COTTON RESEARCH AND DEVELOPMENT CORPORATION

CRDC
AUSTRALIA

Review of Beneficials in Cotton Farming Systems.

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Acknowledgements

We thank all the researchers, students, and industry members who, over the years, have contributed to our knowledge and understanding of beneficials in our agro-ecosystems. Although much remains to be done at least some foundations have been laid. We also thank those researchers who shared unpublished data and project details and the various Research and Development Corporations for providing information on projects and funding. Finally we appreciate financial assistance provided from the Cotton Research and Development Corporation.

Terms of Reference

Cotton farmers are placing increased emphasis on the preservation and use of beneficial species in their pest management programs. In order to improve the level of understanding and information available to farmers and consultants, CRDC wishes to review previous and current research and extension information on beneficials in farming systems within which cotton is grown.

The reviewers are asked to:

- Conduct a literature review of previous research on the major beneficials known to occur in cotton and cotton farming systems in Australia. Reference to overseas research should be included if it is considered to be relevant.
- Where practical, liase with relevant researchers and RDCs to consider current research projects studying beneficials in cotton/grain farming systems.
- Comment on the current extension information available to cotton farmers on beneficials in cotton.
- Identify the major gaps in our knowledge on key beneficials (from the perspective of the science involved and IPM programs that attempt to make use of beneficials in daily pest management decisions).
- A report should be prepared within three months of signing of the contract with the Corporation.
- The report should also form the basis for a discussion at a workshop of relevant researchers who are studying beneficials or IPM in cotton farming systems. The workshop will be convened by CRDC and the Australian Cotton CRC. In conjunction with the report from this review, the major outcome from the workshop will be the development of a more strategic approach for the Australian Cotton CRC and CRDC to follow for research and extension on beneficials in the cotton farming system.

Executive Summary

In this document, we review the research that has been undertaken on beneficial organisms (predators, parasites and pathogens) affecting pests in cotton systems over the last 30 years. We estimate that $A20-25 million has been spent on over 100 research projects over the last 10 years, by rural Research and Development Corporations, Co-operative Research Centres, CSIRO, State Agriculture Departments, and Universities. This research has resulted in a broad understanding of the role beneficials play in the population dynamics of pests, and of their potential contribution to pest management. While it is clear that beneficials, on their own, are unlikely to limit populations of *Helicoverpa* spp. to levels below current economic thresholds, it is also clear that they can have a major impact as part of an integrated pest management system. We show that even limited current guidelines for integrated pest management, which incorporate the effects of beneficials, have the potential to save growers almost $A1 billion, if implemented over the next 10 years. On this basis, the benefit:cost ratio for research on beneficials could be about 40:1, which compares well with benefit:cost ratios for biological control around the world.

We also show that there has been a major effort to extend information about beneficials to the growers, through printed material and decision support systems such as CottonLOGIC. Recent information on the economic benefits of conserving beneficials provides an excellent platform to reinforce the messages contained in this material, and facilitate the adoption of integrated pest management throughout the cotton industry. This is one part of the challenge for future research and development on the role of beneficials in cotton pest management.

The second part of the challenge is to develop techniques that allow explicit manipulation and exploitation of benefical insects in cotton systems, not just their conservation through the use of soft insecticides. Much remains to be done to achieve this goal. The abundance of beneficials within Australian agro-ecosystems is dynamic and population levels fluctuate at a number of temporal and spatial scales. The unpredictability of beneficials limits their use in pest management programs at present, and there are significant problems in developing

research methods that will generate the understanding required to overcome this unpredictability. The research required falls into the following categories:

1. *Basic biological and ecological knowledge.* Beneficial insects have frequently been studied at the community level, with their impacts on pest populations being assessed through comparisons of yield and pest control costs in different management regimes. Consequently, we know little about the ecological requirements, and in some cases even the basic biology, of some of our most common predators and parasites. There is a need for autecological studies which focus on one, or a limited number, of beneficials and which investigate their life cycles, prey, habitat requirements and other basic aspects of their ecology.
2. *Knowledge of distribution and movement in and between cotton, other crops, and natural vegetation*. A greater understanding of variation in the within field distribution of beneficials is required to develop accurate beneficial sampling schemes. The development of novel techniques for quantifying predator movement between and within fields and non-crop vegetation requires greater attention. Correlative studies alone do not provide enough evidence for the movement of beneficials between adjacent and non-adjacent fields within a region.
3. *Understanding the impact of beneficial insects on pest populations*. Abundance of a beneficial by itself does not necessarily mean that it is having a significant impact on the survival and abundance of a pest. We need to develop techniques for measuring prey consumption, and relating it to the population dynamics of pests. At present we can only assess the impact of a predator through prey consumption studies in the laboratory or in field cages. Both these techniques have significant limitations. Recent developments in the use of egg cards to assess both predation and parasitism may help in field assessments, but also have limitations. Serological methods show promise but require further development. Visual observations are laborious but essential. Combinations of all these methods are required, but these are often beyond the resources of current research projects. The development of novel experimental methods for measuring impact should be a priority. For parasitoids, percentage parasitism methods are widely used but need to be placed in the context of host phenology and abundance.

4. *Further understanding of the effects of pesticides on beneficials.* Laboratory studies of pesticide effects may be experimentally and statistically valid but not biologically meaningful and field applicable. While crude ratings of "hardness" currently exist, better experimental techniques for assessing impacts in the field are required. Current methods are confounded by factors in the environment and methodology, and may fail to account for indirect effects. The lack of standardised assessment protocols makes comparison of results between studies difficult, thus generalised statements regarding the toxicity of a pesticide group to a predatory group are impossible to formulate. An initial and residual toxicity rating is required by farmers to plan strategic pesticide applications. This information would be best presented on the pesticide label.
5. *Improved decision support tools for using beneficial insects.* These include simpler and less time consuming sampling methods that are likely to be widely adopted by consultants. For parasitoids and diseases, diagnostic kits which can measure the incidence of affected larvae in the field are required. We also need more sophisticated means of incorporating beneficial counts into decision making beyond the simple predator:prey ratios now available.

In summary, we believe that extensive research over many years has placed the cotton industry in a position where growers now have sufficient confidence in beneficial insects to allow the widespread adoption of integrated pest management. Conservation of beneficials through the use of selective pesticides is a key element. This alone will reap significant financial benefits for growers, as well as indirect benefits to the wider community through the reduction of pesticide use. However, much remains to be done to achieve the next step: a framework for manipulating agricultural systems in a deliberate and planned fashion, in order to maximise the effectiveness of biological control of cotton pests.

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Review of Beneficials in Cotton Farming Systems

1. Introduction: Previous research on the major beneficials known to occur in Australian cotton farming systems

Twenty years ago Ives (1980) highlighted the fact that our knowledge of the effectiveness of various predators was inadequate. As a result we are bound to utilise beneficial insects in a passive way. We hope the survivors of pesticide treatments will impose some undefined mortality on the pests. An active approach, in which predictions of the effects of beneficials on pest populations are used to modify our responses, would be preferable but, as Wilson (1994) pointed out, "perhaps the greatest deficiency in IPM at the moment is our inability to effectively incorporate predation into decision making". Little appears to have changed over 20 years!

Beneficials are at least recognised as qualitatively important, if the extension literature is any guide, and there is a desire to preserve them by judicious pesticide selection. However, not many growers or pest management consultants accurately and reliably sample for beneficials as a group or at a species level and include this information in decision making. This situation in part reflects the lack of incisive research that clearly shows the circumstances under which beneficials will have sufficient impact on pest abundance to keep them below threshold. Until such work is undertaken the full use of beneficials in pest management will remain problematic. The research work that needs to be undertaken is inherently complicated by the dynamic nature of arthropod populations and agro-ecosystems.

