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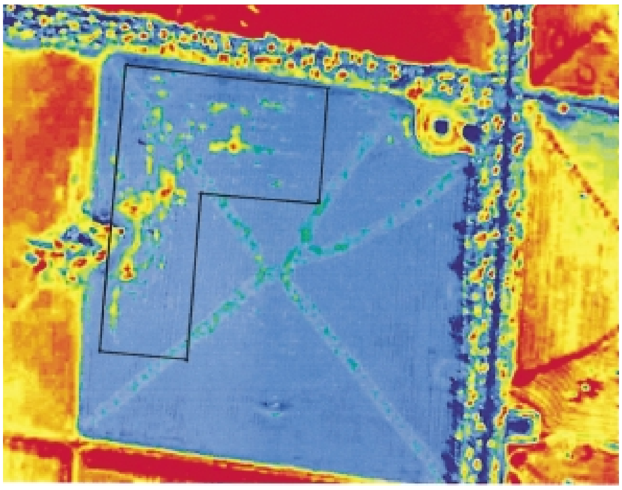

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Inter-seasonal population dynamics and cultural management of *Helicoverpa* spp. in a Central Queensland cropping system

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Abstract. A strategic trap cropping program targeting *Helicoverpa* spp. on cotton was developed and implemented in the Emerald irrigation area of Central Queensland beginning in the winter of 1997. Growers were advised to plant 1% of total cropping area to a trap crop of chickpea (*Cicer arietinum*) in winter and pigeon pea (*Cajanus cajan*) in summer. The population dynamics of *Helicoverpa* spp. in relation to the Emerald cropping system was studied over a 3-year period (August 1996–July 1999) to provide a framework for testing the validity of key assumptions underlying the trap cropping strategy and optimising the implementation of the program.

The population dynamics study showed continuous production of *Helicoverpa* pupae (moths) in the crop production system during each calendar year. The pattern of pupae production was consistent with cycling of *Helicoverpa* populations between irrigation and rainfed cropping components of the system. Spring rainfall and the availability of host plant resources is shown to impact on the population dynamics of *Helicoverpa* in the cropping system and its pest status on early-season cotton. Performance and potential impact of the trap crops are discussed within the context of host plant availability and resource bottlenecks. It is shown that the impact of the trap crops on abundance of *Helicoverpa* spp. early in the growing season could not be distinguished from that of naturally occurring host plant resource bottlenecks in spring most likely as a result of suboptimal timing of trap crop destruction. The potential contribution of cultural control tactics to integrated pest management of *Helicoverpa* spp. in cropping systems is discussed.

Additional keywords: integrated pest management, trap cropping, population dynamics, area-wide management.

Introduction

Helicoverpa armigera (Hübner) and *H. punctigera* (Wallengren) are serious pests of cotton (*Gossypium hirsutum* L.) in Australia (Fitt 1994). *Helicoverpa punctigera* is endemic to Australia and occurs throughout the continent. *Helicoverpa armigera* is found largely on the east coast of Australia and is also an important pest of field crops in Asia and Africa (Fitt 1989). Grower estimates put the typical cost of insect control on cotton at roughly A$30/ha in 1966 increasing rapidly to more than $800/ha in 1998 (Bligh 1998). The bulk of this cost is usually apportioned to control of *Helicoverpa* spp. throughout the season. McGahan *et al.* (1991) estimated that in the late 1980s and early 1990s *Helicoverpa* spp. alone accounted for a yield reduction of 7% in Queensland cotton crops despite expenditure of about A$7.5 million on control. Difficulties in controlling *Helicoverpa* during the late 1990s would have seen losses grow even larger (Adamson *et al.* 1997).

Despite increased adoption of integrated pest management techniques such as economic thresholds, cultural control (pupae destruction by cultivation), biological insecticides (*Bacillus thuringiensis* and nuclear polyhedrosis virus formulations) and soft-option chemical insecticides in recent years, the Australian cotton production system still relies primarily on chemical control for management of *Helicoverpa* spp. (Fitt 1994). The reliance on chemical control has resulted in the evolution of *H. armigera* populations that are highly resistant to commonly used insecticides (Gunning and Easton 1989; Forrester *et al.* 1993; Gunning 1994). Increasing difficulty in controlling *H. armigera* on cotton in recent years has heightened the need to develop and adopt alternative, non-chemical pest management techniques.

Trap cropping is a cultural pest management technique with a long history of usage in agricultural systems (Kogan and Turnipseed 1987; Pedigo 1989). Insect pest management using trap crops to divert pest pressure away from the main crop has been practiced for centuries and is still used in many traditional farming systems (Hokkanen 1991; Javaid and Joshi 1995). In the winter of 1997, cotton growers in the Emerald Irrigation Area (EIA) of Central Queensland implemented a trap-cropping program as a first step in the development of an area-wide management strategy for *Helicoverpa* spp. This was the first commercial-scale trial of trap cropping as a pest management tool in Australian field crops. Development and implementation of the program was

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driven by 2 factors. First, rising levels of *Helicoverpa* resistance to chemical insecticides, the resulting poor efficacy of sprays and rising costs of controlling the pest on cotton all served to question the viability of the *status quo*. Second, it was envisaged that the development of a pre-emptive population and resistance management strategy for the area would facilitate the introduction of cottons carrying bacterial transgenes into Central Queensland.

Due to a lack of substantive data on the population dynamics of *Helicoverpa* spp. in the local cropping system, the strategic foundation of the trap cropping program was underpinned by largely untested assumptions and anecdotal observations of pest movement between crops and seasons. Concurrent with the implementation of the program, a study on the population dynamics of *Helicoverpa* spp. in relation to the cropping system was undertaken to validate key assumptions, objectives and in-field protocols.

