Estimation of some characteristic dispersal ranges of diamondback moth (Plutella xylostella) (Lepidoptera: Plutellidae)

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Abstract
The dispersal ranges of the diamondback moth (Plutella xylostella) were estimated with mark-recapture collected during 1998-2000 in commercial cauliflower and broccoli crops in the northern Adelaide plains. Moths were marked with fluorescent powder and released at one or more points within the experimental fields. Recaptures of the marked moths were made with pheromone traps and yellow sticky buckets (YSB), the latter were used to trap both sexes of the moth. Four indices of dispersal ranges were estimated, the average dispersal distances and the distances within which 95, 99 and 99.9% of the released moths were expected to remain. The average dispersal distances estimated from the recapture data with pheromone traps were 21-35 m and those from the YSB recapture data were 14-18 m for the males and 13-24 m for the females. The 95, 99 and 99.9% distances estimated from YSB recapture data were 41-54 m, 69-90 m and 117-164 m respectively for the males and 40-72 m, 63-120 m and 113 –203 m respectively for the females. The corresponding distances estimated from the recapture data with pheromone traps were 62-106 m, 104-177 m and 176-300 m respectively. Implications of the results in the designing and implementation of insecticide resistance management strategies and in a number of alternative control strategies are discussed.

Keywords
mark-recapture, sticky traps

Introduction
Diamondback moth (DBM), Plutella xylostella (L.) (Lepidoptera: Plutellidae), is known to be able to migrate over long distances (Mackenzie 1958, Lorimer 1981, Chu 1986). However, little is known about its dispersal ranges within active host crops or local dispersal ranges. Such information is crucial in the designing and/or implementation of a number of new management strategies for DBM. These include rotations of insecticides (Liu & Tabashnik 1997, Mo et al. 1999), provision of susceptible populations (Shelton et al. 2000), mating disruption (McLaughlin et al. 1994, Mitchell et al. 1997, Schroeder et al. 2000), crop-break (Heisswolf et al. 1996), pathogen auto-dissemination (Pell et al. 1993, Furlong 1995) and trap crops (Srinivasan & Moorthy 1991, Pawar & Lawande 1995). For insecticide rotations, ideally the same rotation plan should be uniformly implemented across an entire region. Where uniform implementation is not feasible, areas under different rotation plans should be separated by large enough distances so that exchange of individuals among local populations is below a predefined level. Similarly, dispersal information is needed to determine the minimal separation distance between host crop areas managed and not managed by the crop-break strategy or the mating disruption strategy. Another IRM strategy is the provision of refuges for insecticide-susceptible populations. For this strategy to be effective, the refuges should be set up within certain distances from the target populations to ensure significant exchanges of individuals between susceptible and resistant populations. Similarly, dispersal information is needed to determine the maximal separation distances between the trap crop and target crop, and the maximal trap intervals in the pathogen auto-dissemination strategy.

As part of a national project on the integrated management of DBM, a local dispersal study of DBM was conducted in South Australia between during 1998-2000. The objectives of this study were to estimate the dispersal ranges of male and female DBM moths within active host crops, in particular the likelihood of the moths dispersing beyond given distances.
Materials and methods

Test insects

Moths used in this study were from laboratory colonies reared with potted canola, cabbage, or Chinese cabbage. Rearing conditions were 25 – 28°C and 12L:12D light cycle. Each spring, a new colony was started with wild DBM larvae/adults collected from Brassica weeds/canola crops. The colony was reinvigorated every 2-3 months by introducing wild individuals.

Marking and release

Fluorescent powder (Magruder Color Co., Elizabeth, NJ) was chosen as the marking agent. Marking was done in flat Décor® containers (26 x 19 x 6 cm). Moths were introduced into the marking container through a mesh sleeve opening to a circular hole cut in the centre of the cover. About 500 moths were placed in each container. The marking containers were transported to the experiment sites in an Esky® (40 L) cooler box with ice packs inside. Just before the release, 0.05–1.00 g of the fluorescent powder was placed into each container and shaken for a few seconds. The moths were then released by opening the caps of the marking containers.

