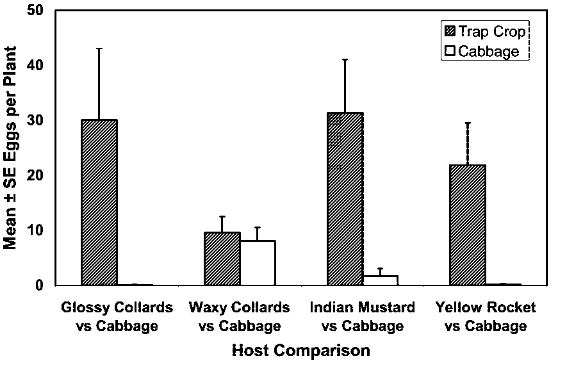

Fig. 3. *P. xylostella* ovipositional preference between cabbage and glossy collards, waxy collards, Indian mustard, and yellow rocket (two-choice test in screenhouse).

with 12-wk-old yellow rocket, 10-wk-old cabbage and collards, and 6-wk-old Indian mustard plants. The experiment was replicated three times. Larvae of *P. xylostella* were observed every 2 d until they pupated. Larval survival data were recorded as percentage of eggs that reached pupation. The number of days to reach pupation also was recorded.

Statistical Analyses. Data were analyzed using analysis of variance (ANOVA) with the PROC GLM procedure of SAS (SAS Institute 1999), except for data collected during the olfactometer experiment. When significant treatment differences were indicated, means were separated by Fisher's protected least significant difference (LSD) following a significant F-test at $P \leq 0.05$ (SAS Institute 1999). To normalize the residuals, before analysis data were transformed using a natural log $(x + 1)$ and a square root (x) function for the ovipositional preference and the larval survival tests, respectively. Data for the first choice between both arms of the olfactometer were treated as a binomial distribution in which the probability of first choice varied depending on the host volatiles (either cabbage or trap crop) and analyzed as a logit model with host as a sole factor using the PROC GENMOD procedure of SAS (SAS Institute 1999). Data for the time spent in the arms of the olfactometer were first transformed using a square root (x) function and then analyzed using a paired *t*-test with the PROC TTEST procedure of SAS (SAS Institute 1999). PROC TTEST gives the *P* values for a two-sided test; however, because we wanted to test whether moths spent more time in the olfactometer arm with the trap crop than in the olfactometer arm with the cabbage volatiles (one-sided test), *P* values were divided by 2. Although all tests of significance were based on the transformed data, only untransformed data are presented.

Results

Ovipositional Preference Experiments Conducted in Screenhouses. For the multiple-choice test, the number of eggs laid per plant varied significantly across hosts ($F = 33.30$; df = 3, 15; $P < 0.001$) (Fig. 2). Numbers of eggs laid on glossy collards, Indian mustard, and yellow rocket were 3, 18, and 12 times higher than on cabbage, respectively. Indian mustard and yellow rocket were preferred over glossy collards and cabbage. No significant differences in number of eggs between Indian mustard and yellow rocket, or between glossy collards and cabbage existed. For the two-choice test, *P. xylostella* showed a significant preference for glossy collards ($F = 45.10$; df = 1, 3; $P < 0.001$), Indian mustard ($F = 27.18$; df = 1, 3; $P = 0.002$), and yellow rocket ($F = 53.62$; df = 1, 3; $P < 0.001$) over cabbage (Fig. 3). Numbers of eggs laid on glossy collards, Indian mustard, and yellow rocket were 300, 19, and 110 times greater than on cabbage, respectively. Number of eggs laid on waxy collards and cabbage did not differ significantly ($F = 2.38$; df = 1, 3; $P = 0.174$).