Cultivated cotton in Australia has a wide variety of pests, the control of which historically has relied on frequent applications of chemicals. Strategies reliant on broad spectrum chemical pest control inevitably lead to problems, such as the resurgence of original target species populations following pesticide application, secondary pest outbreaks and the development of resistance to insecticides (Guttierrez 1995). Problems inherent in a cropping system entirely dependent on the chemical control are reflected in the dramatic collapse of the Ord River

Irrigation Area cotton industry in the 1970's, within ten years of the initiation of commercial production.

Modern Integrated Pest Management (IPM) techniques for insect pest control in cotton emphasise a) the limited use of chemicals and b) selection of chemicals that are preferably "soft" on beneficial species. Broad-spectrum insecticides are used only when necessary in order to limit their negative effect on beneficial populations, especially parasitoid populations that are relatively susceptible. Recently introduced transgenic cotton varieties capable of expressing toxins that target the major pest species of Lepidoptera (Fitt *et al.* 1994) have reduced the dependence on pesticides, and help maximise the impact of beneficials both locally and on an area wide basis.

Here we review what is known about the use of beneficials in cotton farming systems. The review necessarily covers more than what happens in cotton fields alone as the abundance of beneficials in any one field is in part a reflection of what has happened in surrounding areas. We begin by asking how much time and money has been actually spent on this area of research. This in part assesses how seriously beneficials, as a resource for pest management, are viewed by research funding bodies. We then ask what this expenditure has led to in terms of knowledge. We finally address a number of key questions that would need to be answered if beneficials are to be strategically used in pest management.

We make use of a number of sources of information: theses, published papers, reports, conference papers, software, unpublished data and personal communication. The review by Zalucki *et al.* (1986) has been used as a starting reference point.

1.1 Funding research on beneficials: the last 10 years

Despite extensive research into their suppression, the larvae of *Helicoverpa armigera* Hübner and *Helicoverpa punctigera* (Wallengren) (Lepidoptera: Noctuidae) (from here on referred to as heliothis for convenience) cause considerable damage to cotton and other crops Australia wide (Adamson *et al.* 1997). Since 1990 $A11 million has been spent by the major Research and Development Corporations (The Grains Research and Development Corporation, GRDC and the Cotton Research and Development Corporation, CRDC) on research related to biological control of heliothis and other pests (Table 1, Appendix 1). This figure does not include the amounts spent by the Cooperative Research Centres, Universities, the Horticultural Research and Development Corporation, State Departments of Agriculture or private sectors on similar research. The amounts spent by these bodies are not readily obtainable, nor is the data for the Barley, Grain Legume, Oilseeds and Wheat Research Councils that existed prior to October 1990 when the GRDC was formed. Similar data were accessible for the Cotton Research Council before it became the CRDC in October 1990. We believe it is reasonable to assume that funding from sources other than the Research and Development Corporations, whether provided in cash or in kind, would approximately equal the amounts provided by the Corporations. Thus, a rough estimate of the total amount spent on research into beneficials in cotton systems since 1990 would be $A20-25 million.

In an attempt to make a direct comparison between GRDC and CRDC during the last decade (from 1990/91 to 1999/2000) the data from the former Cotton Research Council is presented (Appendix 1) but not included in the analysis (Table 1).

The GRDC and CRDC are large providers of research and development funds in Australia (Table 1). The amount spent overall has generally increased each year during the past decade. GRDC has by far the largest expenditure on R&D projects but, when biological control related projects are considered, GRDC has funded fewer projects (n=35) and consequently less money has been generally spent in this area. These projects represent only 0.9% (range 0.2%–1.8%) of all GRDC funded projects. In contrast, CRDC has a smaller R&D budget (by a factor of 10) but has funded more biological control projects (n=52) that represent about 9.5% (range 5.3%-15.6%) of all CRDC projects. Furthermore, the absolute dollar value spent on these projects by CRDC was greater than GRDC until 1997/98. This difference possibly reflects the level of importance placed on biological control of invertebrate pests in each system. GRDC concentrates its research in the areas of crop rotation and resistant varieties, and biological control research attracts proportionally less of the budget.

TABLE 1
Summary of annual expenditure by the CRDC and GRDC on biological control (B/C) related pest management research from 1990/91 to 1999/00.
See Appendix 1 for further details.

	YEAR	90/91	91/92	92/93	93/94	94/95
CRDC	Sum B/C	207157	233192	524064	658573	737784
	Total	3013457	4426548	3991273	4775474	4727023
	% B/C	6.87	5.27	13.13	13.79	15.61
GRDC	Sum B/C	50632	95036	149118	368423	359824
	Total	32091929	29437968	32225738	44130324	43769141
	% B/C	0.16	0.32	0.46	0.83	0.82

	YEAR	95/96	96/97	97/98	98/99	99/00	Total
CRDC	Sum B/C	451896	540761	761659	841980	717267	5674333
	Total	4897783	6151086	8660761	10651772	12600000	63895177
	% B/C	9.23	8.79	8.79	7.90	5.69	8.88
GRDC	Sum B/C	293439	484575	1197816	1342866	1290032	5631761
	Total	50335642	60793250	67511421	81685177	95899204	537879794
	% B/C	0.58	0.80	1.77	1.64	1.35	1.05

However, more than two thirds (69%, n=35) of the GRDC funded biological control projects have objectives entirely focused on biological control (these are assigned to Category One in Appendix 1). In contrast, only 35% (n=52) of CRDC's biological control related projects have similarly focussed objectives. Category One projects are those focused entirely on biological control. Category Two projects have only a partial focus on biological control. Category Three projects only involve travel with a biological control related focus.

Funded research has lead to a number of outcomes ranging from termination reports (not always accessible), published papers in journals and conferences, to information for the primary beneficiary of this work – the grower and insect pests manager. For all these biological control projects, it would be interesting to assess how the degree of fulfilment of project objectives has impacted on pest management strategies adopted by industry. Here we partly address this question by asking the following questions. What are the main findings of this research to date and where are the gaps in our knowledge?

2. Beneficials occurring in cotton farming systems

2.1 Predators

Predators, animals that make a living by hunting, finding, killing and consuming many living prey items, are present in every ecosystem. By the way they make their living predators cause mortality of their prey which reduces their local abundance. The benefit of this reduced abundance, if the prey happens to be a pest, is rarely quantified. Yet when predators and their effects are eliminated, as happens with overuse of certain pesticides, pest outbreaks ensue and then their loss is acutely felt. The 'ecosystem services' of background pest mortality provided by the diversity of predators that occur, even in managed agricultural systems, has in part sustained agriculture from its inception. For various reasons the abundance of some pests can exceed the ability of predators and other mortality agents to keep them below damaging levels. In this situation other management options need to be used.

A review by Zalucki *et al*. (1986) lists 29 species of arthropods from 18 families (in six orders) as potential heliothis predators in cotton. No mention was made of their abundance or importance in terms of mortality inflicted on heliothis. Anthocoridae, Reduviidae and Formicidae (ants) are absent from this list. The major published research on beneficials in cotton farming systems during the period up to 1986 was by Awan 1981, Bishop (1978), Bishop and Blood (1977, 1980, 1981), Bishop and Holtkamp (1982), Broadly (1980), Cooper (1979), Evans (1985), Pyke (1980), Richards (1968), Room (1979), Samson and Blood (1979, 1980), Shepard *et al.* (1983) and Waite (1983).

What additional information has accrued since 1986? A number of research projects by Annetts (2000 unpublished data), Gregg *et al.* (1998), Grundy (2000 unpublished data), Johnson (1999), Lytton-Hitchins (1998, 1999), Mensah (1997, 1999b), Murray *et al.* (1994b), Scholz (2000 unpublished data), Stanley (1997), Titmarsh (1992), Wade (1999), Walker *et al.* (1998), and Yee (1998), and compilations by Pyke and Brown (1996) and Wilson *et al.* (1996, 1998) have expanded the list of predatory species presently identified in agro-ecosystems, attempted to estimate predator abundance (see section 3) and in some instances related mortality of the pest to beneficials (see section 5 and Table 2).