To determine the effect of marking on the mortality of marked moths, healthy pupae from the culture were sorted into males and females and placed in individual glass tubes. Emergence of the pupae was checked daily. Moths emerged on the same day from each sex were randomly divided into two groups with equal numbers in each group. Moths from one group in each sex were marked with the fluorescent powder according the method described above and transferred back into clean glass tubes. The test moths were checked daily for life-death status until the last moth had died. The test condition was the same as in rearing. Significant differences in the average life span between marked and unmarked individuals were checked with two-sample t-tests.

The effect of marking on the response of marked males to the pheromone sources was studied in a wind tunnel (temperature: 20°C; wind speed: 0.1 m/s; light period: 12L:12D). A pheromone trap (25 cm x 35 cm) baited with a 3-component DBM sex pheromone (R. Vickers, CSIRO Long Pocket Laboratories, Brisbane, Australia) was placed in the centre of the upwind end (10 cm away) at a height of 30 cm. Marked and unmarked virgin males were released in the downwind end of the wind tunnel and allowed to respond to the pheromone source for 24 h. The number of moths caught in each category (marked or un-marked) was recorded at the end of the test and the differences were analysed with chi-squared tests.

To determine the effect of irrigation and rain on the persistence of the marking on the moth bodies, marked moths were placed in a cylindrical bag made of coarse mesh and showered with a constant flow of water from a sprinkler for either 0.5 h or 1.0 h. The diameter of the bag was made about the same as that of the sprinkler to ensure full coverage of the bag with the shower. After the draining of excess water, the moths were checked for fluorescent marking with an UV spotlight (TrAc Pack Pro, Labino AB, Sweden).

Experiment sites and host crops

All mark-recapture experiments were conducted on a commercial broccoli and cauliflower farm in the northern Adelaide plains (34°43’S, 138°33’E). The crops were planted continuously throughout the year, resulting in a mixture of different ages of the crops at any time. Each planting was made in adjacent rectangular blocks (10 m wide, 110 – 230 m long) separated by 5-m wide tractor paths. The distance between adjacent plants within a block was about 0.5 m. The crops were regularly irrigated with overhead sprinklers. All experiments were conducted when the crops were about 6-10 weeks old.

Recapture of released moths was made with delta pheromone traps and yellow sticky buckets (YSB). The pheromone traps were made out of 2 L blank milk cartons. The side length of the triangular opening of the trap was 25 cm and the length of the trap 35 cm. A cardboard piece (25 x 35 cm) coated with Tanglefoot® was inserted on the base of the pheromone trap. A rubber tube impregnated with the 2-component sex pheromone of the DBM (Long Pocket Laboratories of the CSIRO Division of Entomology) was placed in the centre of the sticky base. The YSB consisted of an inverted plastic bucket (base diameter: 25 cm, opening diameter: 35 cm, height: 35 cm) and a 5 cm wide ring made from particleboard (Figure 1). The outer surface of the bucket and the upper surface of the ring were coated with Tanglefoot®. A square hole was cut in the centre of the bucket base to allow a wooden stake to poke through. The height of the trap was controlled with a bull clip placed on the wooden stake. The ring of the YSB was designed to increase the
trapping efficiency as observations showed that a considerable number of moths that bumped into the bucket wall did not get stuck, but fell to the ground. Pheromone traps were placed at a height of ca. 50 cm and YSB ca. 30 cm (from the ring to the ground).

![Illustration of the yellow sticky bucket (YSB) trap. The exterior surface of the plastic bucket and the upper surface of the ring were painted with Tanglefoot®.](image)

**Figure 1.** An illustration of the yellow sticky bucket (YSB) trap. The exterior surface of the plastic bucket and the upper surface of the ring were painted with Tanglefoot®.

**Experimental design**

Traps were placed in grid patterns across continuous patches of host fields. The inter-trap distance was fixed at 10 m. The dimensions of grids in terms of the number of rows of traps and the number of traps per row varied from 5 x 21 to 7 x 21, depending on the dimensions of the crop fields available for experiments. Marked moths were released in the centre of the grids. To minimise possible artefacts arising from moths bumping into the traps immediately following the releases, the centre traps were not placed until 1 h after the releases. The total number of moths released in each experiment varied from 1000 to 3000. Six grid-based experiments were conducted, three with pheromone traps and three with YSB. In most experiments, more than one release was made. With multiple releases, separations of recaptures from different releases were made possible by the use of different colours of the fluorescent powder. Recapture data from different releases were treated as different data sets. In experiments using pheromone traps, the sticky bases of the pheromone traps were replaced every 1-2 days. All sticky bases and the traps were checked under UV light for marked moths at the end of each experiment. In experiments using YSB, the buckets were checked daily at the site with a portable UV light. Duration of the experiments ranged from five to nine days.