Relationship between Total Leaf Area and Number of Eggs Laid on Cabbage, Glossy and Waxy Collards, Indian Mustard, and Yellow Rocket. Total leaf areas were significantly different across hosts ($F = 23.41$; df = 3, 12; $P < 0.001$) (Fig. 4). The total leaf area of cabbage was the largest (1022.61 cm^2); however, it was not significantly different from the total leaf areas of glossy collards (860.93 cm^2) and waxy collards (841.32 cm^2). The total leaf area of Indian mustard (752.75 cm^2) was significantly smaller than the total leaf area of cabbage, but it did not differ significantly from that of glossy and waxy collards. Yellow rocket had the

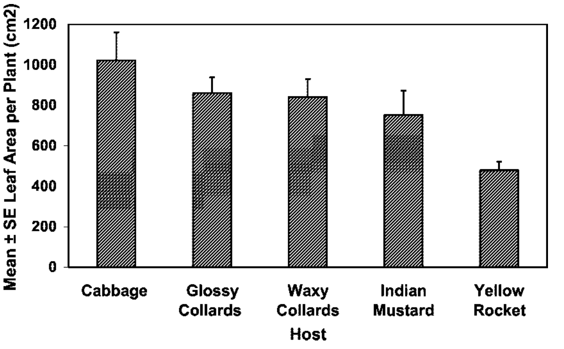

Fig. 4. Total leaf areas of glossy collards, waxy collards, Indian mustard, and yellow rocket.

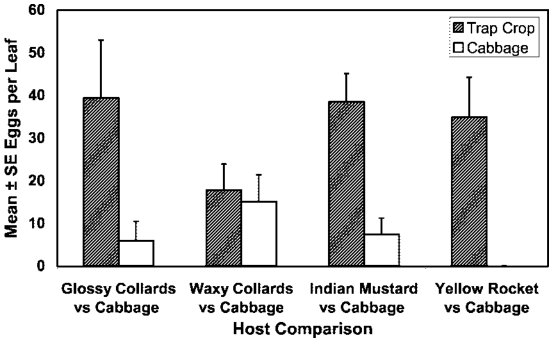

Fig. 5. *P. xylostella* ovipositional preference between cabbage and glossy collards, waxy collards, Indian mustard, and yellow rocket (two-choice test in Plexiglas tubes).

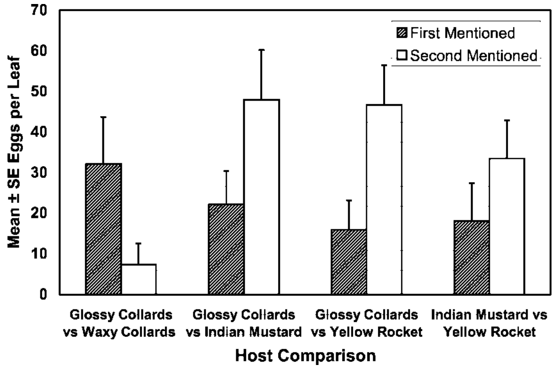

Fig. 6. *P. xylostella* ovipositional preference in pair comparisons among trap crops: glossy collards versus waxy collards, glossy collards versus Indian mustard, glossy collards versus yellow rocket, and Indian mustard versus yellow rocket (two-choice test in Plexiglas tubes).

smallest total leaf area (479.52 cm^2). If total leaf area were an important factor in ovipositional preference, ovipositional preference across hosts with similar total leaf areas would be similar. Cabbage and glossy and waxy collards had similar leaf areas, but ovipositional preference was not the same for these hosts (Figs. 2–5). Thus, total leaf area does not seem to be a major factor determining *P. xylostella* ovipositional preference across hosts.

Ovipositional Preference Experiment Conducted in Plexiglas Tubes. Females laid significantly more eggs on yellow rocket ($F = 25.18$; df = 1, 9; $P < 0.001$), Indian mustard ($F = 16.25$; df = 1, 9; $P < 0.001$), and glossy collards ($F = 12.48$; df = 1, 9; $P = 0.002$) than on cabbage (Fig. 5). The difference in oviposition for the comparison between cabbage and waxy collards was not significant ($F = 1.87$; df = 1, 9; $P = 0.283$). These results further indicate that total leaf area, leaf shape, and plant architecture are not major factors affecting ovipositional preference by *P. xylostella.* For pair comparisons among trap crops, glossy collards had lower numbers of eggs than Indian mustard ($F = 4.85$; df = 1, 9; $P = 0.045$), and yellow rocket ($F = 6.50$; df = 1, 9; $P = 0.020$), but higher numbers of eggs than waxy collards ($F = 13.25$; df = 1, 9; $P = 0.002$) (Fig. 6). Differences in oviposition between Indian mustard and yellow rocket ($F = 0.94$; df = 1, 9; $P = 0.3454$) were not significant.

