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COTTON RESEARCH AND DEVELOPMENT CORPORATION

Project Title: Quantifying Local Movement and Colonisation of Cotton Crops By Adult *Heliothis*.

Project Code: CSE3C

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FINAL REPORT

Aims:

(i) to quantify the contribution of alternative host crops to the dynamics of *Heliothis* on cotton using an elemental analysis technique developed in a previous project.

(ii) to study the colonisation of cotton crops by adults and subsequent development of populations using night vision devices, pheromone and light traps and direct sampling techniques.

(iii) to quantify the catch efficiency of pheromone traps and factors affecting efficiency in cotton at different times of the season.

(iv) to study patterns of local movement from discrete source crops, using mark-recapture, elemental analysis, night vision devices and trapping systems.

1. Quantifying intercrop movement using elemental analysis.

A technique to identify the host crop of *Heliothis* moths by analysis of elemental content has been progressively developed over several seasons (CRC Project CS13L, Fitt 1986). In this grant period we finalised statistical analyses of the existing database for individuals from known hosts and have developed a procedure for allocating unknown individuals collected in cotton crops to probable hosts (developed by Dr. Richard Morton CSIRO Biometry Unit). The procedure (based on Newton's method with gradient matrix calculated by formula) allows for moths to be allocated to one of five major host crops or to a class derived from none of the major crops and includes a facility to use only a subset of possible hosts in an allocation run. The procedure gives acceptably accurate estimates of the proportion of a sample of moths derived from major hosts, though to date it has been validated nsing the same database as used to produce it. Further data for individuals from known hosts is being collected this season for validation purposes. We have commenced processing elemental data for unknowns collected in 1985/86 using the procedure but have encountered a problem which may be due to dust contamination of field caught moths. The elements Fe, P, and Mn are the most important in discriminating moths from different crops (accounting for 85-90% of the variation), but most of the moths taken from traps show levels of Fe (and Al and Si) outside the range of any of those reared from crops, while levels of other elements are similar to those for moths reared on

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crops. Elevated concentrations of Fe, Al and Si are characteristic of sample being contaminated with soil, which may easily occur in pheromone traps from which the moths are collected.

There are several other possible explanations for this anomaly; elemental profiles may change as moths age, mated males may have a different profile to virgins, or flight activity may alter the balance of elements. These possibilities were explored with a series of experiments using male H. punctigera moths from a chickpea crop. Elemental profiles were determined for males of different age, for mated and unmated males of known age and for "flown" and unflown males. As yet these results have not been fully analysed, but it may be necessary to rework the allocation procedure excluding Fe, albeit with considerable loss of discrimination. Elemental analyses of moths collected at several sites in cotton over the 1985/86 to 1987/88 have been completed. Analyses of the 1988/89 samples will commence shortly giving elemental profiles over four full seasons. The information provided in this way will be invaluable to validation of the *Heliothis* population dynamics model and for interpreting past patterns of insecticide resistance in *H. armigera.*

2. Nocturnal behaviour and measurements of trap responsiveness.

In 1988/89 a 10 ha block on the research station was sown with two 4 ha. blocks of cotton separated by 1 ha. blocks of maize and pigeon pea. The maize (sown Sept. 19) produced an emergence during January, while the pigeon pea (sown Dec. 16) produced adults in early March. The development of populations on all crops was monitored by visual sampling for eggs and larvae and by a grid of pheromone and light traps. One period of nocturnal observations using Night Vision Goggles (NVG) was completed (Dec. 14-18) coinciding with silking of the maize crop. The aim was to quantify the densities of *Heliothis* adults active throughout the night within each crop and at crop boundaries and to measure the efficiency of pheromone traps.

Unfortunately the general scarcity of *Heliothis* throughout the Namoi Valley in 1988/89 greatly limited the success of this work. Very few eggs were laid on any crops and only small populations of pupae were produced on the maize and pigeon pea. Nocturnal observations were discontinued after the December session, except for a few nights during February and March.

In the second season (1989/90) an 8 ha block on the research station is being used. This was sown with 4 ha of cotton (2 ha on each end), and 2 ha each of maize and pigeon pea. Again the maize will produce a January emergence of *H. armigera* and the pigeon pea a March emergence. An additional 8 ha block was sown with chickpea to allow observations of the development and emigration of a spring population.

Two periods of intensive nocturnal observations were completed. During each period a series of observations were made using a variety of techniques, some associated with Project CSE7L. The first period of nocturnal and radar observations was completed (November 29-December 12) coinciding with emergence of the approximately 1.3 million moths from the chickpea (a mixture of *H.punctigera* and *H. armigera*) and the start of silking of the maize. Most details of the nocturnal observations and measurements of activity and movement are described in Drake and Fitt (1990, attached).

Data was collected for the first time on the timing of adult emergence from the soil throughout the night and of the initial flight. Emergence occurred from 2000 to 0100, with a peak between 2100 and 2200. Most moths took off on their initial short flight about 2 hours after emergence. In general these flights do not take the moths far from the emergence site. Major take-off and emigration from the emergence site occurs at dusk on the following night. We also quantified this dusk take-off for comparison with the radar observations, by recording the number of moths undertaking rapid vertical flight out the chickpea. We were able to confirm that such vertical take-off does occur, with moths climbing almost vertically to about 10 metres above the crop, thence climbing at about 60^{o} in the direction of the prevailing wind. Peak vertical take-off occurred between 2010 and 2025 each night, though there was great variability in numbers taking off each night, which was not related to the numbers which had emerged the previous night. Similar observations will be made during the January and March emergence periods.

An impontant consequence of our direct observations of moths behaviour around crops has been the discovery of a previously undescribed behaviour in *Heliothis* in which adults turn back, or rebound, into an attractive crop when they encounter the patch boundary. The behaviour was first observed at boundaries between maize and cotton crops and between cotton and fallow. Observations in the 1990/91 season further confirmed the occurrence of the behaviour at boundaries of maize/ sunflower, sorghum/cotton and sorghum/sunflower crops both at NARS and at sites on the Breeza Plain and near Toowoomba. Rebounding into the crop was most intense around silking maize crops and much less pronounced on the other crops. The observations show that moths are able to perceive and respond to crop boundaries and that their movements may be effectively constrained to an attractive host patch once colonisation has occurred. Whether moths respond to the physical boudary or some chemical gradient is not yet known, though the rapidity of response (within 1 m of the edge) suggests a response to the physical edge of the canopy. This may explain why the behaviour was most pronounced on maize (the tallest crop observed). The observations warrant further investigation and have implications in understanding the process of host location and the use of trap cropping as a means of managing *Heliothis* (3,4).

Measurements of pheromone trap efficiency were made at monthly intervals during 1989/90 season. As in the past canister traps proved highly inefficient at all times, capturing only 2-5% of moths attracted to them. These spring trap observations confirmed that the characteristically high trap catches at that time are not due to improved trap efficiency when nights are cooler, but reflect enormous densities of moths. Males were observed responding to traps at temperatures as low as 7^{o}.

3. **Mark-recapture studies of *Heliothis* movement.**

Mark-recapture studies of moth emigration from source crops were conducted in spring of both 1989/90 and 1990/91 to coincide with the other observations of emergence and local movement. The aim was to label each of the source crops with the heavy metal strontium (in the form of strontium chloride, $StCl_2$) in an attempt to mark the naturally produced population of moths. Chemical analysis of moths trapped in a widespread network of traps then shows the direction and distances travelled by moths produced at the discrete source. Preliminary studies were conducted in 1988/89 with maize and pigeon pea. Labelling of the maize crop with two applications of $StCl_2$ (@3.0 kg/ha) was unsuccessful; only 1 of 50 moths analysed being marked. However, excellent results were obtained with pigeon pea. A range of concentrations from 10 to 80 kg $StCl_2$ was applied. Plant tissues and 90-95% of the adult moths produced were unequivocally marked by applications of 10-20 kg./ha. However, the total population produced on pigeon pea in that year was too small to consider a mark-recapture experiment.