This paper presents a synopsis of the *Helicoverpa* problem in the EIA and the trap-cropping program designed to counter it within the context of the cropping system. The strategic framework underlying the trap-cropping program is discussed and a preliminary qualitative assessment of the outcomes is presented. The pest status of *Helicoverpa* spp. on cotton in relation to population dynamics and availability of host plant resources within the cropping system is examined. The potential contribution of cultural control tactics to management of *Helicoverpa* spp. on cotton is discussed.

Emerald cropping system

Emerald lies just above the Tropic of Capricorn at 200 m above sea level and 275 km inland from the east coast of Australia. The EIA, comprising 26 000 ha of intensively cultivated land, forms the core of the system. The Emerald cropping system may be defined as the irrigated core surrounded by a rainfed cropping area, the bulk of which lies within a radius of about 100 km around Emerald. The majority of rainfed crops are found within a radius of 65 km around Emerald.

Cotton has been grown commercially in the EIA since 1976. The area under cotton varies between seasons but is usually about 20 000 ha. This makes cotton the largest and most important crop within the irrigation area. The spring–summer cropping season stretches from September to May. The cotton window stretches from late September to March. Significant areas of seedling cotton can be found in most years by the end of October. Cotton harvesting in the EIA is usually complete by the end of April. In most years the irrigation area is largely fallow between June and September.

Small areas of spring-planted maize (*Zea mays* L.), sunflower (*Helianthus annuus* L.) and legumes such as mungbean [*Phaseolus* (*Vigna*) *aureus* Roxb.] and soybean [*Glycine max* (L.)] can be found in the irrigation area in years when availability of water is limited early in the season. Under favourable rainfall conditions small areas of summer sorghum [*Sorghum bicolor* (L.)], sunflower and legume crops may also be found within the irrigation area. These crops are normally sown in January and February.

Summer rainfed crops, mainly sorghum and sunflower, are planted from late December onwards and harvested by May or June. The 2 main rainfed winter crops in Central Queensland are chickpea (*Cicer arietinum* L.) and wheat (*Triticum* L. spp.). The optimal sowing window for both crops is from late April to the end of May. Chickpea and wheat crops sown in the optimal window begin to mature and dry by early September.

The perceived *Helicoverpa* problem

Four distinct components of the production system are thought to contribute to the pest problem in the Emerald area. These components are: (i) native host vegetation and volunteer crop plants; (ii) cotton and other spring-sown crops such as corn, sorghum and mung bean; (iii) mid-summer crops such as sorghum, sunflower, grain and ley legumes, and horticultural crops; and (iv) winter crops, particularly chickpea. Grower experiences, observations of professional crop consultants in the area and the general structure of the system (e.g. sequence of sowing times) point to a pattern of *Helicoverpa* movement among components as suggested by the arrows in Figure 1. The size and direction of the arrows are indicative of the potential strength and direction of moth movement.

Data from other areas in Australia and overseas suggest that native vegetation and volunteer crop plants are important factors in the regional population dynamics of *Helicoverpa* spp. (Wardhaugh *et al.* 1980; Fitt 1989). The contribution of this component of the Emerald cropping system to *Helicoverpa* populations in spring has not been determined. Uncultivated host plants may be particularly important in the annual spring replenishment of *H. punctigera* populations (Wardhaugh *et al.* 1980; Fitt 1989). In contrast, spring numbers of *H. armigera* in irrigation areas are likely to be more dependent on the cropping sequence and level of diapause within these areas (Fitt 1989).

Cotton is perceived to be the largest producer of moths in the spring–summer cropping season. In late February and March oviposition pressure on maturing cotton appears to decline. At about the same time, significant infestations are often observed on young flowering rainfed crops of sunflower and sorghum sown in December and January. Such observations suggest that a large proportion of moths emerging from cotton in February and March migrates out of the irrigation area in search of younger, more attractive flowering crops in rainfed areas, whereas the remainder may go on to infest the following late summer crops within the EIA.

The contribution of summer legume crops within the EIA to late summer and winter populations of *Helicoverpa* appears to vary considerably between years. In some years