Preference between Cabbage and Glossy and Waxy Collards, Indian Mustard, and Yellow Rocket Volatiles. Moths became more active in the presence of host volatiles than in clean air. There was increased movement of antennae, head turns, short flights, and walking, particularly upwind, in the presence of plant volatiles, whereas in clean air moths spent more time quiescent in the stem of the olfactometer. Responses by *P. xylostella* for plant volatiles differed slightly between the two populations; therefore, responses are discussed separately for each population.

For the Geneva population, the odds of *P. xylostella* choosing the trap crop volatiles as a first choice over cabbage were statistically significant for Indian mustard ($\chi^2 = 3.70$, $P = 0.050$) and yellow rocket ($\chi^2 = 4.35$, $P = 0.037$), and nearly significant for glossy collards ($\chi^2 = 2.10$, $P = 0.147$), but not for waxy collards ($\chi^2 = 0.39$, $P = 0.529$) (Table 1). For the Camilla population, the odds of *P. xylostella* population choosing the trap crop volatiles as a first choice over cabbage were statistically significant for glossy collards ($\chi^2 = 3.70$, $P = 0.050$), Indian mustard ($\chi^2 = 4.35$, $P = 0.037$), and yellow rocket ($\chi^2 = 4.82$, $P = 0.028$), but not for waxy collards ($\chi^2 = 0.49$, $= 0.484$). For the Geneva population, time spent in the olfactometer arm with the trap crop volatiles was significantly higher than time spent in the olfactometer arm with the cabbage volatiles for glossy collards ($t = 1.92$; df = 1, 10; $P = 0.042$), Indian mustard ($t = 2.44$; df = 1, 10; $P = 0.018$), and yellow rocket ($t = 5.88$; df = 1, 9; $P < 0.001$), but not for waxy collards ($t = 0.5$; df = 1, 9; $P = 0.314$). For the *P. xylostella* population from Camilla, time spent in the olfactometer arm with the trap crop volatiles was significantly higher than time spent in the olfactometer arm with the cabbage volatiles for glossy collards ($t = 3.53$; df = 1, 10; $P = 0.003$), Indian mustard ($t = 5.36$; df = 1, 10; $P < 0.001$), and yellow rocket ($t = 6.80$; df = 1, 10; $P < 0.001$), but not for waxy collards ($t = 1.04$; df = 1, 7; $P = 0.166$).

Larval Survival and Development on Cabbage, Glossy and Waxy Collards, Indian Mustard, and Yellow Rocket. Survival of *P. xylostella* larvae until pupation differed significantly among hosts ($F = 9.38$; df = 4, 8; $P = 0.004$) (Table 2). Survival was highest on Indian mustard (24.4%), but not significantly different from survival on cabbage (22.2%) or waxy collards (18.9%). Survival was lowest on yellow rocket (0%), but it was not significantly lower than survival on glossy collards (6.7%). The number of days from egg to pupation also was significantly different among hosts ($F = 16.07$; df = 3, 8; $P = 0.002$). Pupation was reached earliest on Indian mustard (14.6 d).