**Meteorological data**

Temperature, relative humidity, wind direction and wind speed were recorded hourly during the experiments with a data logger (STARLOG, Model 6004, UNIDATA, Western Australia) with a wind speed and direction sensor (Model 6504-FS, UNIDATA, Western Australia). The data logger and the temperature and relative humidity probes were placed inside a Stevenson’s Screen placed at the experimental sites.

**Data analyses**

Recaptures from individual traps were grouped according to the distances of the traps to the release point. The average number of recaptures per trap (y) was then calculated for each distance (x). The relationship between Y and X was modelled with the empirical dispersal equation of Hawkes (1972):

\[
y = \exp(a - bx^\frac{1}{2})
\]

Parameters a and b were estimated with non-linear regression. Equation (1) gives the density of moths at a given point. Since dispersal occurs in all directions, the density of moths at a given distance should be the point density multiplied by 2πx, i.e. 2πxy. The number of moths remaining within a distance of x_c is estimated by:

\[
\int_{0}^{x_c} 2\pi xy \, dx
\]
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The distance within which the probability of moths remains is $p$, $x_p$, is therefore given by the following equation:

$$\int_0^x 2\pi y = p \int_0^x 2\pi y$$  \hspace{1cm} (3)

For each experiment, $x_p$ was estimated for $p = 0.95$, $0.99$, and $0.999$. These were the estimated distances from the release point within which $95\%$, $99\%$, and $99.9\%$ of the moths would remain. The estimates were obtained with numerical integrations. The average dispersal distances were estimated as $20/b^2$ (Hawkes 1972), where $b$ is the parameter in equation (1).

**Results**

No significant differences were detected in the longevity between marked and un-marked moths ($P>0.05$, Student-t tests), irrespective of the sexes (Figure 2). Wind tunnel experiments revealed no significant differences in the percentages of moths caught by the pheromone trap between marked and unmarked males ($P>0.05$, Chi-squared tests) (Figure 3). All marked moths could be clearly detected under UV light after having been subjected to a constant flow of water from a sprinkler for 0.5 h or 1.0 h.

**Figure 2.** Comparisons of longevity between diamondback moths marked with fluorescent powder and un-marked moths. The number of moths tested in each category and each sex was 10. The bars show the 95% confidence intervals.

**Figure 3.** Percentages of marked and unmarked diamondback moths caught by a delta pheromone trap inside a wind tunnel. The $P$-Values were obtained with Chi-squared tests.

A total of 11 data sets had non-zero recaptures at more than five different distances, five from pheromone trap based experiments and six from YSB based experiments. All were satisfactorily fitted with the dispersal model, as indicated by the high $r^2$ values (Table 1). The recapture-distance relationships in all data sets were characterised by a rapid decline of the number of recaptures as the traps moved away from the release point (Figure 4).
Table 1. Fitted parameters of the dispersal model $y = \exp(a - b \sqrt{x})$ and the estimated dispersal ranges based on the model. The 95, 99 and 99.9% distances are distances from the release point within which 95, 99 and 99.9% of the released moths are expected to remain respectively.

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The estimated dispersal ranges based on the relationships are given in Table 1. The average dispersal distances were 21-35 m for males from pheromone recapture data, 14-18 m for males from YSB recapture data and 13-24 m for females from YSB recapture data. The estimated distances within which 95, 99 and 99.9% of the males remained were 62-106, 104-177 and 176-300 m respectively for pheromone recapture data and 41-54, 69-90 and 117-164 m for YSB recapture data. The corresponding distances for females were 40-72, 67-120 and 113-203 m respectively.