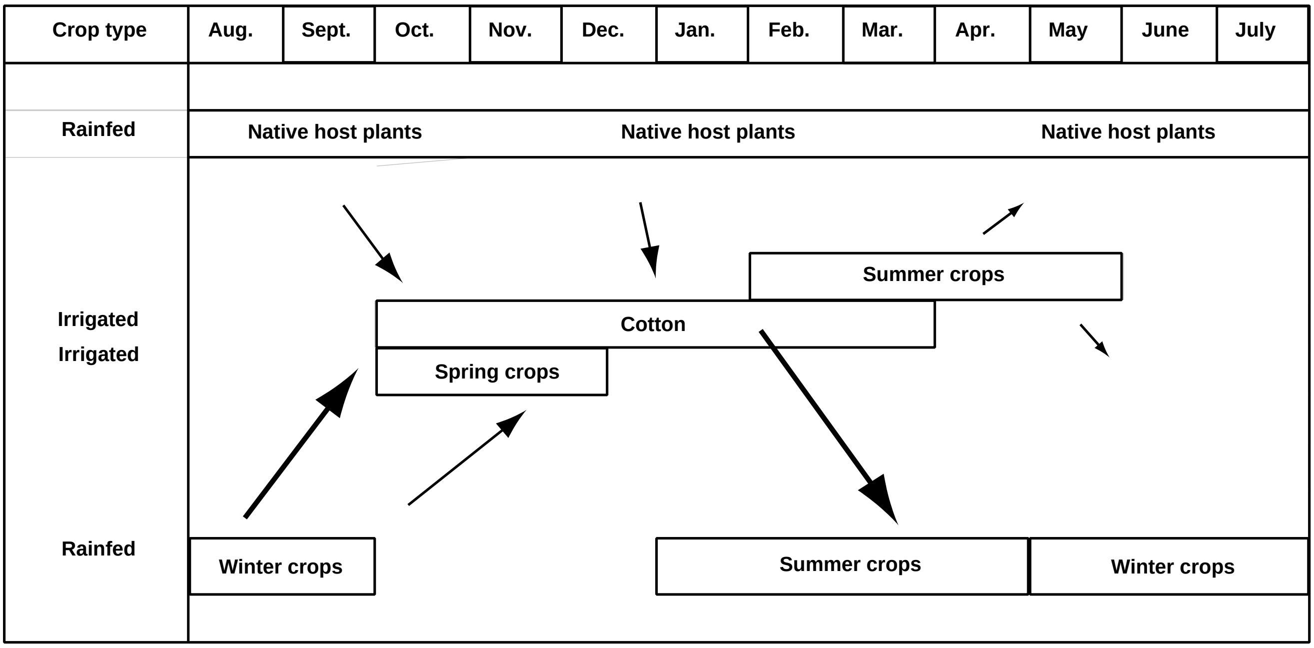

Figure 1. Perceived pattern of *Helicoverpa* movement and major components of the cropping system in the Emerald area. See text for explanation.

the summer crops largely escape infestation presumably due to a time lag between the commencement of flowering in these crops and maturity of cotton.

Amongst the winter crops, wheat is known to support low density populations of *H. armigera* in certain years but there is little evidence of large-scale breeding on this host plant (Wardhaugh *et al.* 1980). In Central Queensland, crop consultants and grain growers do not consider *H. armigera* to be an economic pest of wheat. Both *Helicoverpa* spp. are, however, serious pests of chickpea in Queensland (Knights *et al.* 1980). Chickpea is observed to support significant populations of *Helicoverpa* even in the early vegetative phase of the crop. Significant larval populations are observed on chickpea in August and early September, indicating that chickpea crops are likely to be the principal nurseries of *H. armigera* in spring.

The trap-cropping program

In-field protocol

The program recommended the sowing of one trap crop patch on every farm in the EIA at the beginning and end of the spring–summer growing season (BEOS model hereafter). Patches were required to comprise the greater of 1% or 2 ha of total farm area. Spring trap crops of chickpea were to be sown in autumn–winter and destroyed in spring just before the start of the cotton sowing window (25 September–31 October). The recommended procedure for crop destruction included slashing and soil cultivation to destroy pupal chambers in the soil. Summer trap crops of pigeon pea (*Cajanus cajan* L.) were to be sown concurrently with or after cotton and destroyed by slashing and soil cultivation just before cotton harvesting. Management guidelines for the trap crops permitted use of only biological insecticides on the spring chickpea crops to keep larval numbers within manageable limits but precluded insecticidal control of larvae on the summer pigeon pea crops.

The patch size of 1% was proposed for 2 reasons. First, the value reflected growers' readiness to sacrifice potential cotton area. Second, given the fact that the EIA is largely fallow in winter and planted predominantly to cotton from September to March, it was felt that a mosaic pattern consisting of small patches of extremely attractive trap crops could be just as effective and more manageable than larger patches. The expectation was that if the patches were well distributed, moths flying around the area would be likely to find at least one of the patches and deposit their eggs. Although the trap crops would attract both *Helicoverpa* spp., *H. armigera* was the principal target because of its dominance of the insect pest spectrum in Central Queensland and resistance to chemical insecticides.

Strategic framework and assumptions

The BEOS model of trap cropping for the EIA was based partly on the theory and experience of area-wide management of heliothine moths in the USA (Stadelbacher 1981; Knipling and Stadelbacher 1983; Mueller *et al.* 1984). The objective of the spring trap crops was to destroy the offspring of the first 1 or 2 spring generations of *H. armigera* so as to delay the build-up of the pest and minimise damage to crops early in the growing season. The summer trap crops targeted the offspring of the last *Helicoverpa* generation emerging from cotton so that insecticide resistance developed over the season could be confined to the irrigation area and minimised.

The strategic framework underlying the BEOS model was based on 3 fundamental assumptions. The first of these was that population dynamics of *H. armigera* was driven substantially by recruitment within the Emerald cropping system (as defined above). This assumption is consistent with the prevailing view that in comparison to other heliothine species *H. armigera* tends to be more sedentary and prevalent in cropping areas where a continuous supply of host plant resources is available (Wardaugh *et al.* 1980; Fitt 1989). The development of high levels of insecticide resistance in *H. armigera* is also consistent with substantial local recruitment in cropping systems (Forrester *et al.* 1993). Local recruitment would increase the likelihood of successfully targeting and controlling the founding populations of the pest in spring.

The second assumption was that a bottleneck in the availability of *Helicoverpa* host plant resources within the cropping system develops every year. Chickpea crops grown in the optimal winter cropping window (April–October) normally mature in early September. Substantial areas of spring-planted crops including cotton are normally not available for oviposition until early November. This can result in a period of several weeks when there is an acute paucity of cultivated host plants and few suitable weed host plants in uncultivated areas. The presence of trap crops timed to occur during such resource (host plant) bottlenecks in spring could potentially augment the pest population bottlenecks that inevitably follow.

The third assumption provided the rationale for the summer component of the trap-cropping strategy. Cotton was assumed to be the largest producer of moths in mid-summer and, as the largest consumer of insecticides in the cropping system, also the vehicle of selection for resistance in *H. armigera*.

Helicoverpa pupae production in the Emerald cropping system, 1996–99

Before the implementation of the trap-cropping program in 1997, a 3-year survey of *Helicoverpa* pupal abundance and temporal distribution under crops grown in the Emerald cropping system was initiated in October 1996. The objective of the exercise was to validate the basic assumptions of the trap-cropping program against the observed dynamics of moth production and inferred pattern of movement between crops or components of the system.