Discussion

Based on our criteria of an ideal trap crop for *P. xylostella,* yellow rocket was the best candidate evaluated in our study. Ovipositional preference was

Table 1. *P. xylostella* first choice and time spent in both arms of a Y-tube olfactometer as a response to plant volatiles of cabbage and glossy collards, waxy collards, Indian mustard, and yellow rocket

Host comparison	First choice between arms of olfactometer (%)[a]			Time spent in each arm of olfactometer (mean % ± SE)[b]	
	Population	Cabbage volatiles	Trap crop volatiles	Cabbage volatiles	Trap crop volatiles
Cabbage vs. glossy collards	Geneva, NY	25.0a	66.7a	16.4 ± 6.2a	42.4 ± 8.6b
	Camilla, GA	16.7a	75.0b	18.9 ± 4.8a	46.7 ± 6.1b
Cabbage vs. waxy collards	Geneva, NY	33.3a	50.0a	32.9 ± 8.2a	38.6 ± 7.9a
	Camilla, GA	25.0a	41.7a	26.6 ± 6.8a	37.5 ± 7.1b
Cabbage vs. indian mustard	Geneva, NY	16.7a	75.0b	13.5 ± 4.9a	45.1 ± 8.8b
	Camilla, GA	8.3a	75.0b	7.6 ± 2.2a	54.9 ± 8.5b
Cabbage vs. yellow rocket	Geneva, NY	8.3a	75.0b	9.4 ± 1.9a	58.1 ± 6.1b
	Camilla, GA	0.0a	91.7b	7.6 ± 1.9a	64.7 ± 6.4b
Clean air	Geneva, NY	0.0a	0.0a	0.0 ± 0.0a	0.0 ± 0.0a
	Camilla, GA	0.0a	0.0a	0.0 ± 0.0a	0.0 ± 0.0a

[a] Means within a row followed by different letters are significantly different, $P \leq 0.05$ (SAS PROC GENMOD procedure, SAS Institute 1999).
[b] Means within a row followed by different letters are significantly different, $P \leq 0.05$ (SAS PROC TTEST paired one-sided procedure, SAS Institute 1999). Moths spent the rest of the time up to 100% in the stem of the olfactometer.

much greater and larval survival was much lower on yellow rocket than on cabbage. Besides being a lethal host for *P. xylostella*, yellow rocket also has been shown to be resistant to larvae of the mustard white butterfly, *Pieris napi oleracea* (Harris) (Renwick 2002) and the flea beetles *Phyllotreta nemorum* L. (Agerbirk et al. 2001), *Phyllotreta cruciferae* Goeze, and *Phyllotreta striolata* (F.) (F.R.B.-P., unpublished data). Flea beetles are common specialist pests of crucifers (Capinera 2001), so resistance or tolerance to them is another advantage of using yellow rocket as a trap crop. Two triterpenoid saponins acting as feeding deterrents seem responsible for *P. xylostella* resistance in yellow rocket (Shinoda et al. 2002, Agerbirk et al. 2003). Although larvae from *P. xylostella* are not able to survive on yellow rocket, larvae from other insects such as imported cabbageworm, *Pieris rapae* (L.) (F.R.B.-P., unpublished data) and black cutworm, *Agrotis ipsilon* Hufnagel (Busching and Turpin 1977), are able to develop and pupate successfully on this host. This shows that some insects can be at least partly immune to the feeding deterrents contained in yellow rocket. Despite yellow rocket being considered a weed (MacDonald and Cavers 1991), the fact that it is a biannual plant severely limits its flowering, bolting, and accumulation of seeds in the seedbank during the crop cycle. Furthermore, if planted 2 or 3 wk before cabbage, both yellow rocket and cabbage can be transplanted simultaneously.

Table 2. *P. xylostella* larval survival and development from egg to pupal stage on cabbage, glossy collards, waxy collards, Indian mustard, and yellow rocket

Host	Larval survival (%)	Time to pupate (d)
Cabbage	22.2 ± 5.6a	17.5 ± 0.3a
Glossy collards	6.7 ± 5.1b	17.6 ± 0.4a
Waxy collards	18.9 ± 5.9a	16.9 ± 0.3a
Indian mustard	24.4 ± 8.0a	14.6 ± 0.4b
Yellow rocket	0b	—[a]

Mean ± SE, means within a column followed by different letters are significantly different, $P \leq 0.05$ (Fisher's protected LSD, SAS Institute 1999).
[a] No larvae reached pupation on yellow rocket.