To date some 123 species of predator have been recorded in Australian farming systems (Table 2). Most are insects (80 species in ten orders), followed by spiders (at least 41 species in 11 orders), one species in the class Collembola (springtails) and one in the Acarina (mites). This data was compiled from studies that identified arthropod species collected in crops from Western Australia, Northern Territory, New South Wales and Queensland. These studies concentrated on predators of heliothis and the two-spotted mite *Tetranychus urticae* (Wilson *et al.* 1998). A species was considered to be a known predator if it had been "observed" to feed on some stage of heliothis or mite. This included field and laboratory studies (Awan 1981, Room 1979) on feeding preferences as well as anecdotal observations made by the researchers (Bishop and Blood 1977, Room 1979, Shepard *et al.* 1983). Whilst these species are considered to be predators their impact on prey, and alternative prey preferences, are largely unknown.

Some references (Bishop & Holtkamp 1982, Evans 1985, Richards 1968) included lists of the entire invertebrate assemblage collected, making no comment on the feeding strategies of the species recorded (predacious, phytophagous etc.). Only those species that had previously been recorded as predators in other references were included in Table 2. There are a great number of species that were not included in this table because their feeding strategies are unknown. Some of these unknown species may potentially be predacious. No doubt further species will be identified with more extensive sampling, evaluation and taxonomic skills. For instance most sampling to date has been on aerial plant parts using techniques such as direct observations, sweep nets, and/or vacuum sampling. As sampling of the predatory ground fauna has been inadequate this component is likely to be under- represented.

TABLE 2
Known Predators of Crop Pests in Australia

* NA = unspecified location in northern Australia (Qld & NT), SEQ = South East Queensland, NN = Northern NSW, NV = Namoi valley NSW, HV = Hunter Valley NSW, WA = Western Australia
** GL = Grain Legumes (e.g. Soybean); C = Cotton; SC = Sweet corn; L = Lucerne
*** 1 = Shepard et al. 1983; 2 = Bishop & Blood 1977; 3 = Scholz 2000; 4 = Pyke & Brown 1996; 5 = Evans 1985; 6 = Stanley 1997; 7 = Room 1979; 8 = Bishop1980; 9 = Bishop & Blood 1980; 10 = Bishop & Holtkamp 1982; 11 = Strickland 1981; 12 = Richards 1968; 13 = Lytton-Hitchins 1999; 14 = Wilson et al. (1998)

HE = *Helicoverpa* spp. eggs, HL = *Helicoverpa* spp. larvae, HP = *Helicoverpa* spp. Pupae, HA = *Helicoverpa* spp. adults, TU = *Tetranychus urticae* (Two-spotted spider mite), A = Aphids, ADB = Apple Dimpling Bug, L = Loopers, T = Thrips, phyto. = Phytophagous, pred. = Predatory, FI = Flying insects

SCIENTIFIC NAME	REGION*	CROP**	REF.***	PREY#
Coleoptera, Cantharidae				
Chauliognathus tricolor (Castelnau)	NA	GL	1	
Chauliognathus pulchellus Erichson	NA, SEQ, NV	GL, C, SC	1,2,3,4,5,7	HE, HL
Carabidae				
Calosoma schayeri Erichson	NA, SEQ, NV, HV	GL,C, L	1,4,5,7,10,13	HL
Chlaenius flaviguttatus Macleay	NA, SEQ, NV, WA	GL, C, L	1,9,10,12	
Chlaenius australis Dejean	SEQ, WA	GL	5,12	
Chlaenius maculatis Castille	SEQ	GL	5	
Geoscaptus sp.	NA, NV, WA	GL, L	1,10,12	
Geoscaptus laevissimus	NV	C	13	
Gnathaphanus pulcher (Dejean)	NA, SEQ, NV, WA	GL, L	1,5,10,12	
Notogonum sp.	NA, SEQ	GL, C	1,9	
Mictolestodes macleayi (Csiki)	NN	C	6	
Pheropsophus verticalis (Dejean)	NA, SEQ, HV	GL, C, L	1,5,9,10	
Helluo insignis Sloane	NV	C	7	HP
Coccinellidae				
Coccinella arcuata	SEQ, WA	C	2,12	
Coccinella transversalis (Fabricius)	NA,SEQ, NN, NV, HV, WA	GL,C, SC, L	1,3,4,5,6,7,10,12, 14	HE, HL, TU
Coelophora inaequalis (Fabricius)	NA, SEQ	GL, C, SC	1,2,3,5,14	HE, TU
Diomus notescens (Blackburn)	NA, SEQ, NN, NV, HV	GL, C, SC, L	1,2,3,4,5,6,7,10,14	HE, HL, TU
Harmonia arcuata (Fabricius)	NA,NV	GL,C	1,7	HE, HL
Harmonia octomaculata (Fabricius)	SEQ	C, SC	3,4,5,14	HE, TU
Harmonia conformis (Boisduval)	NA, SEQ, NN, HV	GL,C, SC, L	1,3,5,6,10,14	HE, TU
Leis conformis	SEQ	C	2	
Micraspis frenata (Erichson)	SEQ, NN, HV	C, SC, L	3,4,5,6,10	phyto., HE
Verania fernata Erichson	SEQ, NV	C	2,7	HE, HL
Stethorus spp.	SEQ	C	4,14	TU
Stethorus nigripes (Kapur)	NN	C	6	
Scymnodes spp.	NN	C	6	pred.

SPECIES	REGION*	CROP**	REF.***	PREY#
Melyridae				
Micraspis aphidectoides	NA	GL	1	
Dicranolaius bellulus (Guerin-Meneville)	NA, SEQ, NN, HV	GL, C, SC, L	1,3,4,5,6,10	phyto., HE, HL
Laius sp.	NA, SEQ,NV, WA	GL, C	1,2,7,12	HE, HL
Staphylinidae				
Sepedophilus sp.	NN	C	6	possibly pred.
Paederus cruenticollis Germar	NN	C	6	possibly pred.
Collembola,				
Entomobrya unostrigata Stach	SEQ	SC	3	HE
Dermaptera, Labiduridae				
Labidura truncata Kirby	NA, SEQ, NV, HV	GL, C, L	1,2,4,5,7,9,10,13	caterpillars, HP
Nala lividipes (Dufour)	SEQ, HV	GL, C, L	4,5,9,10,13	
Diptera, Empididae				
Isodrapetis sp.	NN	C	6	pred.
Syrphidae				
sp. ?	SEQ, NN	C	4,6	adults: nectar, pollen; larvae: A
Ischiodon scutellaris (Fabricius)	SEQ	GL	5	
Sphaerophoria macrogaster (Thomson)	SEQ	GL	5	
Asilidae				
Bathypogon sp.	NA	GL	1	
Thereutria pulchra (Schiner)	SEQ	GL	5	
Chrysopogon sp.	NA	GL	1	
Dolichopodidae				
Amblypsilopus discretifasciatus (Macquart)	SEQ, NN	GL, C	5,6	pred.
Hemiptera, Lygaeidae				
Geocoris lubra Kirkaldy	NA, SEQ, NN, NV, HV	GL, C, SC, L	1,3,4,5,6,7, 10, 14	HE, HL, TU
Germalus sp.	NN, NV	C	6,7	HE, HL
Oxycarenus luctuosis	NV, WA	C	7,12	HE
Miridae				
Campylomma seminigricaput (Girault)	NN	C	6	phyto. & pred.
Campylomma liebknechti (Girault)	NA,SEQ, NN, NV, HV	GL,C, SC,L	1,3,4,6,7,10, 14	phyto., HE, HL, TU
Tytthus chinensis (Stal)	NA, SEQ	GL, SC	1,3	phyto., HE
Deraeocoris signatus (Distant)	SEQ, NV	GL, C, SC	3,4,5,7,14	HE,HL,TU,A,ADB
Taylorilygus apicalis (Fieber) *(pallidulus)*	NN	C	6	phyto. & pred.
Nabidae				
Nabis (Tropiconabis) kinbergii Reuter	NA,SEQ, NN,NV, HV, WA	GL, C,SC, L	1,3,4,5,6,7, 10,12,14	HE, HL, TU
Pentatomidae				
Cermatulus nasalis (Westwood)	NA, SEQ, NV, HV	GL, C, L	1,4,5,7,10	HL, L
Oechalia schellenbergii (Guerin-Meneville)	NA, SEQ, NN, NV, HV, WA	GL,C, L	1,4,5,6,7,10, 12	HL, L