In the 1989/90 a highly successful experiment was completed with a marked population of both *H. armigera* and *H. punctigera* produced on a spring crop of chickpea. All details of this work are given in Fitt and Pinkerton (1990, attached). A total of 1.2 million moths (38% *H. armigera*, 62% *H. punctigera)* were produced from the chickpea crop, of which about 30% were unequivocally labelled. Of these 240 labelled *H. armigera* and 28 labelled *H. punctigera* were captured in the trapping network. Further analyses of these results (6) showed that *H. armigera* was less mobile than *H. punctigera* with a high proportion settling on crops within 10km of the source crop, whereas most of the *H. punctigera* moths appeared to leave the study area altogether.

Attempts in that season to label a population of *H. armigera* on maize were again unsuccessful.

In the 1990/91 season a mixed population of *Heliothis* was again successfully labelled on chickpea. This crop produced an estimated 1.04 million moths (73% H. armigera, 27% H. punctigera). A total of 4,340 captured moths from the recapture network were analysed for strontium. However, because the background population of *Heliothis* spp. was much larger in that year (in contrast to 1989/90), a total of only 19 marked moths were captured (in contrast to 268 in the previous season). Detailed statistical analysis of this experiment is not yet complete.

Major Results from This Project.

1. Nocturnal observations of *Heliothis* activity using a variety of techniques provided valuable details and parameters needed to model movement in the associated Project CSE5C.

2. A previously undescribed behaviour pattern was observed in adult *Heliothis* which shows that moths are able to perceive and respond to boundaries and that their movements may be effectively constrained to an attractive host patch once colonisation has occurred.

3. The timing of emergence and first flight were quantified for the first time for Australian species, showing a peak of emergence between 2100 and 2200. First flight occurred approximately 2 hrs after emergence.

4. Mark-recapture was used successfully to demonstrate significant differences between *H. armigera* and *H.punctigera* in local movement. *H. punctigera* was confirmed to be more mobile than *H. armigera* , and may be an obligate migrant species. Both species were shown to be able to locate and colonise small areas of highly attractive hosts (safflower) despite the presence of large areas of squaring cotton. Further studies of *H. armigera* movement during summer will be undertaken under a new project CSE24C.

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A MARK-RECAPTURE STUDY OF *HELIOTHIS* MOVEMENT FROM A SOURCE CROP IN THE NAMOI VALLEY.

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Introduction

The potential for extensive adult movements is one of the key factors contributing to the success of *Heliothis* spp. as pests (Farrow & Daly 1987, Fitt 1989). Adult movements may occur on several spatial scales; from one field to another, between areas within a valley or between regions (see Gregg et al 1990). Quantitative information about adult behaviour, and movement in particular, is required for the *Heliothis* population models currently being developed to provide forecasts of infestations on cotton crops (Dillon & Fitt 1990). There are a number of questions to be answered and these are being tackled using a range of techniques (Drake & Fitt 1990) to provide a comprehensive picture of *Heliothis* movement. In particular we are interested in the behaviour of newly emerged moths produced from crops within the cotton areas. How far do these moths fly before colonising a crop in which to lay eggs? When do they leave? How do they move in relation to the wind? What characteristics of crops cause moths to leave or stay within them to mate and lay eggs? To answer some of these questions we are conducting a series of mark-recapture studies at Myall Vale.

Mark-recapture techniques

Mark-recapture is a technique widely used in studies of insect movement, and has been used elsewhere with *Heliothis* (King et al 1990). It involves marking a large number of insects with a specific identifying mark, releasing them at a known location and later recapturing them, usually by a network of traps. By analysing where the marked insects are recaptured it is possible to calculate the average distance moved in different directions and relate this to various environmental parameters (wind directions, crop attractiveness etc.). In addition an analysis of the proportion of captured moths which are marked can provide estimates of the total population of moths within the study area. Most mark-recapture studies have involved the release of laboratory reared insects marked with a coloured dye or being from laboratory colonies, may not behave in the same way as the natural population. Laboratory insects may not fly as stongly or may not respond normally to environmental cues. Second, the application of the marking agent (dust, dye etc) may alter the survivorship or behaviour of the insect. Third, the insects may be so disturbed by the marking and release procedure that their initial dispersal flight from the point of release is more akin to an escape reaction than to natural emigration behaviour. An alternative approach, which we have used, is to mark a naturally occuring population of insects and then allow them to emigrate from the site without disturbance.

Methods

Producing a population and marking techniques

Large populations of *Heliothis* were produced on specially grown crops at Myall Vale. In the 1989/90 season these were chickpea (spring), maize (summer) and pigeonpea (autumn). This paper deals only with the spring population produced on chickpea (6.2 hectares). The crops were exposed to oviposition by the natural *Heliothis* population and insects were not controlled in any way so as to build high densities of larvae.

To mark the population we used Strontium, a naturally occurring, but rare heavy metal. *Heliothis* moths in the Namoi Valley normally contain strontium at very low concentrations (3-4 parts per million (ppm)). We produced moths with elevated levels of strontium (10-50ppm) by spraying the crop with an aqueous solution of strontium chloride (SrCl) when the larvae were small to medium (3rd-5th instar). The SrCl forms a deposit on the plant surfaces and some is absorbed and transported around the plant. Larvae ingest the SrCl during feeding and a proportion of the resultant adults carry increased levels of strontium. The crop was sprayed 3 times (Oct.31, Nov.3 and Nov.8) with SrCl at a rate of 9-10kg/ha (plus 0.1% Monsoon surfactant/ sticker) at high volume (approx. 560 l/ha). Three applications were applied since the first two were followed immediately by rain (11.2 and 23.2mm respectively) which may have removed much of the strontium from the foliage. One area of the crop (8m x 100m) was left unsprayed to provide estimates of natural levels of strontium in moths.

Emergence and Recapture

Estimates of pupal density were obtained on six occasions (9/11, 15/11, 22/11, 29/11, 6/12, 13/12) by sampling ten to twenty $1m^2$ areas of soil uniformly distributed over the field. Emergence of the population was monitored by means of 20 cages, each 1m x 1m, distributed throughout the field. Moths were collected from these each day to provide a measure of the numbers and species composition of adults which had emerged the previous night. All moths from the pupal samples and from the emergence cages were analysed for strontium content so that numbers of marked and unmarked moths could be determined. Moths from the control (unsprayed) area were collected on 3 nights as they emerged from the soil.

A network of pheromone traps was established to recapture male moths from the marked population. A total of 50 pairs of traps (1 *H. armigera* and 1 *H.punctigera*) were distributed within a circle of approximately 10 km radius centred on the chickpea crop (a recapture area of 314 square kilometres). One set of traps was in the chickpea crop where moths were emerging while the remainder were mostly positioned near attractive crops (44 pairs in cotton, 3 in safflower, 1 in sorghum, 1 in maize and 1 in fallow). The traps were cleared about every 2 days from November 29-December 20 covering the period of adult emergence from the chickpea. All the trapped moths were counted and stored for strontium analysis.

Strontium Analysis

All moths from the pupal samples, from the emergence cages and from the recapture traps were individually analysed for strontium content using wavelength-dispersive X-ray spectroscopy (at CSIRO Plant Industry, Canberra). Each moth was first oven dried at 80^{o}. It was then weighed and an equal weight of a 1:1 mixture of boric acid and glucose powders was added. The moth and diluent were then ground in an agate pestle and mortar, and pressed into a small, thin pellet from which the concentration of strontium was determined automatically using the X-ray spectrometer.

