Field test of a model of migration of moths (Lepidoptera: Noctuidae) in inland Australia

Peter C Gregg,1,* Alice P Del Socorro1 and Wayne A Rochester2

1School of Rural Science and Natural Resources, University of New England, Armidale, NSW 2351, Australia.
2Department of Zoology and Entomology, The University of Queensland, Qld 4072, Australia.

Abstract A migration of Helicoverpa punctigera (Wallengren), Heliothis punctifera (Walker) and Agrotis munda Walker was tracked from Cameron Corner (29°00´S, 141°00´E) in inland Australia to the Wilcannia region, approximately 400 km to the south-east. A relatively isolated source population was located using a distribution model to predict winter breeding, and confirmed by surveys using sweep netting for larvae. When a synoptic weather pattern likely to produce suitable conditions for migration developed, moths were trapped in the source region. The next morning a simulation model of migration using wind-field data generated by a numerical weather-prediction model was run. Surveys using sweep netting for larvae, trapping and flush counts were then conducted in and around the predicted moth fallout area, approximately 400 km to the south-east. Pollen carried on the proboscis of moths caught in this area was compared with that on moths caught in the source area. The survey data and pollen comparisons provided evidence that migration had occurred, and that the migration model gave accurate estimation of the fallout region. The ecological and economic implications of such migrations are discussed.

Key words Agrotis munda, Australia, Helicoverpa punctigera, Heliothis punctifera, Noctuidae, migration.

INTRODUCTION

Moths in the family Noctuidae are among the most migratory of insects (Johnson 1969; Gregg et al. 1993). The semi-arid regions of inland Australia can be important sources of migratory flights of Mythimna con vecta (Walker) (McDonald 1995), Helicoverpa punctigera (Wallengren) and, to a lesser extent, H. armigera (Hübner) (Gregg et al. 1995). In the case of H. punctigera, rainfall in the late autumn and winter is the key to successful breeding in inland regions (Gregg 1995). Above-average rainfall promotes the growth of native host plants, especially those in the families Asteraceae, Fabaceae, Goodeniaceae and Malvaceae (Zalucki et al. 1994). Warm, dry weather in late winter and early spring leads to the senescence of these annual species; this coincides with a virtually synchronous and often large influx of H. punctigera over wide areas of the cropping regions of south-eastern Australia.

The variability of rainfall in inland Australia ensures that in most seasons some areas will be suitable for winter breeding but the location and extent of these areas varies from year to year (Gregg et al. 1995). Maelzer et al. (1996), Maelzer and Zalucki (1999) and Oertel et al. (1999) have shown that the size of the spring generation in cropping regions can be predicted by rainfall in inland regions, notably western Queensland, during May, June and July. These relationships form the basis of a crude medium-to-long-range forecasting system (Dale et al. 1992; Davis et al. 1997; Maelzer & Zalucki 2000).

More accurate, short-range forecasting systems require detailed knowledge of the distribution of winter breeding areas and of migration patterns. Rochester (1999) has recently developed methods for providing such information. Winter breeding areas are identified using a distribution model based on a geographical information system that incorporates bioclimatic indices, soil classifications and vegetation greenness (measured by a normalised difference vegetation index (NDVI), a measure of the difference between two wavelength lengths imaged by satellites). Migration is estimated in near-real time by a trajectory model that incorporates assumptions about the take-off time, flight altitude and flight duration of Helicoverpa spp. The model simulates the flights of many individual moths using wind-field data from numerical prediction models of the Australian Bureau of Meteorology, to produce redistribution patterns following one night’s migration from a defined take-off area (Rochester et al. 1996).

The output of these models is generally consistent with the broad spatial and temporal patterns of Helicoverpa spp. dynamics in eastern Australia. Although statistical tests indicate that the model predictions are at least better than random, the accuracy of the predictions remains poorly quantified. Also, the values of some key parameters have not been measured for moths in the field. Assessment of model performance using data generated for pest management purposes in cropping areas is difficult. Increases in trap catches or oviposition by Helicoverpa spp. in cropping areas can rarely be associated with migrations on a particular night.
because sampling intervals are too broad. Moreover, it is often difficult to separate immigration from increased activity of resident populations. The latter may be associated with the same weather conditions (warm nights) that enable migration.