Estimates of production area for the major crops grown in the system from 1996 to 1999 are listed in Table 1. Minor crops or those grown occasionally are not included in Table 1. Estimates of production area for the minor crops are indicated in context below in this section. It should be noted that all estimates of production area are approximate and intended to serve only as rough indicators of the potential for recruitment of *Helicoverpa* moths. The abundance and distribution of pupae (and implicitly moths) under cultivated crops throughout the survey period is summarised in Figure 2. Crops under which pupae were not detected (e.g. wheat) are not included in the survey results.

The cropping sequence during the 1996–97 spring–summer cropping season facilitated continuous moth production, beginning with late-planted chickpea (about 40 ha) in October 1996 (Fig. 2). Substantial rainfall in late spring (September or October) resulted in an extended chickpea cropping season by inducing renewed vegetative growth and flowering in chickpea. Empty pupal cases encountered during sampling under the chickpea crop, indicated that a previous generation of moths had emerged from this crop during August and September. The chickpea crop presumably served as the initial nursery for the pest in the EIA. Small areas of sorghum, soybean, mung bean and sunflower (about 100 ha of each) would have contributed to the build-up of the *Helicoverpa* population in the irrigation area during the following months.

Cotton was the single largest producer of pupae in the EIA during the 1996–97 season (Fig. 2). An extended spring–summer cropping season resulted in detection of pupae under cotton well into April (Fig. 2). This suggests that cotton facilitated the build-up of the *Helicoverpa* population and movement on to summer sorghum, corn and legume crops (maximum 200 ha production area for each) within the EIA. These late summer crops harboured substantial numbers of overwintering pupae that almost certainly

Table 1. Estimated areas of production (ha) for major cropping options in the Emerald cropping system

Crop	Irrigated[A]				Rainfed			
	1996–97	1997–98	1998–99	1999–00	1996–97	1997–98	1998–99	1999–00
Wheat				200	150 000	140 000	180 000	90 000
Chickpea	50		100	100	15 000	12 000	13 000	7000
Cotton	19 000	22 000	22 000	22 000	5000	5000	5000	5000
Sorghum	500				120 000	40 000	125 000	120 000
Sunflower	100	100			75 000	55 000	40 000	25 000

[A] Grown within the EIA.

contributed to the spring population of moths in 1997. Pupae production in the EIA was matched by complimentary production under rainfed crops. Substantial numbers of pupae were found under sorghum and chickpea in June and July.

With the exception of a small area (about 50 ha) of rainfed linseed there were no substantial sources of *Helicoverpa* pupae in the cropping system from August to November 1997 (Fig. 2). Cotton was again the largest source of *Helicoverpa* in the 1997–98 season, producing pupae from December through to March 1998, albeit at lower densities than in the previous season. During May and June 1998 pupae were detected under late summer corn (about 100 ha) and dolichos (about 25–30 ha) a large proportion of which were observed to be in diapause (see below). These populations are likely to have contributed to the following