Results and Discussion

Emergence

The chickpea crop commenced flowering in mid-September and substantial numbers of eggs were laid from September 29 to October 12 (Julian date 272-285, Fig.1). Larval densities of up to $60/m^2$ were recorded and a final population of 20 $pupae/m^2$ was produced (1.21 million pupae in total). From these a total of 1,063,300 adults emerged successfully; 43% *H. armigera* and 57% *H. punctigera*. Adult emergence began in late November (Jday 328). As Figure 1 shows the HEAPS model quite accurately predicted the phenology of emergence (see also Dillon and Fitt 1990), though the natural emergence peak was more extended than that predicted.

Analyses of the chickpea plants after each application of strontium chloride showed that most of the deposit was on the surfaces of leaves and pods (2200ppm and 300ppm respectively compared to 200ppm and 90ppm in the leaves and pods of untreated plants). Concentrations in the seeds were almost doubled (18 to 31ppm), indicating that some strontium was absorbed and translocated around the plant. Medium and large larvae feed mostly on the developing seeds of chickpea but they would also have ingested some of the marker when chewing through the pod walls to gain access to seeds.

The mean strontium content of moths produced on the chickpea were significantly elevated (Table 1). Moths were deemed to be unequivocally marked if they contained 10ppm or more (dry weight) of strontium. This is a conservative figure since the upper 95% confidence limit around the mean strontium content of males from the unsprayed control area was 3.61 ppm strontium (Table 1). Using the 10ppm criterion about 30% of all males which emerged were unequivocally marked (*H. armigera* -32%, *H. punctigera* - 29%). Thus a total of approximately 150,000 marked males moved out of the crop. By contrast 41% of the females were marked. The reason for this difference is not clear, but has been observed in other studies (King et al 1990). This level of marking is somewhat disappointing but may have been due to our inability to apply sufficiently high volumes of spray. Other studies have achieved levels of around 50% marked (King et al 1990), and in preliminary experiments here we achieved 90% successful marking when Sr Cl was applied by knapsack to pigeon pea.

Figure 1. Numbers of eggs laid and moths emerged from chickpea crop. For moths the figure shows actual emergence and the predicted emergence from the HEAPS *Heliothis* model (simulating from Oct. 26, Jday 299) (note different axes for eggs and moths)

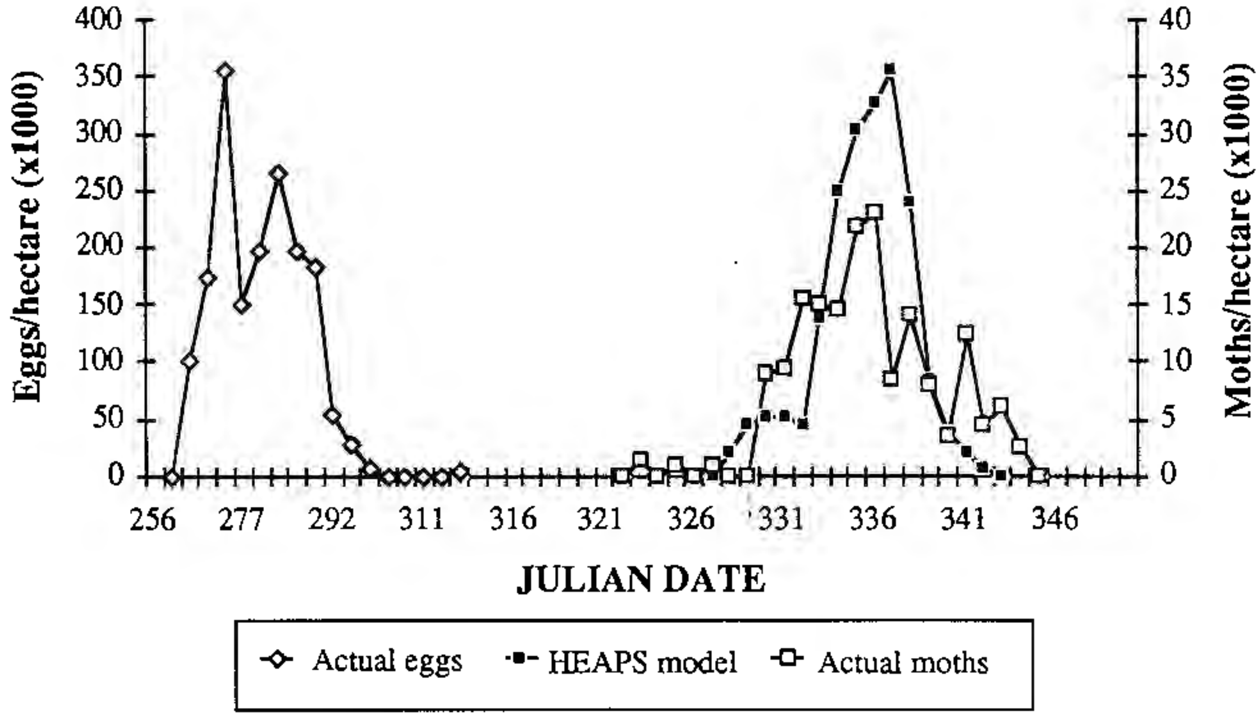
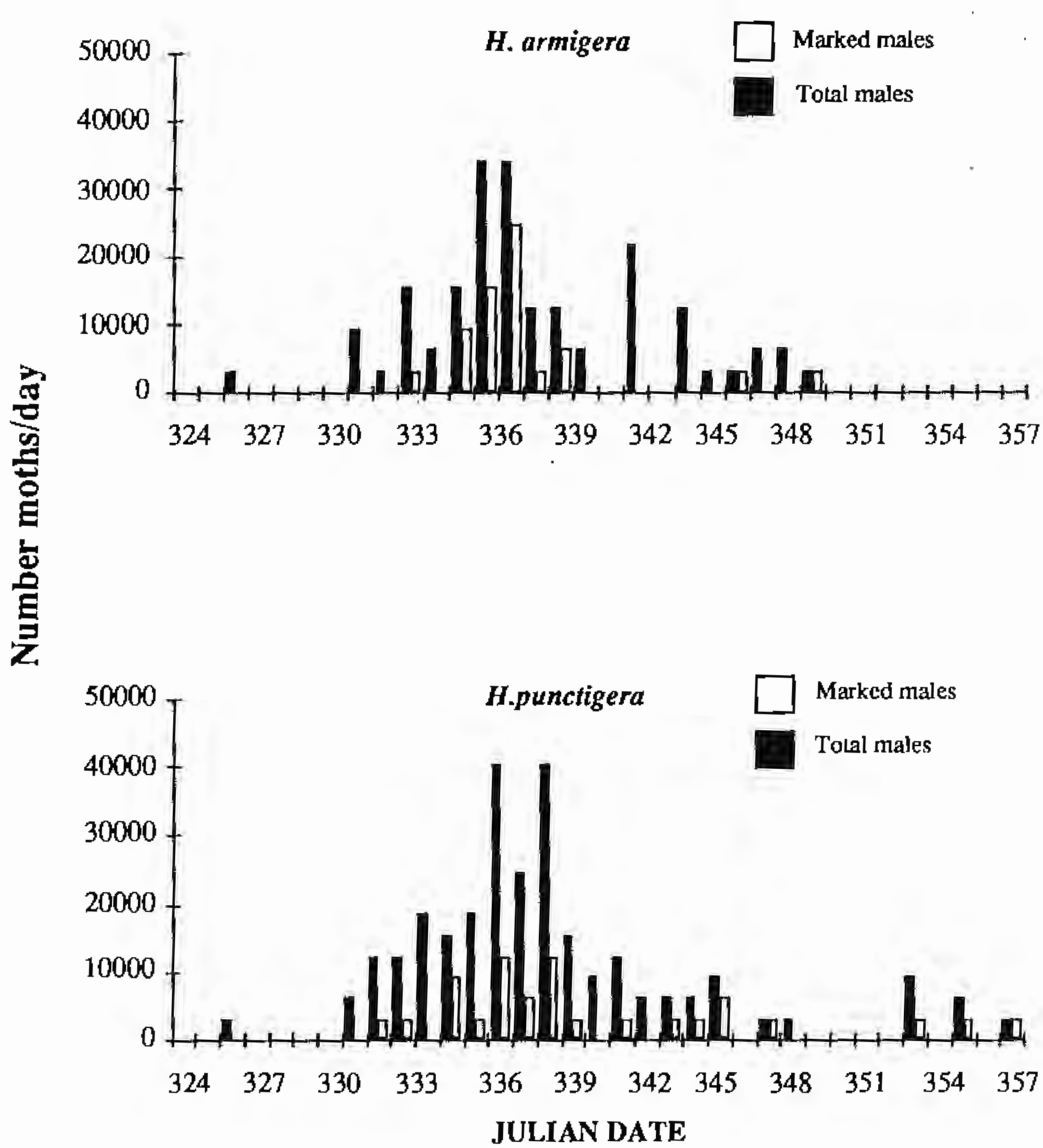