Other species of noctuids apart from *Helicoverpa* spp. are thought to exhibit similar migration patterns from inland Australia in spring. Drake and Farrow (1985) recorded *Heliothis punctifera* (Walker) (listed as *Neolepria punctifera*), *Agrotis infusa* (Boisdulval), and *Chrysodeixis argen-tifera* (Guenée) from aerial catches at Trangie, New South Wales (NSW; 31°59´S, 147°57´E), in late September. Gregg et al. (1993; 1994) collected *A. infusa* and *C. argentinifera*, as well as *Agrotis munda* Walker and *Persectania ewingii* (Westwood) from upward-facing light traps on mountains in northern NSW. Back-tracking suggested an origin in western NSW or Queensland for these presumed migrants, especially for *A. munda*. There is, however, less information on detailed migration patterns of these species than for *Helicoverpa* spp. Their populations are rarely monitored in cropping regions so it is difficult to determine whether migration models such as that of Rochester (1999) can be used for them.

In the present paper we describe an attempt to trace a one-night migration event involving a number of moth species from inland Australia. A relatively isolated winter-breeding area was located using a distribution model (Rochester 1999), and surveys were undertaken to assess larval populations in and around this area in late spring. Insect traps were operated in this potential source region on the night of passage of a weather system likely to favour migration. The migration model was run the following morning and the field-survey team was directed to the forecast destination where further trapping and adult flush counts were undertaken.

Pollen carried on the proboscies of moths collected in the putative source and destination areas was identified by scanning electron microscopy (Gregg 1993) to further investigate the origins of these moths.

**MATERIALS AND METHODS**

Winter-breeding areas were mapped using a distribution model (Rochester 1999), on a monthly basis, during the winter of 1996. The model estimated the probability that larvae would be found at a site given that host plants were present. Because host plants are not present at all sites that are favourable for larvae in terms of the factors included in the model, this probability exceeds the probability that larvae will be found at a randomly selected site. The distribution maps used here indicate where the model-estimated probability exceeded 0.8. This provides a better indication of where larvae are likely to be present than a threshold of 0.5, which is the value that would be used if the probabilities were not conditional on the presence of host plants (Rochester 1999). The 1996 season was dry throughout much of western NSW and Queensland but isolated areas suitable for breeding were detected to the west and north of Cameron Corner (29°00´S, 141°00´E), the point at which the borders of NSW, Queensland and South Australia meet.

On 22 September 1996 the approach of a synoptic weather pattern considered likely to produce migration on the night of 22–23 September was identified (Fig. 1). A survey team travelled from Bourke to Cameron Corner, sampling areas of plants known to support larvae of *Helico-verpa* and *Heliothis* spp. using methods described by Zalucki et al. (1994). At each site, five sets of 20 sweeps with a

![Fig. 1. Synoptic chart for 09.00 hours on 23 September 1996, showing the passage of a cold front through the Cameron Corner area. Arrows indicate wind direction recorded at Cameron Corner during the night of 22–23 September before the cold front, and on the morning of 23 September after the cold front. CC, Cameron Corner; W, Wilcannia.](image)
38-cm diameter net were made. The numbers and size categories (very small; small; medium; large) of any heliothine larvae found were recorded and the larvae transferred to artificial diet for subsequent rearing and identification.

At Cameron Corner four light traps consisting of 12 V, 8 W black-light fluorescent tubes in fiberglass cones (Kvedaras et al. 2000) were operated overnight on 22–23 September. Four Texas traps (Gregg & Wilson 1991) baited with pheromone lures for *H. punctigera*, and one baited with *H. armigera* pheromone, were also operated. Moths were collected the following morning and frozen for later analysis of pollen loads. Measurements of wind speed and temperature at a height of approximately 1.4 m were made at irregular intervals during the night, using a hand-held anemometer and thermometer.