SPECIES	REGION*	CROP**	REF.***	PREY#
Reduviidae				
Coranus trabeatus Horvath	NA, SEQ	GL	1,5	
Gminatus wallengreni Stal	NA	GL	1	
Trachylestes aspericollis (Stal)	NA	GL	1	
Pristhesancus plagipennis Walker	NA, SEQ,WA	GL, C	1,4,5,12	insects
Oncocephalus fuscirostris Stal	SEQ,NV	GL, C	5,7	HL
Pirates ephippiger White	SEQ,NV, HV,WA	GL,C, L	5,7,10,12	HL
Sastrapada australica	NA	GL	1	
Anthocoridae				
Orius sp.	SEQ, NN	GL, C, SC	3,4,5,6,14	HE, TU, T
Lampronanella sp.	SEQ	GL	5	
Hymenoptera, Formicidae				
Iridomyrex spp. *rufoniger group*	NA, SEQ, NN, NV, WA	GL, C, SC	1,3,6,7,12,13	HE, HL
Pheidole megacephala (Fabricius)	SEQ,NV,WA	GL, C, SC	3,5,7,12	HE, HL
Rhytidoponera spp.	NV, HV,WA	C, L	7,10,12,13	HE, HL
Mantodea, Mantidae				
Orthodera ministralis (Fabricius)	NA,WA	GL	1,12	
Sphodropoda tristis (Brunner in Saussure)	SEQ	GL	5	
Bolbe sp.	NV	C	7	HL
Tenodera sp.	NA	GL	1	
Neuroptera, Chrysopidae				
Mallada signatus (Schneider)	NA, SEQ,NN,NV, HV,WA	GL, C, SC, L	1,3,4,5,6,7, 10,12	HE, HL
Hemerobiidae				
Micromus tasmaniae (Walker)	SEQ, NN,NV,HV	C, SC, L	3,4,6,7,10,14	adults: HE; larvae: TU
Odonata, Aeshnidae				
Hemianax papuensis (Burmeister)	NA, NV,WA	GL, C	1,7,12	HA
Coenagrionidae				
Austroagrion cyane (Selys)	NA	GL	1	
Ischnura aurora (Brauer)	NA,WA	GL	1,12	
Ischnura heterosticta (Burmeister)	NA	GL	1	
Libellulidae				
Diplacodes bipunctata (Brauer)	NA,SEQ,WA	GL	1,5,12	
Orthetrum caledonicum (Brauer)	NA, NV,WA	GL, C	1,7,12	HA
Pantala flavescens (Fabricius)	NA,WA	GL	1,12	
Orthoptera, Tetrigidae				
Pteronembius sp.	SEQ	SC	3	HE
Tettigoniidae				
Conocephalus sp. *H5*	NV,WA	C	7,12	HE, HL
Thysanoptera, Thripidae				
Scolothrips sexmaculatus (Pergande)	NV	C	14	TU
Acarina, Phytoseiidae				
Amblyseius masiaka Blommers & Chazeau	NV	C	14	TU

SPECIES	REGION*	CROP**	REF.***	PREY#
Araneae, Amaurobiidae				
Ixeuticus longinquus (L. Koch)	SEQ	C	8	
Ixeuticus sp. *(?) scalaris* (L. Koch)	SEQ	C	8	
Badumna longinquus	SEQ	C	2	
Badumna sp. *(?) scalaris*	SEQ	C	2	
Araneidae				
Araneus heroine (L. Koch)	NA,SEQ	GL,C	1,2,4,8	HA, FI
Araneus theisi Koch	NA,SEQ,NV	GL,C	1,2,4,7,8	HL, HA, FI
Argiope protensa	NA,SEQ,HV	GL,C,L	1,4,10	HA, FI
Argiope trifasciata	NA,SEQ	GL,C	1,2,4,8	HA, FI
Argiope extensa Rainbow	SEQ,NV	C	2,7,8	HA, HL
Gasteracantha minax Thorell	SEQ	C	2,8	
Leucauge dromedaria	SEQ	C	2	
Leucauge granulata (L. Koch)	SEQ	C	8	
Clubionidae				
Cheiracanthium diversum Koch	NA, SEQ, NV	GL, C	1,2,7,8	HE, HL, HA
Cheiracanthium sp.	NN, HV	C,L	6,10	
Clubiona sp.	NA, SEQ, HV	GL, C,L	1,2,8,10	
Lycosidae				
Lycosa spp.	NA, SEQ,NV	GL, C	1,2,4,5,7,8,9	large HL
Lycosa godeffroyi	NV	C	13	larvae
Oxyopidae				
Oxyopes macilentus	NA, SEQ,NN	GL,C	1,4,6	small HL
Oxyopes elegans Koch	NV,HV	C,L	7,10	HL
Oxyopes molarius	NA,NV	GL, C	1,7	HL
Oxyopes mundulus L. Koch	NA, SEQ,HV	GL, C, L	1,2,8,10	HL
Oxyopes amoenus L. Koch	SEQ	C	2,8	
Oxyopes spp.	NA,HV	GL, L	1,10	
Pisauridae				
Dolomedes sp.	NA,HV	GL,L	1,10	
Salticidae				
Astia spp.	NA,SEQ,NN	GL, C	1,4,6	small HL
Bianor concolor (Keys)	SEQ	C	2,8	
Habrocestum sp.	SEQ	C	2,8	
Cytaea sp.	NA	GL	1	
Gangus longulus	NA	GL	1	
Myrmarachne sp.	NA, SEQ,HV	GL, C, L	1,2,8,10	
Heteropodidae				
Hasarius obscurus L.K.	NV	C	7	HL
Theridiidae				
Neosparassus spp. *(Olios* spp.*)*	NA	GL	1	
Achaearanea veruculata (Urquhart)	NA, SEQ,NV	GL, C	1,2,3,7,8,14	HL, TU
Euryopis sp.	NA	GL	1	
Latrodectus hasselti Thorell	NA, SEQ,NV,HV	GL, C, L	1,2,4,5,7,8,10	HL, HA
Theridion sp.	SEQ	C	8	
Steatoda sp.	SEQ,HV	C, L	8,10	

SPECIES	REGION*	CROP**	REF.***	PREY#
Thomisidae				
Diaea sp. *(D. variabilis)*	NA, SEQ,NV,HV	GL, C, L	1,2,4,7,10	HL, small insects
Tetragnathidae				
Diaea prasina L. Koch	SEQ	C	8	
Uloboridae				
Uroborus sp.	SEQ,HV	C, L	8,10	
Gnaphosidae				
Anzacia sp.	SEQ,HV	C, L	8,10	

The majority of the 123 species listed in Table 2 belong to three orders, the spiders (32% n=41 species), Coleoptera (25% n=31 species) and Hemiptera (17% n=20 species). Other orders represented by a few species include Collembolla, Dermaptera, Diptera, Hymenoptera, Thysanoptera, Acarina, Orthoptera, Mantodea, Neuroptera, and Odonata. Some species are recorded exclusively in cotton (34 species), others only in crops such as sweet corn, soybean, lucerne or other grain legumes (n=33 species), and the remainder in at least two crops (n=56 species). Of the latter, for 48 species one of the crops included cotton. From a cotton manager's perspective there appears to be a substantial predatory fauna that either occurs on cotton alone or occurs on cotton and other crop plants likely to be grown in the general vicinity of cotton. However, this conclusion could be misleading. To date most of the work on predators has been done in cotton and fewer, less detailed, taxonomic surveys have been conducted in the other crops.