Data from the YSB provided direct comparisons of the dispersal ranges of the males and the females. The estimated dispersal ranges were similar in males and females in three of the six data sets and slightly higher in females in the other data sets (Tables 2-3). Comparisons of the mean recapture distances revealed no significant differences between males and females in four data sets ($P>0.05$, t-test). In the remaining two data sets, the mean recapture distance was significantly higher in females in one data set and significantly higher in males in the other data set ($P<0.01$, t-test) (Figure 5).
Figure 4. Fitted relationships between recaptures of diamondback moth and distance from release point.
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Discussion

This paper reports, for the first time, estimates of some characteristic dispersal ranges of male and female diamondback moths based on quantitative relationships between distance and moth density. The results suggest very limited movement of both sexes of the adults within healthy host crops. Less than 5% are expected to disperse over 110 m and less than 1% are expected to disperse over 200 m. Dispersal ranges estimated from pheromone traps were higher than those from YSB. This was probably because of different trapping capacities of the two types of traps. The trapping surface of the YSB is over 10 times larger than that of the pheromone trap. As a result, recaptures by pheromone traps close to the release point may have been artificially limited and hence a more gentle decline of recaptures over the distances. There was no compelling evidence suggesting different dispersal distances of the two sexes of DBM adults.

Shirai and Nakamura (1994) reported much higher average dispersal ranges for the males (286 – 615 m). However, their estimates were based on a few individuals caught in the non-release fields. The majority of the moths (80 – 94%), which were caught in the release fields, were not included in their calculations. When calculated over all recaptured moths, the average dispersal range was as low as 17 m, similar to the average dispersal distances ranges obtained in this study. Elsewhere, Caprio and Tabashnik (1992) noted that over 92% of the marked moths were caught by traps located within 10 m of the release point in their small-scale and non-replicated mark-recapture experiment. Some indirect data such as seasonal patterns of pheromone trap catches and spatial patterns of resistance levels also suggested short dispersal distances by residential DBM populations (Shirai & Nakamura 1994). Observations with night vision goggles by the authors showed that most DBM moths flew close to the ground and below the plant canopy, again suggesting mostly trivial movements and hence limited dispersal ranges.

Results from this study can be used in the designing and/or implementation of a number of IPM/IRM strategies against DBM. The success of resistance dilution with the provision of susceptible refuge populations relies on frequent gene flow between the target populations and the refuge populations. Hence the refuge populations should not be placed too far away from the target populations. Using the average dispersal distances as a guideline, the suggested maximal separation of refuge and crop is 35 m, the latter being the highest average dispersal distance obtained from this study. This distance may also be considered as the maximal trap interval for the alternative control strategy of pathogen auto-dissemination. However, for maximal effect, the trap interval may have to be <20 m, the distance around which the average dispersal distances from most experiments were centred.

Some strategies require that target populations be isolated from non-target populations, such as mating disruption, rotations of insecticides and crop-break. These strategies should ideally be implemented uniformly across the whole crop production area to minimise migrants from non-target populations. However, when uniform implementation is not possible because of some practical difficulties (e.g. disagreements between farmers), the target populations should be separated from the non-target populations by some minimal distances. Results from this study showed that 99% of the moths would not disperse in excess of 300 m. Multiplied by a safety factor of two, this gives a minimal separation distance of 600 m between target and non-target populations.
Dispersal within healthy host crops represents only one aspect of DBM movement. The movement patterns of the insect from harvested crops are likely to be quite different from those in healthy host crops, due to the need to find suitable host patches. Depending on the location of the closest host patches, moths from harvested crops may have to travel hundreds of metres to kilometres. Since growers normally plant their crops sequentially during the growing season, it is likely that crops of all ages will be present at any given time. Hence dispersal from harvested crops should be considered as common events. Long-distance migration is another movement process that needs to be addressed. The insect is known to engage in long distance migrations (Mackenzie 1958, Lorimer 1981, Chu 1986). In the southern states of Australia, there is an annual influx of DBM in the spring (Goodwin & Danthanarayana 1984). The likely sources of migrants are local Brassica weeds or canola crops or populations from warmer areas. Unlike local dispersal, migrations of moths are normally wind-assisted and can cover hundreds of kilometres. To better understand the dispersal process and use the information to fine tune relevant management strategies, it is important that dispersal from harvested crops, weeds and canola crops be studied.

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References