On the morning of 23 September the wind field from the previous night was obtained from the Australian Bureau of Meteorology and the migration model was run. The fieldsurvey team was directed to the centre of the predicted moth fallout region, near Wilcannia and approximately 400 km south-east of Cameron Corner. The light and pheromone traps were operated on the night of 23–24 September at a site 34 km north-west of Wilcannia, and additional moths were collected by sweep netting around the street lights of the town.

On 24 September the survey team travelled from Wilcannia to Bourke (approximately perpendicular to the long axis of the predicted moth fallout region), sweep netting hosts for larvae and conducting flush counts of moths. For flush counts, transects of 50 m were walked and the observer noted the number of moths which flew up in a zone 2 m wide, making a total of 100 m² sampled. *Helicoverpa punctigera* moths could usually be distinguished from *H. punctifera* and from other species. To standardise the procedure, flush counts were conducted on the same vegetation, flowering stands of *Ixiolaena brevicompta* F. Muell. (Asteraceae). This plant is a good host for both *H. punctigera* and *H. punctifera* (Zalucki et al. 1994). It grows in fairly dense and uniform stands along the floodplain of the Darling River, which the survey route followed.

Pollen analyses of the probosces of moths were done by scanning electron microscopy using methods described by Gregg (1993). The proportion of moths bearing one or more grains of different pollen types was compared with the abundance of flowering plants of various families noted around Cameron Corner and Wilcannia. Abundance was classified as absent (0), scattered (+), common (++) or abundant (+++) from notes made during the field surveys.

**RESULTS**

**Winter breeding and larval populations**

No breeding was predicted by the distribution model in the region around Bourke. Scattered regions were predicted to be suitable north of Bourke, towards Cunnamulla (Fig. 2) although earlier surveys during winter had not found larvae in this region. The area between Bourke and Cameron Corner was predicted to be unsuitable for breeding, and field

---

**Fig. 2.** Areas predicted to be suitable for winter breeding by the distribution model (grey shading) and locations where sweep net sampling for larvae (Table 1) was undertaken. Shaded areas of circles are *Helicoverpa punctigera*, open areas are *Heliothis punctifera*. The area of the circles is proportional to the numbers of larvae collected. X represents sites where no larvae were found.
surveys found that this region was very dry, with only scattered host plants. In the area west of Cameron Corner the model predicted successful breeding on areas of sandy soil, where surveys found that annual daisies (especially Polycalyx stuartii (Sonder) Benth. and Senecio gregorii F. Muell.) were abundant.

Only low numbers of larvae, mostly small- or medium-sized and all *H. punctifera*, were found east of Cameron Corner on 22 and 24 September (Table 1; Fig. 2). In the regions between Wanaaring and Cameron Corner, and between Cameron Corner and Wilcannia, sampling was not conducted because no suitable host plants were found. In two samples collected west of Cameron Corner, high numbers of larvae were found; the average size was larger than those collected further east and the majority were *H. punctifera*.

### Moth counts and predicted migration

On the night of 22–23 September there were large numbers of noctuid moths (a mixture of *H. punctigera*, *H. punctifera* and *A. munda*) active in the Cameron Corner area. Trap catches were low (totals of 10, 15 and 7 of the three aforementioned species in the four light traps and none in the pheromone traps). Using a spotlight, however, many moths could be seen flying at altitudes of up to 50 m. The temperature at sunset was 21°C, falling to 15°C by midnight. Surface winds were 20–40 km h⁻¹ from the north-west during the period from sunset to midnight. The wind direction shifted to westerly and began to fall at approximately 06.00 hours, shortly after sunrise.

At Wilcannia on the following night the wind speed had fallen to approximately 5 km h⁻¹ at sunset. Wind direction was westerly and the temperature at sunset was 16°C. A total of 242 *H. punctigera*, three *A. munda* and one *H. punctigera* were collected from the light traps. There were again no *Helicoverpa* spp. in the pheromone traps but substantial numbers of moths were observed around street lights. These were mostly *H. punctifera* but there were also some *H. punctigera* and *A. munda*, and 10 of each species were collected for pollen analysis.