A number of predators (n=9) occurred on all crops sampled (cotton, sweet corn, lucerne, various grain legumes). These were *Diomus notescens* (Blackburn) [minute two spotted ladybird], *Dicranolaius bellulus* (Guerin-Meneville) [red and blue beetle], *Geocoris lubra* Kirkaldy [bigeyed bug], *Mallada signatus* (Schneider) [green lacewing], *Harmonia conformis* (Boisduval) [common spotted ladybird], *Coccinella transversalis* (Fabricius) [transverse ladybird], *Nabis kinbergii* Reuter [damsel bug], *Micraspis frenata* (Erichson) [striped ladybird] and *Campylomma liebknechti* (Girault) [apple dimpling bug].

Only some 29 species (24% of the predatory fauna recorded to date) have been recorded in both cotton and lucerne (*Medicago sativa)* (Table 2). This combination of plants has been suggested as a pest management strategy to manipulate predator abundance; lucerne serving as a source of beneficials for the cotton (Mensah and Harris 1996ab, Mensah *et al.* 1996). Many of the predacious species on this list also utilise non-crop habitats, such as native vegetation remnants, weedy road verges and grasses along field edges (Johnson 1999, Yee 1998).

2.2 Pathogens and nematodes

Nine different types of insect pathogens of heliothis have been recorded in Australian cropping systems. They include four types of fungus, three viruses, a bacterium, a protozoan and a nematode (Table 3). Some have only been recorded in cotton (granulosis virus, *Nosema heliothidis*, *Spicaria rileyi)*, whilst others appear to be active in a number of crops (Table 3). Only limited conclusions can be drawn from this table because the identification and sampling for pathogens has not been widespread. As with all beneficials, assessing the level of mortality caused by the agent is problematic, but perhaps more so with pathogens. Animals become infected in the field, die and disappear before we are able to record them. In an attempt to measure infection levels, field collected host insects are returned to the laboratory for subsequent observation. However, it is uncertain whether they would die from the same agent in the field. Identifying the disease-causing organism is difficult because the expertise is even less available than the now rare insect taxonomist! There have been few systematic surveys published for disease causing organisms and the level of infection they achieve in Australian agriculture. Titmarsh (1992) recorded the proportion of larvae dying in collections made from various crops on the Darling Downs from 1985/6 to 1987/8. The most common pathogen recorded was NPV accounting for some 28% of overall mortality in collected larvae (Instars III-VI). The disease levels recorded ranged from 0-87% depending on the crop, field and season. Fungi caused about 2% mortality.

TABLE 3
Potential Pathogens of Crop Pests in Australia

* NA = unspecified location in Northern Australia (Qld & NT), SEQ = South east Queensland, SA = South Australia

** GL: grain legumes, C: cotton, Ch:Chickpea, M:Maize, Mb:Mungbean, Pp:Pigeonpea, S:Sorghum, Sb:Soybean, Sf:Sunflower, N:Navybeans

*** HL = *Helicoverpa* spp. larvae, HA = *Helicoverpa* spp. adults, H = unspecified stage of *Helicoverpa* spp., CL = cotton loopers, L = loopers, CC = cluster caterpillar, TL = tobacco looper, A = armyworms

1:Shepard et al. 1983, 2:Bishop & Blood 1977, 3:Pyke & Brown 1996, 4:Titmarsh 1992, 5:Teakle 1973, 6: Poinar 1975, 7: Cullen 1969, 8: Cooper 1979, 9: Forrester 1994, 10: Teakle 1994, 11: Teakle et al. 1985, 12: Graham 2000, 13: Murray et al. 1994a

SCIENTIFIC NAME	REGION*	CROP**	TARGET PEST***	COMMERCIAL FORMULATION	REFERENCE#
Bacteria					
Bacillus thuringiensis (Berliner)	SEQ	C	HA, Lep. larvae	Yes, e.g.Dipel[R]	3,8,9,10
Fungus					
Spicaria rileyi	SEQ	C	H	No	2
Beauveria bassiana (Balsamo)	SEQ, SA	C, Ch, M, Mb, Pp, S, Sb, Sf	HA, CL, CC, A	No	3,4,8
Nomuraea rileyi (Farlow)	NA, SEQ	GL, C, Ch, M, Mb, Pp, S, Sb, Sf	HA, CL, CC, TL, A	No	1,3,4,8
Entomophthora sp.	NA	GL	L	No	1
Virus					
Nuclear polyhedrosis virus	NA, SEQ	GL, C, Ch, M, Mb, Pp, S, Sb, Sf	HA, CL, CC	Yes, e.g.Gemstar[R], Elcar[R]	1,2,3,4,5,8,11
Granulosis virus	SEQ, SA	C	H	No	2,5,7,8
Ascovirus	SEQ	C, S, Sf, N	HA	No	12, 13 (I. Newton *pers. comm.*)
Protozoa					
Nosema heliothidis	SEQ	C	HA	No	8
Nematoda					
Heterorhabditis bacteriophora	SA	L	HA	No	6,8

In more recent times ascovirus infection of heliothis has been found to cause mortality levels of up to 48% in unsprayed navybeans, sorghum and sunflower (Graham 2000). Preliminary molecular testing has verified the visual diagnosis of ascovirus. In one block ascovirus prevalence was recorded at 89% and averaged 51% over the course of the season (January to March 1995). Ascovirus prevalence reaches a maximum around February of each year (D.A.H. Murray pers. comm.)

2.3 Parasitoids

Insect parasitoids utilise host tissue for the growth and development of their own immature stages. They may develop within or attached to the outside of their hosts as endo- or ecto-parasitoids, respectively. In order to locate potential hosts, female parasitoids follow a complex sequential procedure governed by physical and chemical cues (Schmidt 1994). Once the located host has been examined and accepted, oviposition and larval development induces deterioration and ultimately host mortality. Parasitoids can play a vital role in the reduction of host species abundance within and across generations (Hawkins 1994).

Many species of native and introduced parasitoids occur in Australian cotton (Table 4). The majority seem to target heliothis (see section 5). Another egg parasitoid, *Telenomus*, has frequently been recorded parasitising cotton pests, yet is relatively little studied. Larval parasitoids of heliothis have received more attention with both native and introduced species examined. Parasitised larvae tend to persist to pupation, displaying reduced feeding and associated damage until the adult parasitoids emerge.

Heliothis larvae are commonly parasitised by the braconid *Microplitis demolitor* (Wilkinson). The ichneumonids, *Heteropelma scaposum* (Morley), *Netelia producta* (Brullé), *Lissopimpla excelsa* (Costa) and tachinids in the genera, *Carcelia*, *Exorista*, *Goniothalmus* and *Chaetophalmus* parasitise larvae but host development continues till either the pre-pupal or pupal stages. They are larval/pupal parasitoids. Levels of parasitism by these species are discussed in section 5.