Figure 2. Emergence of total and labelled (>10 ppm strontium) male *H. armigera* and *H.punctigera*



Since only male moths were recaptured in the pheromone trap network the remainder of this paper refers only to the male portion of the population. Figure 2 shows the period of emergence of marked and total males of both species. The earliest moths to emerge were not marked, probably having pupated before the marker was applied. The bulk of the marked males emerged during the period from November 30 - December 7 (Figure 2).

Table 1. Mean strontium content (ppm) of *Heliothis* moths which (i) emerged from the unsprayed chickpeas (controls) (ii) those collected as pupae and (iii) those collected as they emerged from the areas sprayed with strontium chloride.

Group	Sex	Mean Sr (ppm)	Range	95% confidence limits lower	upper
(i) Controls	Male	3.07	0.5-11	2.52	3.61
(unmarked)	Female	3.66	0.5-10	2.72	4.60
(ii) Collected as	Male	7.42	0.5-77	6.34	8.50
pupae	Female	11.58	0.5-156	9.85	13.31
(iii) Collected in	Male	8.43	0.5-69	6.97	9.88
emergence cages	Female	12.25	0.5-78	10.29	14.21

Recaptured moths

A total of 12,000 moths were trapped during the total emergence period from November 28-December 25. These preliminary results are based on analyses of 3964 moths completed to date (June 1990) and focuses on the main emergence period (Nov.30-Dec. 12). During this period a total of 5250 *H. armigera* males were trapped of which 8.8% were marked, while 3172 *H. punctigera* males were trapped of which only 2.3% were marked. These high levels of capture of marked moths relative to the unmarked population arise because we were lucky enough to conduct the study in a season when the natural *Heliothis* population was not abundant. When the level of unequivocal marking (30%) is taken into account the data suggests that about 27% of the total *H. armigera* population in the recapture area was produced on the source crop, while about 7% of the *H. punctigera* population was from the chickpea source.

There are a number of ways we might analyse the recapture data, and these analyses are far from complete. Nevertheless some striking patterns are apparent. Firstly we can crudely analyse recaptures by distance from the source by aggregating trap sites into annuli of 500 metres (ie. all traps between 0 and 500 metres, 500-1000, 1000-1500 and so on). We can then ask what proportion of moths captured within each distance were marked and how many marked moths were captured at each distance (proportion marked multiplied by the total number of moths captured). Figure 3 shows these two results for the two species. For *H. armigera* a high proportion of moths captured close to the source were marked (most of these were in an adjacent silking maize crop), with a general decline in % marked with distance (y = -0.411 x + 12.35, R^2=0.36). Even so 11 marked *H. armigera* were recaptured at 9800 metres (in a safflower crop, see below) and 5 were recaptured as far as 13 km away (in a couple of traps outside the main recapture network).

For *H. punctigera* the proportion of marked moths was clearly much lower, but there was no decline in this proportion with distance (y = -0.067 x + 2.40, NS). Since more marked *H. punctigera* left the chickpea than *H. armigera* (85,500 vs 64,500 (males only)) the results suggest the majority of the *H. punctigera* left the trapping area altogether whereas many of the *H. armigera* colonised crops within 10 km of their emergence site.

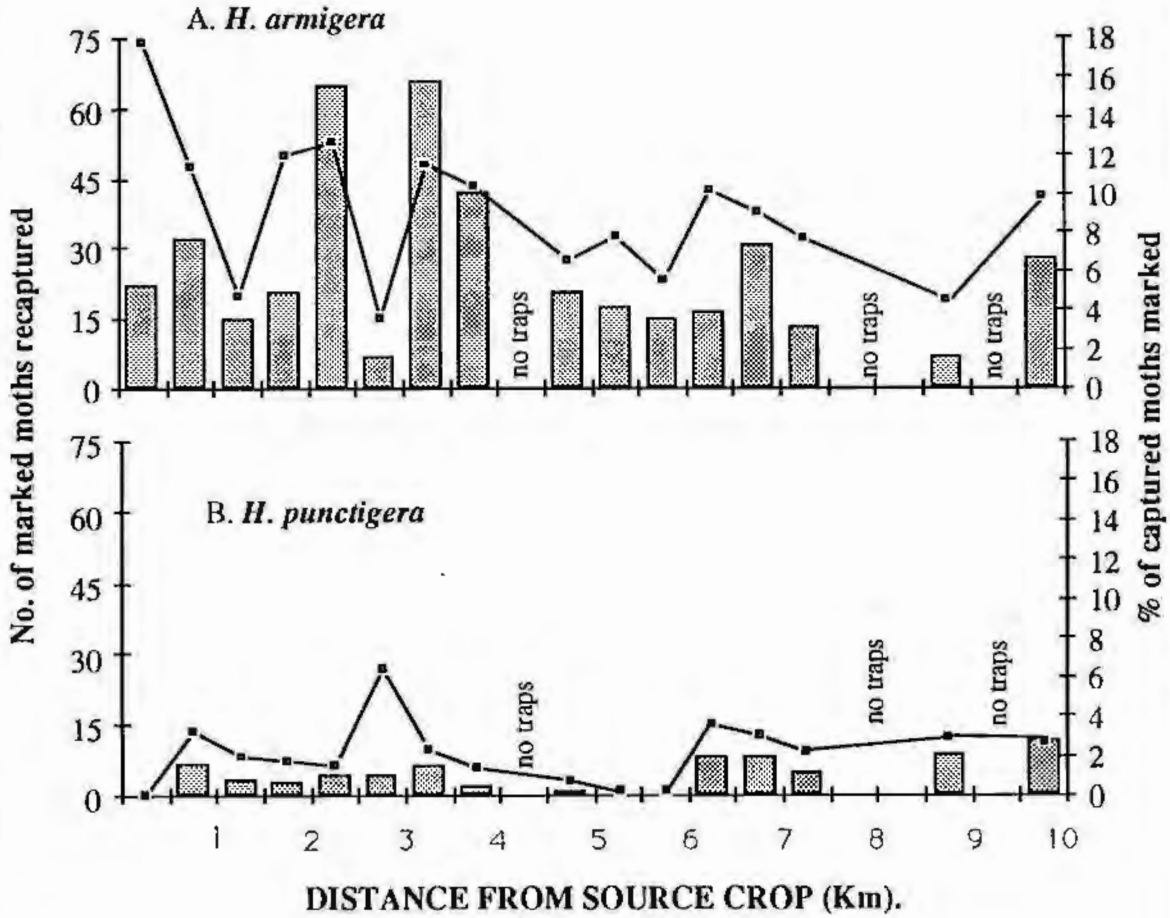
Closer analysis of the recaptures shows just where the moths ended up. Of the marked *H. armigera* which were recaptured, 27% (73 of 240 marked *H.armigera*) were in 4 traps in safflower crops which were flowering at the time. These were at 2200 and 3380m to the south-east, 3820 to the NNW and 9850m to the NNW from the chickpea. A further 17% were caught in a group of 4 adjacent traps in cotton crops at distances of 4800-6200 metres to the south of the crop. A further 10% were caught in traps in the source crop or within 100m of it. Thus over half the marked *H. armigera* moths were caught in just 11 of the 50 traps.