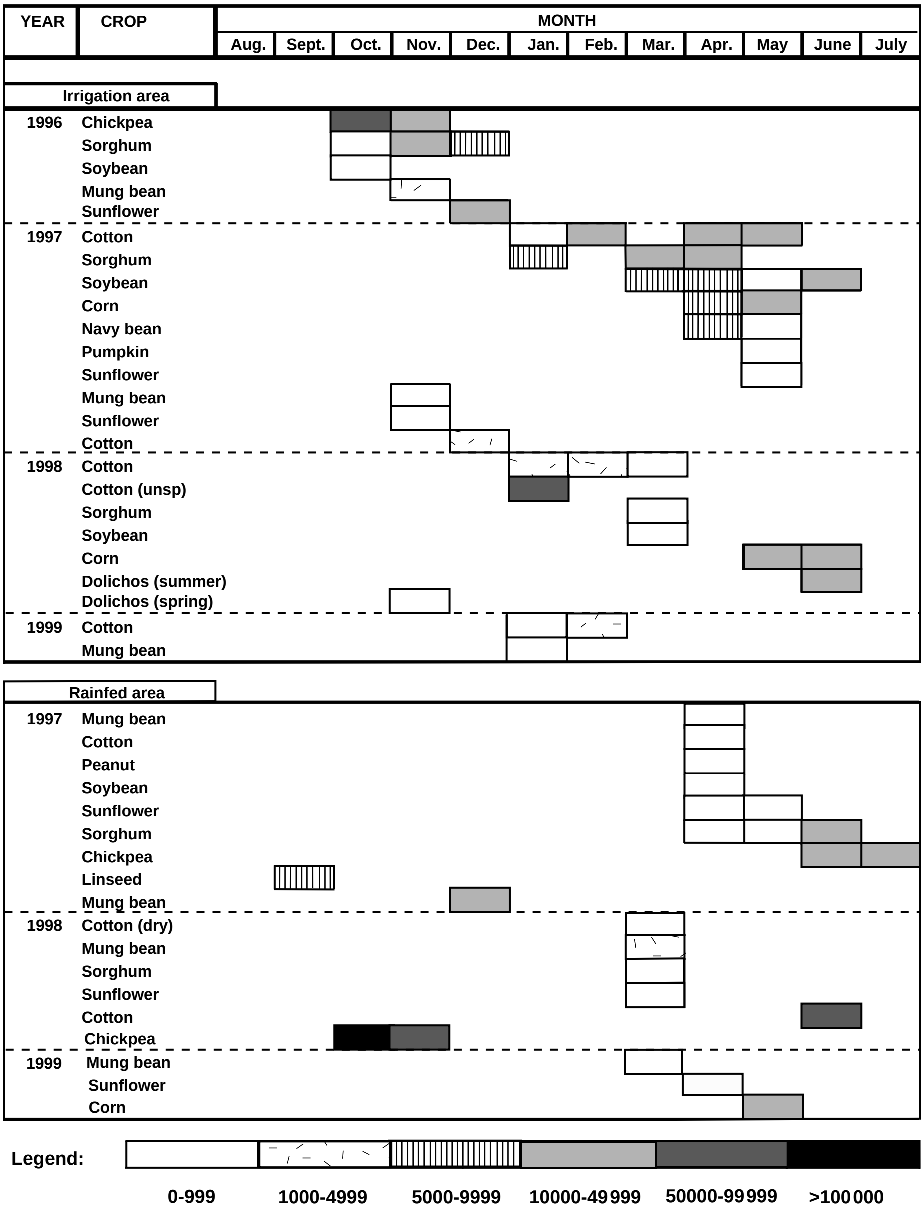

Figure 2. Abundance (pupae/ha) and temporal distribution of *Helicoverpa pupae* in relation to the crops grown and the cropping system in the Emerald area, 1996–99. Note that 3 distinct types of cotton crops are recognised, namely irrigated and protected with insecticides (cotton), irrigated but completely unsprayed [cotton (unsp)], and rainfed and protected with insecticides [cotton (dry)]. Estimates of pupal abundance for each crop are based on the number of pupae found in 20 random 1-m^2 soil samples. Each crop was sampled from 1 to 6 times. *Dolichus* was sown in late summer and spring.

spring population in the EIA. Low to moderate pupae numbers were found under rainfed mung bean crops (production area for Central Queensland >10 000 ha) in March.

Substantial rainfall in August–October 1998 (see below) resulted in a marked extension of the winter cropping season well into the 1998–99 spring–summer season. The large area sown to commercial rainfed chickpea crops in 1998 (Table 1) combined with very high densities of pupae in October and November (Fig. 2) translated into a potentially large pest problem for cultivated crops during the season. Cotton crops in the EIA were subjected to high *Helicoverpa* pressure from October to mid December. The EIA was largely free of non-cotton crops between October 1998 and September 1999. Cotton was the only significant source of pupae in the irrigation area in February 1999. A small area of mung bean (about 50 ha) with negligible density of pupae was the only other source of *Helicoverpa* encountered within the EIA.

Low rainfall after February 1999 prevented sowing of late summer crops in the EIA. Few crops were grown in the rainfed area. Corn (max. 1000 ha) was the only substantial source of pupae in May 1999 (Fig. 2). Lack of moisture in the soil profile resulted in a dramatically reduced acreage of chickpea crops during the winter of 1999 (Table 1). There were no chickpea crops within about 50 km from the irrigation area.

Over the survey period a total of 4171 pupae were collected of which 86% were *H. armigera*. Pupae collected in late summer in the EIA and rainfed areas tended to be almost all *H. armigera*. A total of 429 pupae were collected from May to July over the survey period. Of these winter-collected pupae, 76% were observed to be in diapause.

The pattern of pupae production under cotton (Fig. 2) and egg/larval densities on the crop (R. Sequeira unpublished data) indicates that under environmental conditions experienced in the EIA the final or penultimate generation of *Helicoverpa* moths from cotton emerges in February. The overall pattern of pupae production under various crops (Fig. 2) by itself does not constitute evidence of moth movement between crops and seasons as suggested in Figure 1. However, the temporal distribution of pupae within the irrigation area together with complimentary pupae production in rainfed areas is strongly suggestive of a cyclical pattern of moth movement as shown in Figure 1.

The data on abundance and temporal distribution of pupae (Fig. 2) is consistent with the first and third assumptions underlying the strategic framework of the trap-cropping program. The magnitude and pattern of pupae production in the Emerald cropping system over the entire survey period indicate substantial 'local' recruitments within the cropping system. The data show clearly that cotton is the largest and most important source of *Helicoverpa* pupae, and implicitly the vehicle for development of resistance to insecticides in *H. armigera*. The second assumption, that a host plant resource bottleneck occurs in spring each year, is only partially valid.

The continuous pattern of pupae production in the cropping system in the 12 months to August 1997 (Fig. 2) suggests the absence of a resource bottleneck in the spring of 1996. Similarly, an extended winter cropping season in the spring of 1998 appears to have prevented the development of a resource bottleneck in that year. The absence of substantial cropping and sources of pupae in August–September of 1997 and 1999 does not prove but is consistent with the development of a resource bottleneck in these 2 years.

Evaluation of the trap-cropping program

Trap crop performance

The trap crop plants, chickpea and pigeon pea, were selected on the basis of differing criteria. Chickpea was the ideal candidate for a spring trap crop, being a substantive cultivated winter host of *Helicoverpa* spp. in the region. The choice of pigeon pea as the summer trap crop was based on literature reports of its attractiveness to *Helicoverpa* spp. (e.g. Abate 1988). The first spring trap crops were sown in May–June 1997 and destroyed in late August. The summer trap crops were sown for the first time in October 1997 and destroyed in March 1998, just before cotton harvesting.

Of some 63 individual farms or farming units in the EIA, at least 55 (87%) planted a total of between 120 and 140 ha of chickpea trap crops over the 3-year period. Random drop-sheet sampling under the trap crops (10 m^2 areas of 2 crops in 1997, 6 crops in 1998 and 4 crops in 1999) between July and September indicated population densities ranging from 5 to 30 larvae/m^2 (Fig. 3). *Helicoverpa armigera* constituted 86% and about 90% of the larval population on the trap crops in 1997 and 1999, respectively. Species identification of larvae was not done in 1998 but pupae collections from chickpea contained over 90% *H. armigera*. Using a conservative mean of 10 larvae/m^2

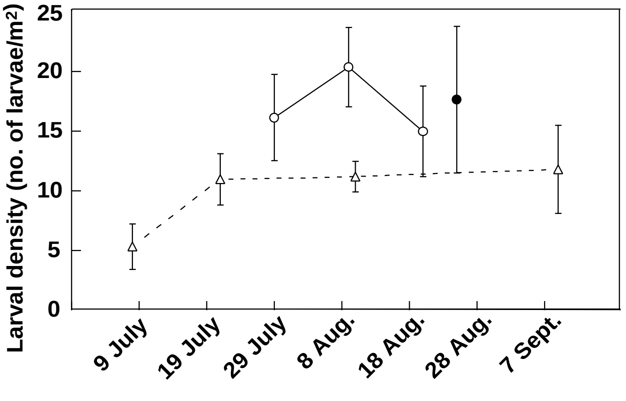

Figure 3. Mean *Helicoverpa* larval counts on chickpea trap crops in the winter and spring of 1997 (●), 1998 (○) and 1999 (△). Error bars show the standard error of the mean.

over all 3 years, destruction of the trap crops in late August–early September potentially eliminated more than 12 million larvae each year before spring planting of cotton and other crops.