TABLE 4
Potential beneficial parasitoids of pests on cotton and other crops in Australia

*A = unspecified location within Australia, NNSW = Northern New South Wales, SEQ = South East Queensland,
WA = Ord River region Western Australia
**C = cotton, CA = canola, CH = chickpea, F = field collected, FP = field pea, GL = grain legume, L = linseed, LP = lupin,
LU = lucerne, MA = maize, MB = mungbean, P = pigeonpea, PN = peanut, PO = potato, SA = safflower, SB = soybean,
SO = sorghum, SU = sunflower, T = tobacco
***1 = Bishop & Blood 1977, 2 = Evans 1985, 3 = Michael & Woods 1978, 4 = Michael & Woods 1980, 5 = Miles & Bull 2000,
6 = Murray 1982a, 7 = Murray 1982b, 8 = Murray & Zalucki 1994, 9 = Pyke & Brown 1996, 10 = Room 1979, 11 = Scholz 1991,
12 = Scholz & Murray 1995, 13 = Shepard *et al.* 1983, 14 = Stanley 1997, 15 = Strickland 1981, 16 = Strickland & Lacey 1996,
17 = Titmarsh 1992, 18 = Twine 1973, 19 = Twine 1975, 20 = Twine 1976, 21 = Twine & Lloyd 1982, 22 = Waite 1983,
23 = Zalucki *et al.* 1986
! = potential secondary parasitoid

SPECIES	REGION*	CROP**	PEST	REFERENCE***
Diptera				
Tachinidae				
Actia sp.	SEQ	C		1
Anamastax braueri (Hardy)	A	SU	*Heliothis* sp.	23
Anamastax sp.	A	T	*Heliothis* sp.	23
Aplomya sp.	SEQ	SB	*Zizina labradus* (Godart)	2
Argyrophylax proclinata Crosskey	A	C	*Conogethes punctiferalis* (Guenee)	9
Boria sp.	SEQ	C		1
Carcelia (?) cosmophilae Curran	A	GL		13
Carcelia illota (Curran)	SEQ	F,SU		8,17
Carcelia noctuae (Curran)	A,NNSW,SEQ	C,SO,SU	*Heliothis* sp.	1,10,23
Carcelia sp.	A,SEQ	C,GL,SB,SU,T	False loopers *Heliothis* sp. *Z. labradus*	2,13,23
Chaetophthalmus dorsalis (Malloch)	A,NNSW,SEQ	C,LU,MA,P,SO,SU	*Heliothis* sp.	1,10,17,23
Chaetophthalmus sp.	A	LU,SB,SU	*Heliothis* sp.	23
Chaetoria spinicosta (Thomson)	SEQ	SB	*Leptomeris recessata* *Leptomeris* sp.	2
Compsilura concinnata (Meigen)	A,SEQ	SB,SU	*Thysanoplusia orichalcea*(F.) *Heliothis* sp. *Spodoptera litura* (F.)	2,17,23
Cuphocera sp.	A	SU	*Heliothis* sp.	23
Exorista curriei (Curran)	A,SEQ	C,MA,SO,SU	*Heliothis* sp.	17,23
Exorista sp.	A	GL,SU,T	*Heliothis* sp.	13,23
Goniophthalmus australis (Baranov)	A,SEQ	C,F,GL,SA,SB,SO, SU	*Heliothis* sp.	2,8,13,17,23
Goniophthalmus sp.	A	C,T	*Heliothis* sp.	9,23
Linnaemya sarcophagoides Cantrell	SEQ	F		8
Linnaemya sp.	SEQ	SB		2
Palexorista sp.	A,SEQ	GL,LU,MA,SB,SO,	*Heliothis* sp.	13,17,23
Paradrino laevicula (Mesnil)	SEQ	SB	*T. orichalcea* *Z. labradus*	2
Paradrino sp.	SEQ	SB	*Z. labradus*	2
Peribaea (?) orbata (Wiedemann)	A,SEQ	GL,SB	*S. litura*	2,13
Peribaea sp.	A	GL		13
Sisyropa sp.	A	T	*Heliothis* sp.	23
Sturmia sp.	SEQ	SB	False loopers	2
Tritaxys heterocera (Macquart)	A	SU	*Heliothis* sp.	23
Voria ruralis Fallen	SEQ	SB	False loopers	2
Hymenoptera				
Aphelinidae				
Aphelinus spp.	WA	F	*Acyrthosiphon kondoi* Shinji	15
Bethylidae				
Goniozus sp.	NNSW	C		14
Rhabdepyris sp.	NNSW	C		14
Braconidae				
Agathis rufithorax Turner	A	GL		13
Agathis sp.	A,NNSW	C,GL		13,14
Apanteles ruficrus (Haliday)	A,WA	F,GL	*Mythimna separata* (Walker)	13,15

SPECIES	REGION*	CROP**	PEST	REFERENCE***
Apanteles sp.	A,SEQ	GL,SB	*Chrysodeixis* sp. *Stomopteryx simplexella* (Walker) *Z. labradus*	2,13
Aphidius spp.	WA	F	*A. kondoi*	15
Bracon spp.	A	GL		13
Cardiochiles sp.	NNSW	C	*Heliothis* sp.	10
Chelonus sp.	A,NNSW,SEQ	C,MA,SB,SO,SU	*Heliothis* sp. *S. litura*	2,14,17,23
Cotesia flavipes (Haliday)	SEQ	MA		17
Cotesia kazak (Telenga)	A	C	*Heliothis* sp.	9
Cremnops dissimilis Turner	A	GL		13
Cremnops sp.	A	GL		13
Cyanopterus sp.	A	GL		13
Eriborus sp.	SEQ	SB	False loopers *Lamprosema abstitalis* (Walker) *S. litura*	2
Microchelonus sp.	SEQ	SB		2
Microgaster sp.	A	SO	*Heliothis* sp.	23
Microplitis demolitor Wilkinson	A,SEQ	C,GL,LU,SB,SO	*Heliothis* sp.	2,5,9,23
Microplitis sp. *(demolitor)*	SEQ	CH,MA,MB,P,SB, SO		17
Microplitis sp.	A,NNSW,SEQ	C,CA,CH,FP,L,SB,	False loopers *Heliothis* sp. *S. litura*	1,2,5,10,23
Rogas sp.	A	LU	*Heliothis* sp.	23
Trioxys complanatus Quilis	WA	F	*Therioaphis trifolii* (Monell)	15
Chalcididae				
Brachymeria rufifemur (Girault)	SEQ	C		1
Brachymeria sp.	A,SEQ	C,F,GL,SB	False loopers *Heliothis* sp.	8,13,23
!*Dirhinus* sp.	A,SEQ	F,GL	Tachinid	8,13
Diapriidae				
!*Trichopria* sp.	SEQ	F	Tachinid	8
!*Spilomicrus* sp.	SEQ	F	Tachinid	8
Dryinidae				
Gonatopus sp.	NNSW	C		14
Encyrtidae				
Euplectrus sp.	SEQ	SB	*Chrysodeixis* sp.	2
Litomastix sp.	A,SEQ	GL,SB	False loopers	2,13
Ichneumonidae				
Charops sp.	A,SEQ	SB	False loopers *Heliothis* sp.	2,23
Heteropelma scaposum (Morley)	A,NNSW,SEQ	C,F,GL,MA,MB,P, SB,SO,SU,T	*Heliothis* sp.	1,2,8,9, 10,13,17,23
Hyposoter didymator Thunberg	A	C	*Heliothis* sp.	9
Ichneumon promissorius (Erichson)	A,NNSW,SEQ	C,F,GL,SB,SO	*Heliothis* sp.	1,8,9,10,23
Mesochorus sp.	SEQ	SB	False loopers	2
Netelia producta (Brulle)	A,NNSW,SEQ	C,F,GL,LU,SB,SO	*Heliothis* sp.	1,8,9,10,13,23
Netelia sp.	A,SEQ	MB,SB,SU	False loopers *Heliothis* sp. *S. litura*	2,17,23
Ophion sp.	A	LU	*Heliothis* sp.	23
Pristomerus sp.	A,SEQ	SU	*Heliothis* sp.	17,23
Temelucha cycnea Kerrich	A	GL		13
Temelucha sp.	SEQ	SB	*S. simplexella*	2
Temelucha Gauld sp. 6	SEQ	SB	*S. simplexella*	2
Pteromalidae				
Eupteromalus sp.	A,SEQ	GL,SB	False loopers	2,13
Perilampus sp.	A	GL		13
!*Trichomalopsis* sp.	SEQ	F	Tachinid	8
Scelionidae				
Gryon sp.	SEQ	SB	*Mirperus scutellaris* *Piezodorus hybneri* (Gmelin)	2