On 24 September large numbers of both *H. punctigera* and *H. punctifera* were observed feeding and ovipositing on *I. brevicompta* and other hosts in the first half of the trip from Wilcannia to Bourke, up to 100 km north-east of Wilcannia. From approximately 160 km north-east of Wilcannia (east of approx. 145°E), much lower numbers were noted (Table 2; Fig. 3). We did not see *A. munda* during these flush counts.

Output from the migration model (Fig. 3) predicted that the fallout area for the night of 22–23 September extended

### Table 1

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Host</th>
<th>Very small</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
<th>Total</th>
<th>Rearing percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>29°57'S, 146°44'E</td>
<td>22 Sept</td>
<td>Medicago polymorpha</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>30°33'S, 146°39'E</td>
<td>22 Sept</td>
<td>Ixiolaena brevicompta</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>30°18'S, 145°37'E</td>
<td>22 Sept</td>
<td>Ixiolaena brevicompta</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>30°00'S, 145°34'E</td>
<td>24 Sept</td>
<td>Rhodanthe floribunda</td>
<td>0.6 ± 0.2</td>
<td>0.8 ± 0.5</td>
<td>0.0</td>
<td>1.2 ± 0.4</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>30°01'S, 145°04'E</td>
<td>24 Sept</td>
<td>Polycalyx stuartii</td>
<td>0.4 ± 0.2</td>
<td>1.4 ± 0.5</td>
<td>1.0 ± 0.0</td>
<td>0.2 ± 0.2</td>
<td>3.0 ± 0.6</td>
<td>0</td>
</tr>
<tr>
<td>30°36'S, 145°03'E</td>
<td>24 Sept</td>
<td>Ixiolaena brevicompta</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>30°48'S, 144°41'E</td>
<td>24 Sept</td>
<td>Ixiolaena brevicompta</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>31°07'S, 144°12'E</td>
<td>24 Sept</td>
<td>Ixiolaena brevicompta</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>31°13'S, 144°01'E</td>
<td>24 Sept</td>
<td>Ixiolaena brevicompta</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>31°28'S, 143°39'E</td>
<td>24 Sept</td>
<td>Ixiolaena brevicompta</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>26°59'S, 140°54'E</td>
<td>22 Sept</td>
<td>Polycalyx stuartii</td>
<td>2.8 ± 0.7</td>
<td>5.0 ± 1.1</td>
<td>3.8 ± 2.2</td>
<td>13.2 ± 1.7</td>
<td>72.2</td>
<td>27.8</td>
</tr>
<tr>
<td>28°59'S, 140°45'E</td>
<td>22 Sept</td>
<td>Senecio gregorii</td>
<td>2.3 ± 0.7</td>
<td>2.7 ± 0.3</td>
<td>2.3 ± 0.3</td>
<td>7.3 ± 0.7</td>
<td>54.5</td>
<td>45.5</td>
</tr>
</tbody>
</table>

Five sets of 20 sweeps were made at each location. Rearing percentage refers to the percentage of positive identifications made during the pupal or larval stage after rearing on artificial diet.

### Table 2

<table>
<thead>
<tr>
<th>Location</th>
<th>No. transects</th>
<th>Moths per 50-m transect</th>
</tr>
</thead>
<tbody>
<tr>
<td>31°28'S, 143°39'E</td>
<td>3 10.0 ± 1.5</td>
<td>17.0 ± 2.6</td>
</tr>
<tr>
<td>31°13'S, 144°01'E</td>
<td>3 16.7 ± 2.3</td>
<td>30.0 ± 7.0</td>
</tr>
<tr>
<td>31°07'S, 144°12'E</td>
<td>3 14.7 ± 2.4</td>
<td>16.3 ± 4.2</td>
</tr>
<tr>
<td>30°48'S, 144°41'E</td>
<td>2 1.0 ± 1.0</td>
<td>1.5 ± 0.5</td>
</tr>
<tr>
<td>30°36'S, 145°03'E</td>
<td>2 0</td>
<td>0.5 ± 0.5</td>
</tr>
<tr>
<td>30°18'S, 145°37'E</td>
<td>3 0</td>
<td>0</td>
</tr>
<tr>
<td>30°33'S, 146°39'E</td>
<td>2 0</td>
<td>1.0 ± 1.0</td>
</tr>
</tbody>
</table>

*Transects were 50 m long by 2 m wide.*

---

PC Gregg et al.