About 120 ha of unsprayed pigeon pea trap crop (var. 'Quest') were sown adjacent to sprayed cotton in the 1997–98 and 1998–99 seasons. Compliance with the summer trap-cropping recommendation was estimated at over 90% of individual farms or farming units in the EIA. Oviposition activity on the trap crops commenced only after the onset of flowering in early December, about 65 days after sowing.

The temporal pattern of pupae production under cotton and pigeon pea in the 1997–98 season was used to determine the level of synchrony between the 2 crops in attractiveness to *Helicoverpa* spp. Detection of substantial numbers of pupae under pigeon pea in December 1997 (Table 2) indicated that the trap crops were becoming attractive for oviposition by early December, very early in the cotton season. The trap crops therefore posed the risk of exacerbating the pest problem by becoming sources of moths during the season. Later sowing of the trap crops (late November–early December) recommended for the 1998–99 cropping season to ensure flowering in February resulted in better synchrony of pigeon pea attractiveness and maturity of cotton, as indicated by the detection of pupae under both in February (Table 2).

Figure 4 shows mean *Helicoverpa* larval density (10 m^2 drop-sheet samples per crop) on unsprayed pigeon pea trap crops in the vicinity of sprayed cotton on 5 farms in February over the 2-year period. These estimates of larval densities are indicative of the trapping potential of the crop. Samples of larvae collected for species identification were 100% *H. armigera* in both seasons. Using a conservative estimate of 20 larvae/m^2 and a trap-crop area of 120 ha, destruction of the trap crops would have potentially eliminated 24 million individuals, most of which would have been highly resistant to a number of chemical insecticides, at the end of the 1997–98 season.

Despite the trapping potential of pigeon pea evident the previous year, implementation of the summer trap cropping component in the 1998–99 season was fraught with agronomic and crop management problems. In addition to low seed viability and supply issues, pigeon pea crops appeared to vary considerably in plant height (and implicitly trapping potential) within and between years, and between farms. Although specific height measurements were not recorded for individual crops, they could be grouped into tall (≥180 cm) and short (≤140 cm) phenotypes relative to the height of adjacent cotton (140–160 cm).

Table 2. Temporal distribution of *Helicoverpa* pupae (mean density/ha) under cotton and pigeon pea trap crops in the Emerald Irrigation Area over two summer cropping seasons

Crop	December	January	February	March
		1997–98		
Cotton	3000	3250	2500	0
Pigeon pea	41 000	26 750	121 129	239 667
		1998–99		
Cotton	0	217	2100	0
Pigeon pea	0	0	4875	0

At the end of the 1997–98 season both tall and short phenotypes were observed under field conditions. Pupal density per hectare under tall crops ($n = 6$, mean ± s.e.m. = $245.15 \times 10^3 \pm 96.28 \times 10^3$) was significantly higher than under short crops [$n = 12$, mean ± s.e.m. = $30.58 \times 10^3 \pm 6.75 \times 10^3$; Kruskal–Wallis rank test, Chi-square = 8.25, d.f. = (1,22), $P<0.01$]. During the 1998–99 season, none of the crops were taller than the adjacent cotton. In 4 crops that were sampled for pupae, mean density was only 4.88×10^3 pupae/ha.

Impact assessment

Currently no attempt has been made to assess the impact of the summer (pigeon pea) trap crops for reasons explained above. Therefore the remainder of this section will focus on the spring component of the trap-cropping program.

The effectiveness of the spring trap crops depends on the timing of moth emergence in spring in relation to the timing of the trap crops and availability of alternate host plants for oviposition. Based on computer simulation studies, the bulk of the first spring generation of *Helicoverpa* (diapausing and non-diapausing) is expected to emerge in August and September under Emerald environmental conditions (Dillon 1998). These predictions are supported by data on

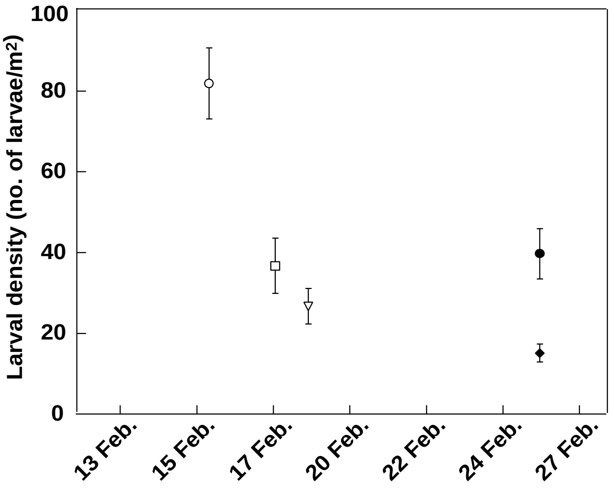

Figure 4. Mean *Helicoverpa* larval densities on pigeon pea trap crops in the Emerald Irrigation Area. Error bars show the standard error of the mean.

termination of diapause in over-wintering pupae and pheromone trap catches showing a spike in mid August (R. Sequeira unpublished data).