Of the marked *H.punctigera* captured none were within 500 m, while 25% were caught in the four safflower traps (7 of 28 marked *H.punctigera*).

Conclusions.

A major advantage of this study was that we were able to quantify the movement of a natural population of both species from the one source and were able to do so at a time when *Heliothis* were generally not abundant, thus maximising our chances of

Figure 3. The percentage of trapped males which were marked (•——•) and the number of marked males captured (% marked * total moths captured) (histogram) at different distances from the source crop.



recapturing marked moths. It may well be that these conditions will not pertain in the future, though we plan a repeat study next season.

The results appear to confirm that *H. punctigera* is more mobile than *H. armigera* (Farrow & Daly 1987) and is a obligate migrant (ie. much of the population leaves an emergence area irrespective of local conditions), whereas *H. armigera* is more a facultative migrant which colonises nearby crops if these are suitable for reproduction. The majority of the *H.punctigera* which emerged from our crop appear to have left the study area altogether and thus flew at least 10 km (and probably much further) even though suitable host crops were present nearby. This interpretation is supported by observations of emigration behaviour using other techniques (Drake & Fitt 1990). It is important to realise nonetheless that this was only one study conducted under one set of environmental parameters. Newly emerged moths may move differently when conditions are different. For example, how would *H. armigera* moths behave if they emerged from a chickpea crop set in the midst of large areas of pasture where few hosts were present nearby ?

A major disadvantage of this type of recapture study is that we monitor only the movement of males and must infer that females move similarly. This is unfortunate since half the moths leaving the source crop were females and a higher proportion of these were marked. Nevertheless it is not practical to operate the large numbers of light traps (and sort the catches!) which would be required to recapture both sexes. In the coming season, when this study will be repeated, we plan to operate up to 10 light traps in strategic locations, in addition to the pheromone trap network.

The results indicate that squaring cotton was much less attractive to both species than was flowering safflower. The emergence site was surrounded in all directions by cotton crops over which the moths would have flown to locate the safflower crops. Although safflower made up only a small proportion of the cropped area many of the *H. armigera* were captured there. This demonstrates that *Heliothis* adults are able to locate small areas of highly attractive crops and highlights the potential for using trap crops in combination with repellants applied to cotton in *Heliothis* management (as suggested in the push/pull strategy by Pyke et al 1986).

What do these results mean for the further development of the HEAPS population model? In HEAPS we explicitly model the movement of adults using a set of simple rules which summarise our understanding of how moths behave. The aim is to predict how a population of moths emerging from one point will be re-distributed throughout a region. Low level wind speed and direction are major factors influencing this movement. Further analysis of these results and those from complimentary radar studies (Drake & Fitt 1990) will allow us to better quantify parameters relating the influence of wind, which we monitor continuously, and crop distributions on the re-distribution of moths.

Acknowledgements.

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Studies of *Heliothis* mobility at Narrabri, summer 1989/90.

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Introduction

The importance of population movement in the development of *Heliothis* infestations, and in the maintenance of pesticide resistance within these populations, is increasingly being recognised (Fitt 1989). Egglaying in a susceptible crop may arise from moths that have emerged elsewhere, perhaps in a neighbouring field where an alternative host plant is starting to senesce, or perhaps at greater distances in dryland crops, pastures, weeds, and native vegetation. With wind assistance, movements of a few hundred kilometres overnight are possible, and have in fact been recorded for *H. punctigera* (Drake *et al.* 1981, Drake & Farrow 1985).

Information about the frequency and intensity of immigration and emigration movements is essential for forecasting *Heliothis* infestation levels in crops, and thus for developing more efficient strategies for managing this pest. In particular, there is a specific need for this information for incorporation into computer models of *Heliothis* population processes that are being developed as aids to pest managers (Dillon & Fitt 1990). To meet this need, a comprehensive study of *Heliothis* movement is being undertaken at Narrabri Agricultural Research Station by researchers from CSIRO's Division of Entomology. In this paper, we outline the research methods being used and present some preliminary results for the first full season of observations, 1989/90.

Methods

Because *Heliothis* movements occur over a range of scales, and with the moths flying at heights from just above the canopy up to about 2 km, a variety of methods is required to determine the frequency and extent of movement. Some of these methods are aimed at particular distances of displacement (or, and almost equivalently, at particular heights of flight), while others provide complementary information about the same type of movement. For example, direct observation of movement will often provide quantitative measures of migration intensity and direction, and the variation of these quantities with time, but it will usually need to be complemented by sampling in order to establish the identity of the migrants and to enable their sex and physiological state to be established.

A strength of the present study is that a wide variety of methods are being used simultaneously, so that the relative frequency of different types of movement can be assessed.

In order to provide sufficient moths for observations and sampling to be effective, special crops were grown specifically as sources of *Heliothis*. The crops were selected because of their ability to carry large numbers of *Heliothis* through to maturation, and were unsprayed. Three crops were grown in 1989/90 (6 ha of chickpeas in spring, 2 ha of maize in summer, and 2 ha of pigeonpeas in autumn), but only the first two produced a suitable study population. The field program was timed to cover the period of emergence of moths from the source crops, and the observations were made within them or in their immediate vicinity. The emergence sites were almost surrounded by cotton crops, which were attractive to *Heliothis* during both study periods.

Emergence timing and intensity. Oviposition within the source crops and the subsequent development of larval populations was monitored by regular surveys which also provided estimates of the density of the infestation. Pupal densities and development were similarly monitored by sampling the soil. The timing of emergence was forecast using the development submodel of the "HEAPS" *Heliothis* population-simulation model (Dillon & Fitt 1990), using conversions for soil and canopy temperatures appropriate for each crop. These results were used to determine whether the moth emergence was likely to be sufficiently intense for detailed observations to be effective, and when these observations should begin. On the basis of this monitoring, intensive observations were made during the two periods 29 November–12 December 1989 (emergence from chickpea) and 16–30 January 1990 (emergence from maize).

Emergence was monitored by means of 20 traps each of area 1-m^2 which were distributed throughout the source crop. These were checked daily and the number and sex of each species, and the number of parasites, were recorded. Regular searches for newly emergent adults were also made along transects through the crop on most nights, so that the timing of emergence, and of the subsequent first flight, could be established.

Cotton crops around the source crop were monitored for eggs and larvae every few days. The egg counts provide an additional indication of moth population levels resulting from local emergence or immigration.

Short-range movements. Short-range movements (those into adjacent fields and out to distances of a few kilometres) usually occur at low altitudes, and are therefore relatively easy to observe directly and to sample. In addition, mark-and-capture type studies are much more practicable if the distance of dispersal from the source region, and hence the reduction in density of the marked population, is relatively small.