---

Table 1 Numbers (mean ± SE) per 20 sweeps of various size categories of larvae of *Helicoverpa punctigera* and *Heliothis punctifera*, collected on various hosts during the field survey

Table 2 Numbers (mean ± SE) of moths of *Helicoverpa punctigera* and *Heliothis punctifera* flushed by an observer walking through stands of *Ixiolaena brevicompta* on 24 September 1996*
for approximately 700 km south-east from Cameron Corner, and was approximately centred on Wilcannia. On the following night the predicted fallout area was much smaller, extending approximately 450 km to the east of Cameron Corner. This reflected the lower wind speeds and more westerly direction of the wind on 23–24 September.

Pollen analyses

At Cameron Corner the most common pollen on all three moth species was from the families Asteraceae and Myoporaceae (Table 3). Flowering species of both families were abundant in the region (P. stuartii, S. gregorii and numerous others from the Asteraceae, and Eremophila spp. from the Myoporaceae). Less commonly found was pollen from the Goodeniaceae, Caesalpiniaceae and (for A. munda only) from the Amaranthaceae. The latter was identified to species level, coming from Pilotus macrocephalus (R. Br.). All these plants were also commonly found in flower at Cameron Corner.

From moths caught around Wilcannia, the most common pollen was again Asteraceae and Myoporaceae, except for A. munda where pollen from Myrtaceae (Eucalyptus spp.) was the most common. Eucalyptus pollen was also found on H. punctigera and H. punctifera. Flowering Eucalyptus spp. were common around Wilcannia but were not seen around Cameron Corner. Pollen from the family Fabaceae (Swainsona spp.) was also found on H. punctigera from Wilcannia, as was pollen from Goodeniaceae on A. munda and H. punctifera.

No unique migration marker pollen (that is, from plants flowering at Cameron Corner but not Wilcannia) was found on any moth species at Wilcannia. At species level the composition of the flowering plant community at Cameron Corner was very different from that at Wilcannia. For example, in the Asteraceae P. stuartii and S. gregorii were abundant at Cameron Corner but absent from Wilcannia, where the dominant Asteraceae were I. brevicompta and Rhodanthe floribunda DC. Unfortunately the pollen from these four species could not be reliably separated on morphological criteria. The situation was similar in the Myoporaceae and Goodeniaceae.

Although it was not possible to identify a unique migration marker pollen, the overall moth-borne pollen loads were quite similar for all species from both locations. Of particular interest was the prevalence of pollen from Myoporaceae on moths from Wilcannia despite the relative shortage of these plants compared to that at Cameron Corner. The major differences in pollen loads, for all three species, were the greater proportion of moths with Eucalyptus pollen at Wilcannia, and the smaller proportion of moths which carried no pollen at all, compared to Cameron Corner. Both these trends were statistically significant (P < 0.05 by chi-squared analysis) for H. punctigera and H. punctifera, but not for A. munda where sample sizes were smaller.
Between moth species the major difference was the relative lack of pollen from Asteraceae on *A. munda* compared to *H. punctigera* and *H. punctifera*. This occurred at both sites although it was statistically significant only at Wilcannia.

**DISCUSSION**

Much of the evidence for noctuid migration throughout the world is circumstantial (Gregg 1995) because unequivocal demonstration of migration is often difficult. Noctuid moths fly at high altitude during the night, may cover hundreds or even thousands of kilometres, and are often inconspicuous by day and therefore difficult to detect in arrival areas. These problems are particularly severe in inland Australia where the human population is sparse and insect pests are rarely monitored because there are no crops.