Glossy collards also may be an acceptable trap crop. Like yellow rocket, glossy collards are the preferred host for oviposition by *P. xylostella* compared with cabbage and larval survival is much lower on it than on cabbage. As has been observed in cabbage varieties with reduced wax, the low larval survival of *P. xylostella* on glossy collards may be due to behavioral changes of neonate larvae caused by a reduction in waxes (Eigenbrode and Shelton 1990, 1992). Glossy collards, however, are very susceptible to damage by *Phyllotreta* spp. (Eigenbrode 1990), which may decrease its effectiveness as a *P. xylostella* trap crop in places where flea beetle populations are high.

P. xylostella was highly attracted to Indian mustard, but larval survival also was high. Thus, Indian mustard may serve as a nursery crop for *P. xylostella* and a source for subsequent infestations in cabbage, unless insecticides are used to prevent this from occurring. Larvae feeding on Indian mustard also reached pupation faster than larvae feeding on the other hosts, which could potentially result in more generations of *P. xylostella* per year. Another drawback of using Indian mustard as a trap crop is that it has to be planted at least twice during the cabbage crop cycle (Srinivasan and Krishna Moorthy 1992).

Insect behavior during host plant selection and oviposition can be divided into three stages: orientation (host patch location), approach (host attraction at shorter distance), and assessment (Renwick 1989). The relative importance of chemical and physical stimuli varies depending on the stage (Renwick 1989, Finch and Collier 2000). Because we released *P. xylostella* near some of its suitable hosts, we assessed stimuli used during the last two stages, approach and assessment. In those stages, differences in attraction were not influenced by total leaf area because some of the trap crops, highly preferred for oviposition, had similar total leaf areas as cabbage. Moreover, when leaf area was kept constant (Plexiglas tube experiments), ovipositional preference for certain trap crop hosts was identical to those in experiments where leaf area was not controlled (whole plant ovipositional preference studies in screenhouses). Therefore, host volatiles, leaf morphology and color, or a combination of these factors are likely major cues responsible for triggering ovipositional preference in *P. xylostella.* Trends in *P. xylostella* oviposition preference for certain trap crop hosts were identical to the trends in attraction that *P. xylostella* had for the same host volatiles. Thus, plant volatiles seem to be a major factor responsible for attracting *P. xylostella* to plants that are then likely used as hosts for oviposition. The fact that three of the hosts, cabbage and glossy and waxy collards, had similar leaf shape and plant architecture, whereas ovipositional preference was not the same, shows that leaf shape and plant architecture are not major factors determining *P. xylostella* ovipositional preference across hosts. Furthermore, the results of the ovipositional preference experiment in Plexiglas tubes, which eliminated the effects of leaf shape and plant architecture, were similar to those in the two-choice tests with whole plants. The effect of color, plant texture, and leaf contact chemicals on *P. xylostella* ovipositional preference across the compared hosts remains to be tested.

Because glucosinolates were present in all tested hosts, the preference observed in the olfactometer experiments must be due either to different concentrations and/or relative proportions of those or the presence of particular chemical compounds. Behavioral studies, together with identification of these compounds and their most attractive combination for *P. xylostella* will help us better understand how olfactory stimuli affect host selection and oviposition.

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References Cited

Agerbirk, N., C. E. Olsen, and J. K. Nielsen. 2001. Seasonal variation in leaf glucosinolates and insect resistance in two types of *B. vulgaris* ssp. *arcuata.* Phytochemistry 58: 91–100.

Agerbirk, N., C. E. Olsen, B. M. Bibby, H. O. Frandsen, L. D. Brown, J. K. Nielsen, and J.A.A. Renwick. 2003. A saponin correlated with variable resistance of *Barbarea vulgaris* to the diamondback moth *Plutella xylostella.* J. Chem. Ecol. 29: 1417–1433.

Åsman, K. 2002. Trap cropping effect on oviposition behaviour of the leek moth *Acrololepsis assectella* and the diamondback moth *Plutella xylostella.* Entomol. Exp. Appl. 105:153–164.

[AVRDC] Asian Vegetable Research and Development Center. 1987. 1985 Progress Report. Asian Vegetable Research and Development Center, Shanhua, Taiwan.