At Narrabri, short-range movements were studied by direct observation, sampling of moths in flight, and a mark-and-capture study. The direct observations were made with night vision goggles (using an infra-red spotlight to illuminate areas of the field), a stereoscopic video system (January 1990 only), and the CSIRO Entomological Radar. The first two provided information on flights at particular localities in the source crops and adjacent cotton fields, both immediately above the canopy and at heights around 10 m, while the radar showed movements at heights of 5–20 m over an area of about 5 km^2 around the source crop. During the summer observation period, the radar was also used to monitor flight activity at heights of 2–10 m over a fallow field adjacent to the source crop. Sampling was undertaken at heights of 2–4 m with an 8-m^2-aperture vehicle-mounted net and at 8–12 m with a 12-m^2-aperture windsock-type net on a tower. The vehicle was driven around a 4-km circuit, mainly between cotton crops and with the source crop near the centre, while the tower was located about 500 m from the source crop. In the mark-and-capture study (Fitt & Pinkerton 1990), moths raised on the chickpea crop were marked with strontium (a rare heavy metal) sprayed on the plants when larval feeding was at its peak. Adults were then captured in a network of pheromone traps extending in all directions out to 10 km.

Long-range movements. Long-range movements, which typically cover distances of 50–300 km and would carry moths to or from the farthest regions of the Namoi valley cotton-growing area, and perhaps beyond it, occur at altitudes of 100–2000 m. Quantitative observations of migration at these heights were made with the CSIRO Entomological Radar, and sampling was undertaken at 100–200 m with a 1-m^2 aperture kite-borne net. Sampling at higher altitudes with an aircraft-borne net had been planned but did not occur because the radar indicated that insect numbers at these heights were so low that it was unlikely that even one individual would be caught. Some indication of the identity of these high-flying migrants can be obtained from radar measurements of target size and wing-beat frequency.

Observations of the initiation of long-distance movement were made by visual observations of emigration flights at dusk. Ascending moths were observed through binoculars against the light of a clear western sky. This take-off flight was also studied with the radar, by measuring the increase in the number of insect targets that occurs at dusk, and by observing plumes of moths ascending and dispersing away from localised source regions such as the experimental crops.

Preliminary results

Emergence. Pupal densities and the number of each species emerging are shown for each source crop in Table 1. *H. punctigera* (57%) was more numerous than *H. armigera* (43%) on the first (chickpea) crop, but only *H. armigera* was produced on the maize. Losses

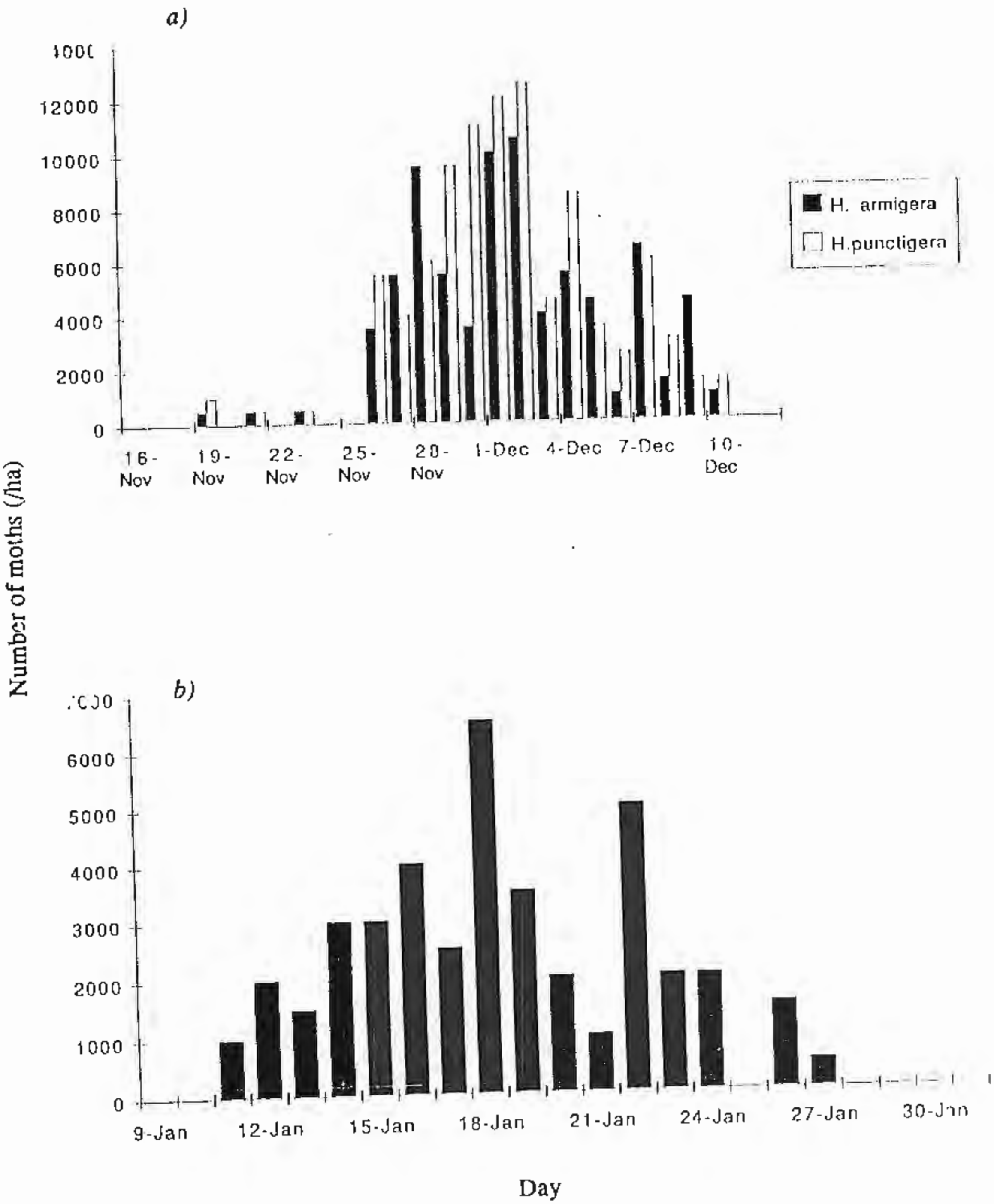

Fig. 1. Emergence of *H. armigera* and *H. punctigera* from source crops at Narrabri Agricultural Research Station, summer 1989/90. *a)* From chickpea (8 ha), November-December 1989. *b)* From maize (2 ha), January 1990 (*H. armigera* only). [Note: The indicated date is that of the morning ... would have occurred during the previous night.]

ichneumonid, *Ichneumon (=Pterocormus) promissorius*. Each emergence extended over a period of about 15 days (Fig. 1), peaking around 1 December for chickpea and 17 January for maize. The two species emerged almost synchronously in November-December, but peak emergence of females was 2–3 days earlier than that of males. Emergence occurred between 20:30 and 23:00 h each night. The moths took off on their first short flight about 2 h after emergence (22:30–01:00 h), but did not travel far. Most emigration from the source crops occurred on the night after emergence.

Table 1. Numbers of pupae and moths produced, and proportion of successful emergence, from two source crops at Narrabri Agricultural Research Station, summer 1989/90.

Crop	Area (ha)	Total Number of *Heliothis* pupae	Total adults emerged *H.a*	*H.p*	% successful emergence
Chickpea	6.2	1,211,460	457,219	606,081	87.8
Maize	2.0	87,150	82,000	–	94.1

Short-range movements. In November-December, when approximately 1 million moths emerged from the chickpea crop (Table 1), the observations with night-vision goggles showed higher densities of moths active above the highly attractive maize crop than over adjacent, less attractive, crops (Fig. 2). At the edges of the maize crop a high proportion of the moths, mainly *H. armigera*, which flew out past the edge were seen to turn back into the crop. This behaviour effectively constrained the population to the small attractive block of maize.