SPECIES	REGION*	CROP**	PEST	REFERENCE***
Telenomus sp.	A,NNSW,SEQ,WA	C,LU,LP,MA,PN,	*Heliothis* sp. *P. hybneri*	1,2,6,7,9, 10,12,23
Telenomus sp. nr. *triptus* Nixon	SEQ	C	*Heliothis* sp.	18
Trissolcus basalis (Wollaston)	A,WA	F,GL	*Nezara viridula* (Linnaeus)	13,15
Trissolcus sp.	SEQ	SB	*Dictyotus caenosus* (Westwood) *N. viridula* *Plautia affinis* (Dallas)	2
Torymidae				
Syntomopus sp.	A	GL		13
Trichogrammatidae				
Aphelinoidea sp.	NNSW	C		14
Trichogramma australicum Girault	A,SEQ,WA	C,L,LU,MA	*Heliothis* sp.	3,11,18,20,23
Trichogramma sp. nr. *brassicae* Voegele	SEQ	C	*Heliothis* sp.	12
Trichogramma carverae Oatman & Pinto	SEQ	C	*Heliothis* sp.	11
Trichogramma funiculatum Carver	SEQ	C	*Heliothis* sp.	12
Trichogramma pretiosum Riley	SEQ,WA	C	*Anomis flava* (Fabricius) *Heliothis* sp.	3,4,16,19
Trichogramma sp. nr. *pretiosum* Riley	SEQ	C	*Heliothis* sp.	21
Trichogramma sp.	A,NNSW,SEQ,WA	C,SO,SU	*An. flava* *Heliothis* sp.	1,4,6,7,9,10, 11,22,23
Trichogrammatoidea bactrae Nagaraja	SEQ	C	*Heliothis* sp.	11,12
Trichogrammatoidea flava Girault	WA	C,L,LU	*An. flava* *Earias* spp. *Heliothis* sp. *Pectinophora gossypiella* (Saunders)	3,23
Trichogrammatoidea sp.	SEQ,WA	C,SO	*Heliothis* sp.	1,6,7
Trichogrammatoides rara Girault	A	C	*Heliothis* sp.	23
Trichogrammatoides sp.	A	C	*Heliothis* sp.	23

Pupae are parasitised by one ichneumonid, *Ichneumon promissorius* (Erichson). Pupal survival is variable (12 –70%) in rain-grown crops on the Darling Downs where pupal mortality agents include parasitism, predation and unknown factors (Murray & Zalucki 1994).

3. Abundance of beneficials

A number of techniques such as sweep net, visual observation, vacuum sampling, whole plant removal, beat bucket and ground cloth can be used alone or in combination to measure predator abundance in the field. Each technique has advantages and disadvantages that must be considered. The sampling efficiency of selected techniques has been evaluated in a number of different crops including cotton (Kauter *et al.* 1999, Mensah & Harris 1994, Stanley 1997, Wilson & Room 1982), soybean (Evans 1985,1987), mungbean (Brier 1997) and sorghum (Titmarsh 1992). Visual sampling, beat cloth and vacuum sampling are the commonly used collection techniques for scouting in commercial crops (Appendix 2). These methods are favoured because they are simple to conduct, and at least for visual and beat cloth require little outlay of money. Although the abundance of predators can generally be estimated in the field their impact is harder to quantify (see section 5). In contrast, parasitoid abundance is much more difficult to determine in the field. Adult parasitoids are generally small and highly mobile and parasitised eggs and larvae are often overlooked, or unrecognised within the crop (Annetts *et al*. 1998).

Sampling efficiency, particularly when using a single collection technique, may vary across the season as the crop morphology changes. Stanley (1997) found predator numbers collected using a small vacuum sampler decreased considerably across the cotton season when compared to collections using a larger vacuum sampler. Regular calibration of the collection technique with an absolute technique throughout the season will help estimate sampling efficiency. Unless sampling efficiency is calibrated, the comparison of relative abundance of beneficials between sampling dates may be misleading.

3.1 Variation in beneficial abundance

Agro-ecosystems are inherently changing environments that feature a range of different crops at various growth stages interspersed with non-crop vegetation patches. The abundance of associated beneficials is dynamic at various temporal and spatial scales. The occurrence and distribution of a particular beneficial species within a crop at any point in time is determined by many biotic and abiotic factors that we know little about. A first step in considering the potential of a beneficial in pest control is to determine if the species is present, and in high enough numbers within the crop at the same time as the target pest (Bishop 1978, Stanley 1997). Identification of factors that limit abundance of beneficials may lead to manipulation of the crop environment or the beneficial species, to enhance their effectiveness in pest control. Here we examine research conducted within Australian cotton farming systems on variation in the abundance of beneficials at a number of temporal (within seasons, between seasons) and spatial (within fields, between fields, between regions) scales.

3.1.1 Temporal variation

For effective biological control to occur seasonal trends in beneficial abundance and activity must be synchronised with those of the pest. If beneficials are abundant within the crop even a few days after high pest pressure, significant crop damage may have already occurred. On the other hand, if high beneficial numbers are maintained within the crop prior to pest immigration, surges in pest numbers and crop damage may be avoided or lessened. In Australian crops, particularly cotton, we are beginning to get a good idea of the within season patterns of abundance of beneficials, and management practices that can disrupt their populations. The change in beneficial abundance during and between growing seasons has been investigated for a number of species (Table 5). Coccinellids are typically abundant early in the cotton season prior to peak flowering, whereas *Geocoris* and *Orius* spp. are prominent later in the season (Gregg *et al.* 1998, Stanley 1997). Overall, predator abundance in cotton crops increases until mid season and then begins to decline (Figure 1) (Gregg *et al.* 1998, Stanley 1997, Walker *et al.* 1998). This profile is common for annual crops in Australia.

TABLE 5
Studies on the seasonal abundance of some predatory species in cotton farming systems.

SPECIES	COMMON NAME	REFERENCE
Dicranolaius bellulus	Red and blue beetle	Stanley 1997, Yee 1998
Harmonia conformis	Common-spotted ladybird	Yee 1998
Harmonia octomaculata	Three-banded ladybird	Yee 1998
Micraspis frenata	Striped ladybeetle	Yee 1998
Coccinella transversalis	Transverse ladybird	Stanley 1997, Yee 1998
Diomus notescens	Minute two-spotted ladybird	Stanley 1997, Yee 1998
Campylomma spp.	Apple dimpling bug	Stanley 1997
Creontiades dilutus	Green mirid	Stanley 1997
Nabis kinbergii	Damsel bug	Stanley 1997
Geocoris spp.	Big-eyed bug	Stanley 1997, Scholz 1998
Germalus sp.		Stanley 1997
Orius spp.	Minute pirate bug	Stanley 1997
Oechalia schellenbergii	Predatory shield bug	Stanley 1997
Mallada signata	Green lacewing	Stanley 1997
Micromus tasmaniae	Brown lacewing	Yee 1998
Formicidae	Ants	Stanley 1997, Lytton-Hitchins 2000
Spiders		Stanley 1997, Scholz 1998, Bishop 1978
Total predators		Stanley 1997, Scholz *et al.* 1998, Walker *et al.* 1998