Banks, J. E., and B. Ekbom. 1999. Modelling herbivore movement and colonization: pest management potential of intercropping and trap cropping. Agric. For. Entomol. 1: 165–170.

Bender, D. A., W. P. Morrison, and J. R. Kern. 1999. Intercropping cabbage and Indian mustard for potential control of lepidopterous and other insects. HortScience 34: 275–279.

Bernays, E. A., and R. F. Chapman. 1994. Host-plant selection by phytophagous insects. Chapman & Hall, New York.

Busching, M. K., and F. T. Turpin. 1977. Survival and development of black cutworm (*Agrotis ipsilon*) larvae on various species of crop plants and weeds. Environ. Entomol. 6: 63–65.

Capinera, J. L. 2001. Handbook of vegetable pests. Academic, New York

Eigenbrode, S. D. 1990. Diamondback moth resistance mechanisms in *Brassica oleracea.* Ph.D. dissertation, Department of Entomology, Cornell University, Ithaca, NY.

Eigenbrode, S. D., and A. M. Shelton. 1990. Behavior of neonate diamondback moth larvae (Lepidoptera: Plutelliadae) on glossy-leaved resistant genotypes of *Brassica oleracea.* Environ. Entomol. 19: 566–571.

Eigenbrode, S. D., and A. M. Shelton. 1992. Survival and behavior of *Plutella xylostella* larvae on cabbages with leaf waxes altered by treatment with S-ethyl dipropylthiocarbamate. Entomol. Exp. Appl. 62: 139–145.

Eigenbrode, S. D., K. A. Stoner, A. M. Shelton, and W. C. Kain. 1991. Characteristics of glossy leaf waxes associated with resistance to diamondback moth (Lepidoptera: Plutellidae) in *Brassica oleracea.* J. Econ. Entomol. 84: 1609–1618.

Finch, S., and R. Collier. 2000. Host-plant selection by insects -a theory based on 'appropriate/inappropriate landings' by pest insects of cruciferous plants. Entomol. Exp. Appl. 96: 91–102.

Goodwin, S., and W. Danthanarayana. 1984. Flight activity of *Plutella xylostella* (L.) (Lepitdopetera: Yponomeutidae). J. Aust. Entomol. Soc. 23: 235–240.

Gupta, P. D., and A. J. Thorsteinson. 1960. Food plant relationships of the diamondback moth (*Plutella maculipennis* [Curt.]). II. Sensory regulation of oviposition of the adult female. Entomol. Exp. Appl. 3: 305–314.

Hooks, C.R.R., and M. W. Johnson. 2003. Impact of agricultural diversification on the insect community of cruciferous crops. Crop Protection 22: 223–238.

Idris, A. B., and E. Grafius. 1994. The potential of using *Barbarea vulgaris* in insecticide-resistant diamondback moth management. Resistance Pest Manage. Newsl. 6: 7–8.

Idris, A. B., and E. Grafius. 1996. Effects of wild and cultivated host plants on oviposition, survival, and development of diamondback moth (Lepidoptera: Plutellidae) and its parasitoid *Diadegma insulare* (Hymenoptera: Ichneumonidae). J. Econ. Entomol. 25: 825–833.

Justus, K. A., L. M. Dosdall, and B. K. Mitchell. 2000. Oviposition by *Plutella xylostella* (Lepidoptera: Plutellidae) and effects of phylloplane waxiness. J. Econ. Entomol. 93: 1152–1159.

Luther, G. C., H. R. Valenzuela, and J. Defrank. 1996. Impact of cruciferous trap crops on lepidopteran pests of cabbage in Hawaii. J. Econ. Entomol. 25: 39–47.

MacDonald, M. A., and P. B. Cavers. 1991. The biology of Canadian weeds. 97. *Barbarea vulgaris* R. Br. Can. J. Plant Sci. 71: 149–166.

Mitchell, E. R., G. Y. Hu, and D. Johanowicz. 2000. Management of diamondback moth (Lepidoptera: Plutellidae) in cabbage using collard as a trap crop. HortScience 35: 875–879.