In January, the general level of flight activity was lower (Fig. 2b). The maize was senescent and densities of moths flying over the maize and cotton crops (then in flower) were similar. Flight activity between 21:00 and 23:00 h varied between nights, partly reflecting changes in numbers of moths emerging the previous night (Fig. 3), but many other factors (temperature, wind conditions, etc.) would also have influenced activity.

These findings were essentially confirmed by the stereoscopic video system during the summer observation period. The number of moths flying immediately above the maize crop was much greater than at 10 m, and the number over an adjacent fallow field was low at both heights. All methods of observing low-altitude flight (radar, video, and night-vision goggle observations over crops and with a vertical beam) showed flight intensity to be high from dusk until about 23:00 h, and then to fall rapidly. Insect densities estimated from simultaneous radar and stereoscopic-video observations over a fallow

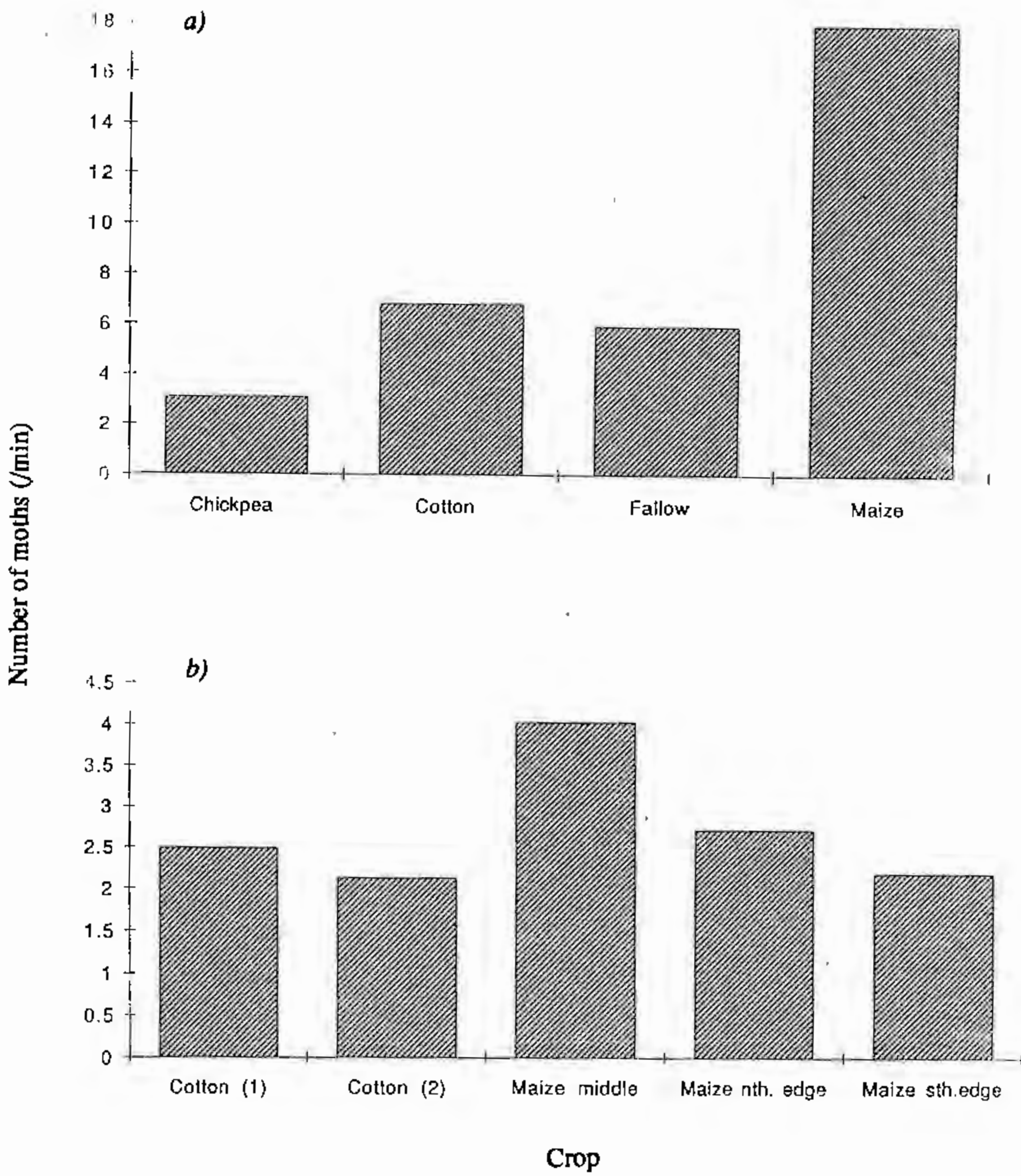

Fig. 2. Relative abundance of *Heliothis* moth flight activity over crops at N.A.R.S., summer 1989/90. The measure of abundance is the average rate at which flying moths appeared within a defined observation volume above each crop between 21:00 and 23:00 h each evening. ***a)*** Activity over senescent chickpea, squaring cotton, a fallow field, and silking maize, December 1989. ***b)*** Activity over flowering cotton and senescent maize, January 1990.

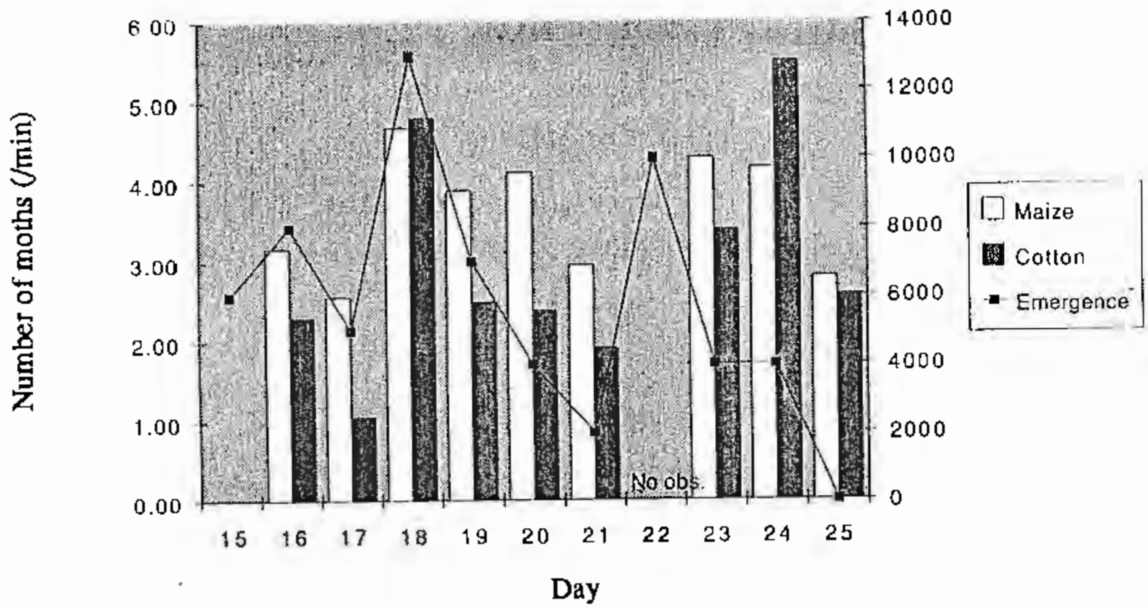

Fig. 3. Night-to-night variation in *Heliothis* moth flight activity over maize and cotton crops, and in emergence from the maize crop, at N.A.R.S. during January 1990. Details as in Figs 1 and 2.