The density of pupae under chickpea (Fig. 2) clearly indicates that the area under commercial chickpea crops is a major determinant of the *Helicoverpa* moth population in spring. A trap crop area of 120 ha equates to <1% of the commercial chickpea cropping area in most years (Table 1). In the absence of a host plant resource bottleneck, the spring trap crops would have little or no impact on *Helicoverpa* abundance later in the season because a minuscule area of trap crops would be competing with a much larger resource area of commercial chickpea and other host plants. Similarly, if the spring trap crops were not timed to occur within the resource bottleneck window, their impact would also be minimal. However, because host plant resource bottlenecks are inevitably followed by pest population bottlenecks, even a relatively small area of well-dispersed trap crops timed to occur within the former could potentially augment the latter.

The cropping sequence and pattern of moth recruitment in the Emerald cropping system (Fig. 2) suggest that spring populations of *Helicoverpa* experienced a resource bottleneck in 1997 and 1999. The resulting *Helicoverpa* population bottleneck in these 2 years would be evident as substantially decreased abundance as measured by oviposition pressure on young cotton crops in comparison to 1996 and 1998 when a resource bottleneck was not apparent.

Figure 5 shows a summary of oviposition activity on cotton in October and November based on commercial crop scouting data for 5 farms in the Emerald area over a period of 11 seasons. Each bar represents mean monthly egg density

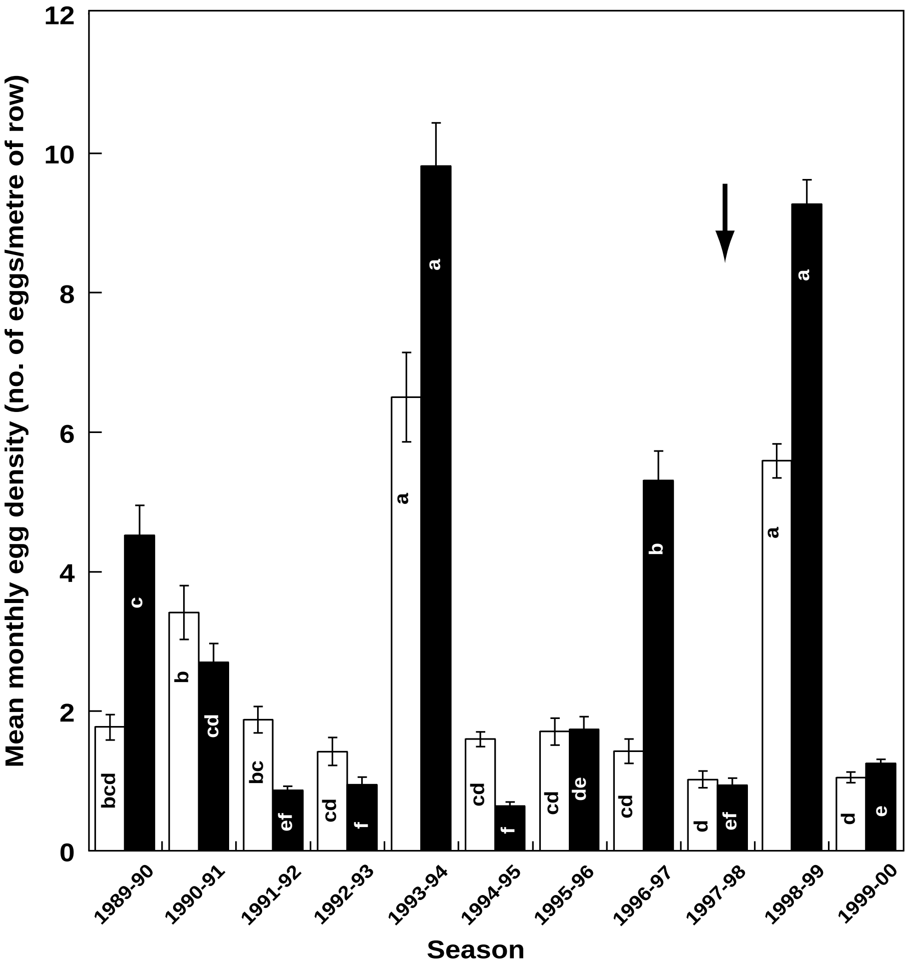

Figure 5. Changes in mean monthly egg density per metre of cotton for October and November over a period of 11 seasons. The arrow marks the beginning of the trap-cropping program in the winter of 1997. Error bars show the standard error of the mean. Means within bar type that share the same letters are not statistically different (Kruskal–Wallis rank test, comparison of mean ranks, $\alpha = 0.05$). Data provided courtesy of A. J. Noone Pty Ltd, Emerald, and Duane Evans Pty Ltd, Emerald.

per metre of row calculated by averaging the daily estimates over fields and farms. For statistical purposes, between-year differences in density recorded during October and November were analysed separately using the Kruskal-Wallis rank test. The arrow marks the beginning of the trap-cropping program in the winter of 1997.

The lowest mean egg density for October was recorded in 1997, followed by 1999. The years 1991, 1992, 1994 and 1997 were categorised as a statistically homogeneous group with the lowest egg density for the month of November. The year 1999 was assigned to the next higher group with marginally higher densities (Fig. 5). The low egg densities in October and November of 1997 and 1999 are consistent with the proposed development of a resource bottleneck in the spring of these 2 years. Similarly, high egg densities in 1996 and 1998 are consistent with the absence of a bottleneck in these years.

The lack of cropping and pupal dynamics data for the period 1989–95 precludes any definitive conclusions about the availability of spring host plant resources in these years. However, the amount of spring rainfall is indicative of resource availability during that period in any year. Substantial spring rainfall results in greater availability of host plant resources for *Helicoverpa* through renewed vegetative growth and flowering in chickpea (and probably other host plants), and often a longer winter cropping season. Figure 6 shows cumulative rainfall over August–October from 1989 to 1999. The striking similarity between the pattern of winter rainfall and average monthly *Helicoverpa* egg density on cotton over the 11-year period (Fig. 5) clearly points to a high correlation between wet springs and *Helicoverpa* abundance.