Ideally, tracing a migration should include demonstrating a plausible source population and atmospheric transport mechanism, showing increases in populations in destination areas that cannot be accounted for by local population dynamics, and demonstrating the presence of a marker of origin, either natural or artificial, on the putative migrants. One of the few examples where most of these requirements have been met is that of the migration of *Helicoverpa zea* Boddie from the lower Rio Grande Valley to southern Texas (Westbrook et al. 1998).

Although not all of these requirements have been met in our study, we have provided some of the best evidence to date for long-range, multispecies moth migrations from the Cameron Corner region of inland Australia in spring. The distribution model predicted, and ground surveys confirmed, suitable breeding conditions with extensive areas of good host plants. Substantial moth numbers of all species had probably been present some weeks before the survey. Although trap catches on the night of migration were low, this was probably because high wind speeds made the traps inefficient. Spotlights revealed large numbers of moths, and many dead moths of all three species were found around lights at settlements in the region.

Further evidence of the extended presence of *H. punctigera* and *H. punctifera* in the source region is the finding of numerous large larvae (Fig. 2). Although no larvae of *A. munda* were found, the sampling technique was not suited to this species, larvae of which are rarely taken by vegetation sweeping. There were also suggestions of extensive moth flight on the night of 23 September, especially during the day.

There was a plausible atmospheric transport system on the night of migration. Cold fronts such as that shown in Fig. 1 have frequently been associated with insect migration, especially in the spring. Warm northerly or north-westerly winds ahead of them can produce temperatures favourable for take-off and sustained flight by moths and other insects. Observations of extensive moth flight on the night of 23 September also suggested that this was occurring even though the light-trap trap catches were low.

### Table 3

<table>
<thead>
<tr>
<th>Location, plant abundance, moth species</th>
<th>Number examined</th>
<th>Asteraceae</th>
<th>Myoporaceae-Myrtaceae</th>
<th>Fabaceae</th>
<th>Goodeniaceae</th>
<th>Caesalpiniaceae</th>
<th>Amaranthaceae</th>
<th>Unknown</th>
<th>No pollen</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cameron Corner</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant abundance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>H. punctigera</em></td>
<td>10</td>
<td>40</td>
<td>40</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td><em>A. munda</em></td>
<td>7</td>
<td>29</td>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>29</td>
<td></td>
</tr>
<tr>
<td><em>H. punctifera</em></td>
<td>10</td>
<td>50</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td><strong>Wilcannia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant abundance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>H. punctigera</em></td>
<td>10</td>
<td>80</td>
<td>40</td>
<td>20</td>
<td>20</td>
<td>+</td>
<td>++</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td><em>A. munda</em></td>
<td>10</td>
<td>10</td>
<td>60</td>
<td>40</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>H. punctifera</em></td>
<td>20</td>
<td>65</td>
<td>45</td>
<td>35</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>H. punctifera</em></td>
<td>10</td>
<td>30</td>
<td>90</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Percentages do not sum to 100 because some moths were carrying more than one type of pollen. Plant abundance is a subjective estimate of the extent and density of flowering plants in each family. +, present; ++, common; ++++, abundant.

* Moths collected at street lights in Wilcannia.
† Moths trapped 34 km north-west of Wilcannia.
catches were low. In the cooler south-westerlies behind cold fronts, conditions are less favourable for moth flight. Observations by the survey team of a shift in wind direction towards the south, a drop in temperature, and the passage of a cloud band suggested that the front passed through Cameron Corner shortly after daylight on 23 September. This would have meant that sustained migration to the south-east might have occurred during the night of 22–23 September but not on 23–24 September. These observations are reflected in the extent and direction of moth fallout predicted by the migration model (Fig. 3).

In the present study we did not have direct information about moth numbers in the destination areas (around Wilcannia) prior to the suggested migration. Inferences, however, can be made from the larval surveys and the distribution of moths recorded in flush counts. There were no larvae of _Helicoverpa punctigera_, suggesting that this species was not present in substantial numbers prior to 23 September. Adults were, however, collected around street lights on 23 September and they were found in large numbers during flush counts in the predicted moth fallout region for 23 September (Fig. 3).