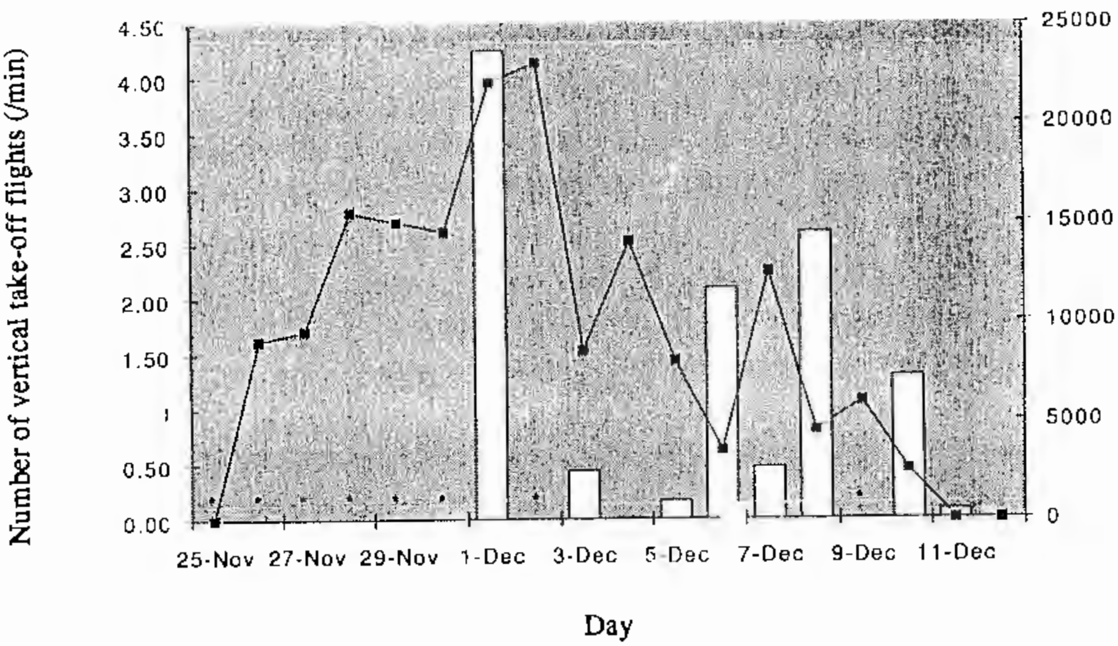

Fig. 4. Night-to-night variation in the number of moths making vertical take-off flights from the chickpea crop between 20:00 and 20:30 h, and of moth emergence the previous night, at N.A.R.S.

field were in broad agreement, suggesting these two techniques were detecting the same class of insect. The relatively large counts obtained during the vertical-beam observations suggest that this technique is sensitive also to smaller insects which are usually more numerous.

Totals of 57 and 6 *Heliothis* moths were caught in the vehicle-mounted trap in December and January respectively. Other similar-sized moths (catches 48 and 8) and orthopteran species (85 and 33) were present. These make interpretation of the radar observations difficult, as the insect echoes clearly cannot all be attributed to *Heliothis*. The tower net caught very few moths positively identifiable as *Heliothis* during the entire observation period. While this may have been partly a result of operational difficulties experienced with this equipment, it does support the video and radar observations that moth numbers at 10 m were very low.

The mark-and-capture study showed that a high proportion of the marked *H. armigera* moths which emerged from the chickpea crop colonised crops within a few kilometres, whereas the bulk of the *H. punctigera* population dispersed further, apparently moving beyond the 10 km radius of the trapping network (Fitt & Pinkerton 1990). This is the first documentation of greater dispersive behaviour in *H. punctigera* compared with *H. armigera* and is consistent with the direct and radar observations of vertical take-off flights described below.

Long-range movements. Insect migration at altitudes from 30–2000 m was monitored from dusk until about midnight throughout the two periods of intensive observations, and the intensity and direction of migration at each altitude was measured regularly. From the strength of the echoes and their behaviour (especially their flight altitude of only a few hundred metres), it is thought likely that these migrants were mainly grasshoppers and crickets. This is partly confirmed by the sampling with the kite-borne net at altitudes of 50–150 m, during which 2 grasshoppers but no moths were caught. Further analysis, especially of radar-target wing-beat frequencies, should provide additional information on the migrants' identity. The conclusion from these observations is therefore that there was no intensive long-distance migration of *Heliothis* over the Namoi valley during the summer of 1989/90.

Moths were seen making rapid, steeply ascending emigration flights during dusk binocular observations over the source crops in December but not in January. The number of emigrants observed varied considerably from night to night (Fig. 4), but did not reflect changes in emergence from day to day. Moths were also seen to be making near-horizontal flights at dusk during both observation periods. On two nights during December, the rapid ascent flight was just detectable on the radar as a steeply rising plume which could be followed up to a height of about 100 m. Generally, however, emigration from the source crop was difficult to distinguish from the widespread take-off flight of other species (probably mainly grasshoppers and crickets) which occurred every evening.

Discussion

The primary findings of this study are:–

- — Apart from the moths emerging from the source crops, *Heliothis* activity was low during the observation periods and indeed for much of the cotton-growing season.
- — The moths emerging in December consisted of *H. armigera* and *H. punctigera* in approximately equal numbers. In January, only *H. armigera* was present.
- — Local movement occurred very low down, at heights of only 1–4 m above the crop canopy.
- — *H. armigera* dispersal was concentrated within about 5 km of the source crop, while *H. punctigera* dispersed more extensively, with much of the population probably emigrating beyond the 10-km radius of the trapping network.
- — There was no intensive long-range migration of *Heliothis* over the Namoi valley during the summer.
- — A proportion of the moths from the source crops initiated a long-distance migration, and hence emigrated from the local region, in December but not in January.

The mark-and-capture study and the observations and sampling at low altitude all indicate that moths of both *Heliothis* species frequently move distances of at least a few kilometres between emergence and oviposition sites. Once a highly attractive host is located, however, they appear to avoid departing from it. Many *H. punctigera* moths probably move considerably further, and effectively depart from the region in which they emerged.

The most likely interpretation of the observations of take-off flights is that the moths initiating long-distance flight in December were *H. punctigera*. This is consistent with earlier evidence that *H. punctigera* is an obligate migrant while *H. armigera* emigrates only when local conditions are poor. When combined with the insignificant level of long-distance *Heliothis* migration over the Namoi valley (and hence immigration into it) during the summer, the obligate emigratory behaviour of *H. punctigera* accounts for the decrease in the proportion of this species from December to January. This decrease occurs regularly each season, and follows an initial heavy infestation in spring. It therefore appears likely that *H. punctigera* migrates into the Namoi valley in spring, probably from native pastures in the inland, and emigrates in early summer, probably to more coastal habitats from which it may reinfest the far inland in autumn.

The low-intensity of long-range migration and of flight at altitudes around 10 m at Narrabri contrasts with observations made at the same season in earlier years in the Darling Downs and Emerald cotton-growing areas of Queensland. In both localities, strong migrations were regularly present at both altitudes. The migrants at 10 m, and probably also those at 100–2000 m, were moths, although whether or not *Heliothis* was present in significant numbers could not be established. It is not yet clear whether these differences arise from the geographic location, especially the more tropical climate, of the two Queensland localities, or whether they are simply variations between seasons. It should be emphasised, however, that there are strong indications that *H. armigera* does move long distances in some circumstances (Fitt 1989), but apparently the conditions at Narrabri during summer 1989/90 were not such as to induce this type of behaviour.

Acknowledgments

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