In years when spring rainfall exceeded 50 mm (Fig. 6) *Helicoverpa* abundance on cotton in November, measured as egg density on cotton, was also markedly higher (Pearson correlation, $r = 0.81$). Similarly, there is also good agreement between rainfall and egg density in October but less so than for November (Pearson correlation, $r = 0.66$). The majority of cotton crops in the EIA are normally in the very early seedling stage in October with the result that *Helicoverpa* egg density in November more accurately reflects pest pressure on cotton early in the season. Close correspondence between substantial spring rainfall and increased *Helicoverpa* abundance in cotton suggests that a resource bottleneck did not develop in 1989, 1990 and 1993.

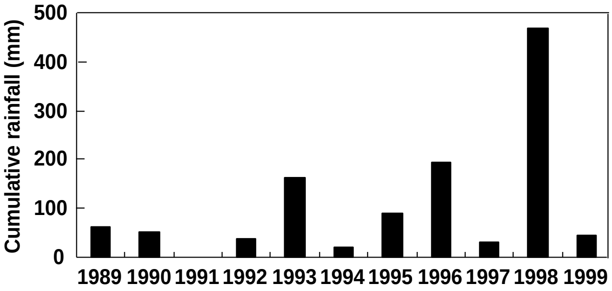

Figure 6. Cumulative rainfall for the months of August, September and October recorded within the Emerald Irrigation Area each year from 1989 to 1999.

A marked reduction in *Helicoverpa* egg density on cotton in 1997 and 1999 relative to other 'bottleneck' years (1991, 1992, 1994 and 1995) would be a qualitative indication of the impact of spring trap crops. It is evident from Figure 5 that the impact, if any, of the trap crops on the population dynamics of *Helicoverpa* cannot be distinguished from the expected consequences of a spring resource bottleneck. The most likely explanation for this result is inopportune destruction of the trap crops in August, before the development of the resource bottleneck expected in September and October. It must also be recognised that based on the current data set (3 sowings) only a preliminary assessment of the spring trap cropping technique is possible.

Discussion

Cultural control tools such as trap cropping seek to exploit specific biological or ecological traits of the target organism. For example, companion or strip cropping is aimed at exploiting pest preferences for certain stages, cultivars or species of host plants. This form of trap cropping involves sowing a block or strip of the trap crop adjacent to the main crops to serve as a 'sink' for the pest population (Abate 1988; Hokkanen 1991). Pre-season trap cropping which assumes substantial 'local' recruitment of the pest has been used successfully for boll-weevil control on cotton in the USA (Isley 1950; Scott *et al.* 1974; Burris *et al.* 1983) and Nicaragua (FAO 1981; Holl *et al.* 1990).

In Australia, Titmarsh (1992) first advocated control of the spring generations of *Helicoverpa* as a means of minimising subsequent population growth and infestation of crops on the Darling Downs. The BEOS trap-cropping program reported on in this paper constitutes the first large-scale test of Titmarsh's proposal. Although the results of this test to date do not provide evidence of a demonstrable impact of trap cropping on *Helicoverpa* population dynamics in cotton crops, the technique must still be considered a promising tool for integrated pest management of cotton within a strategic area-wide management framework.

Several aspects of spring trap cropping such as the size of trap crop area required, crop management and in-field layout, are still poorly understood. One important aspect of the technique is timing of the trap crop in relation to *Helicoverpa* population dynamics in the cropping system. Based on the data and analyses presented here the optimal window for the spring trap crops in the EIA should encompass September and October. This would require sowing of the trap crops in late August or early September followed by destruction in early

November. Spring sowing of the trap crops would also facilitate the use of other crop plants such as corn and sorghum that are known to be highly attractive to *H. armigera*.

When implemented correctly, trap cropping for management of *Helicoverpa* spp. may be a valuable addition to integrated pest management-based, area-wide management strategies. However, the use and proper implementation of trap crops necessarily requires a thorough understanding of the pest's ecology within the whole cropping system. The spring component of the Emerald trap-cropping program is a good example of a strategically sound approach to pest management that does not appear to have any appreciable impact on the target pest, most likely due to incorrect implementation.

Host plant bottlenecks are clearly important factors in the population dynamics and pest status of *Helicoverpa* spp. (Gregg *et al.* 1995). Wilson *et al.* (1979) first alluded to the importance of spring resource bottlenecks and *H. armigera* abundance within cropping systems. More recently, Oertel *et al.* (1999) demonstrated a dependency between winter rainfall in central Australia and the abundance of *H. punctigera* in spring. In this paper I propose that within cropping systems spring resource bottlenecks are important determinants of *H. armigera* pest status early in the spring–summer cropping season.

A dynamic sowing window strategy for cotton in the EIA has the potential to significantly enhance the effectiveness of cultural and insecticide-based pest management options. Substantial spring rainfall potentially enhances availability of host plant resources not only for *Helicoverpa* spp. but also for important sucking pests of cotton such as aphids and mirids (*Creontiades* spp.). In years characterised by substantial spring rainfall a cotton sowing window that places seedling cotton crops out of the spring flush could be of significant benefit in ameliorating the pest management challenge on commercial cotton being experienced under the *status quo*.

The Emerald trap-cropping program has generated considerable interest in alternative (non-chemical based) population management tactics throughout the Australian cotton industry and renewed awareness of the need for integrated pest management in an environment characterised by high levels of insecticide resistance in pest populations. The program has fostered increased communication and exchange of ideas between groups of growers. These are perhaps the most significant benefits of the program to date.

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