Noldus Information Technology. 1996. The observer base package for Windows reference manual. Version 3.0. Noldus Information Technology, Wageningen, The Netherlands.

Pivnick, K. A., B. Jarvis, and G. P. Slater. 1994. Identification of olfactory cues used in host plant finding by diamondback moth, *Plutella xylostella* (Lepidoptera: Plutellidae). J. Chem. Ecol. 20: 1407–1427.

Reed, D. W., K. A. Pivnick, and E. W. Underhill. 1989. Identification of chemical oviposition stimulants for the diamondback moth, *Plutella xylostella,* present in three species of Brassicaceae. Entomol. Exp. Appl. 53: 277–286.

Renwick, J.A.A. 1989. Chemical ecology of oviposition in phytophagous insects. Experientia 45: 223–228.

Renwick, J.A.A. 2002. The chemical world of crucivores: lures, treats and traps. Entomol. Exp. Appl. 104: 35–42.

Root, R. B., and J. O. Tahvanainen. 1969. Role of winter cress, *Barbarea vulgaris,* as a temporal host in the seasonal development of the crucifer fauna. Ann. Entomol. Soc. Am. 62: 852–855.

SAS Institute. 1999. SAS/STAT user's guide, version 8. SAS Institute, Cary, NC.

Shelton, A. M., and B. A. Nault. 2004. Dead-end trap cropping: a technique to improve management of the diamondback moth, *Plutella xylostella* (Lepidoptera: Plutellidae). Crop Protection 23: 497–503.

Shelton, A. M., R. J. Cooley, M. K. Kroening, W. T. Wilsey, and S. D. Eigenbrode. 1991. Comparative analysis of two rearing procedures for diamondback moth (Lepidoptera: Plutellidae). J. Entomol. Sci. 26: 17–26.

Shinoda, T., T. Nagao, M. Nakayama, H. Serizawa, M. Koshioka, H. Okabe, and A. Kawai. 2002. Identification of a triterpenoid saponin for a crucifer, *Barbarea vulgaris,* as a feeding deterrent to the diamondback moth, *Plutella xylostella.* J. Chem. Ecol. 28: 587–599.

Silva-Krott, I. U., P. Singh, T. S. Lali, and R. Muniappan. 1995. Development of a trap cropping system for cabbage in Guam. Pest Manage. Hortic. Ecosys. 1: 27–35.

Spencer, J. L., S. Pillai, and E. A. Bernays. 1999. Synergism in the oviposition behavior of *Plutella xylostella:* sinigrin and wax compounds. J. Insect Behav. 12: 483–500.

Srinivasan, K., and P. N. Krishna Moorthy. 1992. The development and adoption of integrated pest management for major pests of cabbage using Indian mustard as a trap crop, pp. 511–521. *In* N. Talekar [ed.], 2nd International Workshop on the Diamondback Moth and other Cruciferous Pests. Asian Vegetable Research and Development Center, Taipei, Taiwan.

Tabashnik, B. E. 1985. Deterrence of diamondback moth (Lepidoptera, Plutellidae) oviposition by plant compounds. Environ. Entomol. 14: 575–578.

Talekar, N. S. 1992. Management of diamondback moth and other crucifer pests. *In* N. Talekar [ed.], Proceedings of the Second International Workshop Asian Vegetable Research and Development Center, Shanhua, Taiwan.

Talekar, N. S., and A. M. Shelton. 1993. Biology, ecology, and management of the diamondback moth. Annu. Rev. Entomol. 38: 275–301.

Thompson, J. N., and O. Pellmyr. 1991. Evolution of oviposition behavior and host preference in Lepidoptera. Annu. Rev. Entomol. 36: 65–89.

Ulmer, B., C. Gillot, D. Woods, and M. Erlandson. 2002. Diamondback moth, *Plutella xylostella* (L.), feeding and oviposition preferences on glossy and waxy *Brassica rapa* (L.) lines. Crop Protection 21: 327–331.

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