There were a few _H. punctifera_ larvae found, indicating that small numbers of these moths had been present before the proposed migration. Whether they came from earlier migrations from the north-west or emerged from local over-wintering populations is not known. The large numbers seen in flush counts close to Wilcannia, however, and the very close fit of these counts to the predicted fallout area (Fig. 3) suggests that the pre-existing population of _H. punctifera_ was greatly augmented by immigration on the night of 22–23 September.

_Agrotes munda_ were not seen in the flush counts although they were present at lights in Wilcannia. Their absence from the flush counts may be because they appear to be strictly nocturnal, unlike _H. punctigera_ which are sometimes active during the day (Coombs 1992) and can readily be flushed from vegetation, as can _H. punctifera_ (PC Gregg, unpubl. data 1987–96). Another possible reason for the absence of _A. munda_ from the stands of _I. brevicompta_ that we sampled is that it is less attracted than the other two species to Asteraceae, a family that does not feature in the host list given for the species by Common (1990). This explanation would be consistent with the relative shortage of Asteraceae pollen on _A. munda_ at both Cameron Corner and Wilcannia (Table 3).

Moth-borne pollen can be a useful marker of long-distance migration (Hendrix et al. 1987; Gregg 1993; Lingren et al. 1993). For an unequivocal demonstration of migration it is necessary to find a marker pollen that belongs to a plant taxon that either does not occur, or is not flowering at the time, in the destination area (Gregg 1993). We found no such pollen, even though the flowering plant communities of the source and destination areas varied considerably. With a few exceptions moth-borne pollen is readily distinguishable at family but not at species level, and the floral differences between the Cameron Corner and Wilcannia areas at the time of the present study were mostly at species rather than family level. Nevertheless, the general similarity of moth-borne pollen loads in both areas adds support to the hypothesis of migration. Pollen taxa commonly found on moths at Cameron Corner were also common at Wilcannia (Table 3). The occurrence of pollen unique to the Wilcannia area, especially from _Eucalyptus_ spp., can be explained by postarrival feeding on these plants. This phenomenon has been found in previous studies of moth-borne pollen (especially _Eucalyptus_ spp.) on _Helicoverpa_ spp. (Gregg 1993).

In total, our findings provide support for the hypothesis of multispecies migrations in spring, from inland Australia towards the cropping regions in the south-east. These migrations are of both ecological and economic interest. The migration syndrome of an insect and its underlying genetic complex (Drake et al. 1995) reflect the selection pressures determined by the environment of the migration arena. In inland Australia during spring, high temperatures, variable and often low rainfall, high evaporation rates and the lack of suitable host plants make the environment unfavourable for continued breeding by the species we studied. Migration towards the south-east is a way of escaping these conditions. In many seasons a migration of 400–700 km (such as the one postulated here) would locate more favourable conditions. In spring 1996, however, most of the predicted fallout region except its far south-eastern edges would not have been suitable for breeding. Whether moths continue migration on subsequent nights in such conditions remains to be determined, although circumstantial evidence from trap catches suggests that _H. punctigera_ does so (Gregg et al. 1995; Rochester 1999).

From an economic viewpoint the migration we studied would have taken moths to regions where susceptible crops (especially grain legumes) were being grown, but only at the extreme south-eastern limit of the predicted fallout area. Continued migration would have been required to infest major cropping regions and successful breeding in destination areas would have been required for infestation of summer crops such as cotton, sorghum, maize and oilseeds.

The findings of the present study suggest that the winter breeding and migration models of Rochester (1999) are useful predictors of medium- and short-term spatial and temporal changes in populations of _H. punctigera_ and _H. punctifera_, producing grounds for optimism on the prospects of forecasting outbreaks of these and other migratory pest species.

**ACKNOWLEDGEMENTS**

We thank Peter Garlick and Rick Porter (University of New England) for assistance with scanning electron microscopy and pollen identification, and Alistair Drake (Australian Defence Force Academy) for critically reading the manuscript.

**REFERENCES**


Accepted for publication 31 January 2001.
Copyright of Australian Journal of Entomology is the property of Wiley-Blackwell and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.