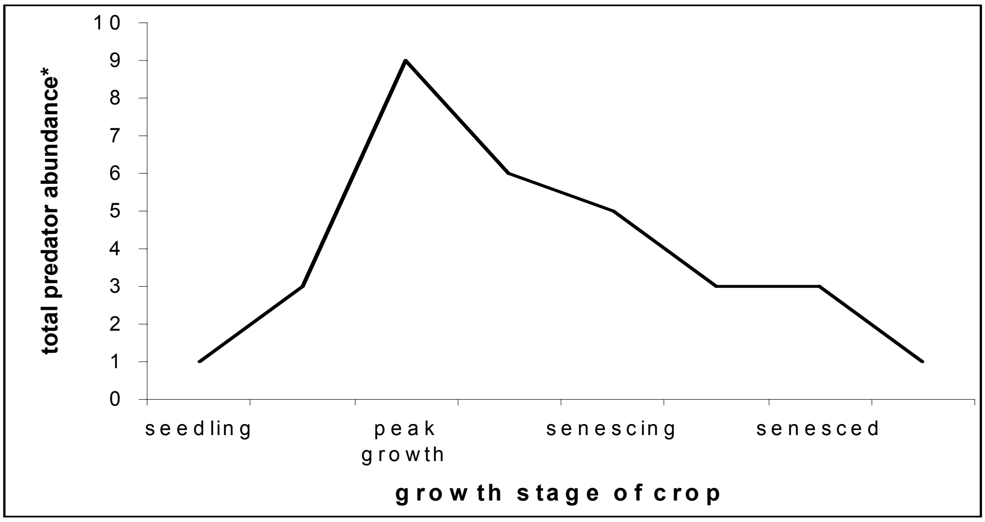

Figure 1. Simulated general trend in total predator abundance in an annual crop. Total predator abundance is ranked on a scale with 0 = low predator numbers and 10 = high predator numbers. Compiled from graphs in Stanley (1997), Yee (1998) and Walker *et al.* (1998).

Factors such as prey abundance, crop phenology, climate, immigration behaviour, reproductive potential, and the effect of insecticides may all contribute to the seasonal abundance profile of beneficials. Yee (1998) found that the variation in *C. transversalis* abundance was significantly related to vegetation phenology and aphid abundance, but not to Lepidopteran abundance. In cotton, heliothis represents only a small proportion of the prey available to generalist predators (Gregg *et al.* 1998, Stanley 1997). Environmental conditions such as high relative humidity, rainfall and low temperatures can affect predator abundance. Rainfall and irrigation may cause predator mortality and movement away from the crop and hence reduce predator abundance within the crop (Murray & Mensah 1996).

Commercial pesticide use within a region can have a dramatic impact on the temporal abundance patterns of predators and parasitoids (Bishop and Blood 1980, Scholz *et al.* 1998, Stanley 1997, see also section 3.3). Widespread pesticide use makes it difficult to accurately assess predator impact in the field because results are confounded by the problem of insecticide drift into unsprayed control plots (see section 5.3). Stanley (1997) found that predator numbers in cotton declined greatly from the onset of regional pesticide use (see also

Ma 2000 unpublished data). In unsprayed cotton this decline did not occur until later in the season.

Variation in the abundance of predators occurs between seasons. It is not unusual for a particular predator to be highly abundant within a crop type or region within one season, and in very low abundance the following season. Stanley (1997) examined the abundance patterns of several predators over two cotton growing seasons in the Namoi Valley, New South Wales. In one year *D. bellulus* (red and blue beetle) was caught in numbers of two to four per 10m suction sample and reached a maximum of 14 per 10m sample under a soft insecticide regime. In the following year numbers were reduced to between one to three per 10m suction sample, under both conventional and soft management regimes. The reduced abundance was explained in part by the onset of pyrethroid use throughout the region. Stanley (1997) notes that *D. notescens* (two spotted ladybird) did not reach appreciable abundance during the 1992/3 cotton season, however larger populations where present at the beginning of the 1993/4 season. These high population levels where severely reduced by the use of thiodicarb. The results of this study show that predators, like pest species, have suitable and unsuitable years for population growth. The suitability of any particular year may be influenced by various weather events (such as droughts or floods), however Stanley (1997) found the application of insecticides could account for many population crashes.

Beneficial abundance can also exhibit variation throughout the seasons of a single year. This is of particular importance for crops that can be grown throughout the year. Scholz (2000 unpublished data) found that beneficials had less impact on heliothis in spring planted corn than in summer planted corn. Natural parasitism of heliothis eggs was rarely greater than 10%, and predator numbers reached a maximum of 2.1 per plant in spring planted corn. In the summer planted corn parasitism was up to 90% and predators reached a maximum of 5.6 per plant. It is common practice to plan crop planting times to avoid periods of high pest activity. In the future it may also be possible to plant some crops to exploit periods of high beneficial abundance, though in long-season crops such as cotton there will be obvious limitations.

3.1.2 Spatial variation

Within field distributions

Less attention has been given to the variation in abundance of beneficials within a single field. Dispersion patterns can either be random, uniform or aggregated, the latter being most commonly found in biological communities (Bishop 1981). Pest management sampling schemes (Appendix 2) suggested for pest and beneficial scouting within a crop often assume that the insect population distribution is random across the field. Often no attempt has been made to account for the underlying distribution patterns, and a sampling protocol developed for another crop type or country has been applied. Evidence from overseas studies (Holland *et al*. 1999) as well as a few Australian projects (Scholz 2000 unpublished data) suggest that this assumption is unfounded. The recent interest in precision farming stems from the realisation that it is impractical to view a field as homogenous in terms of yield potential, crop, soil, and growth characteristics (Blackmore 1994). It is expected that fields of the size utilised in Australia (100ha or greater) will show some degree of heterogeneity in both crop characteristics and invertebrate distribution.

Dillon and Fitt (1990) found that the broad scale distribution of heliothis eggs and larvae within a 100 ha cotton field was characterised by small scale clumping. The patchy distribution of eggs and larvae did not consistently occur in any one area of the field. The current scouting procedures in cotton, which rely on randomly selected sampling points, may provide a good representation of pest abundance because the egg and larvae distributions do not favour any particular area of the field. Little research has been conducted to determine whether beneficials show similar distribution patterns within a field.

Bishop (1981, 1978) investigated the spatial dispersion of spiders within a cotton-field in southeast Queensland. Three spider species, *Chiracanthium diversum*, *Achaearanea verculata*, and *Lycosa* sp., were found to be equally distributed in the outer, middle and inner portions of the field. However, late in the season *A. verculata* was most abundant in the western portion of the field. Bishop (1978) concludes that the temporal and spatial distribution patterns of spiders in cotton fields corresponded well with that of their prey, and this behaviour increased the likelihood of interactions between spider species and their prey.

Scholz (2000 unpublished data) used egg cards placed in a grid pattern in unsprayed sweet corn fields to investigate spatial and temporal variation in egg predation and parasitism. The spatial pattern of activity by predators and egg parasitoids varied from week to week. *Trichogramma* foraged over the entire field throughout the vegetative stage. In contrast, the action of ants was restricted to the crop edges which where close to the nesting sites. Despite the fact that ants were significant predators of heliothis eggs, their patchy distribution within the field is thought to restrict their use in pest management decisions.

Stanley (1997) investigated a density gradient of arthropods in one cotton field. He compared the numbers of arthropods collected from various sides of cotton fields that bordered bushland or neighbouring crops. Only Thysanoptera and one coccinellid species (*C. transversalis*) displayed any indication of density gradients from one side of the field to the other. There was no indication that colonisation occurred from any particular direction or source. Stanley concluded that the condition of the bushland area was poor due to a dry season so the numbers of predators inhabiting the region, and moving to the adjacent field would be low. No arthropod samples where collected within the suspected source areas to determine if these areas actually had the potential to supply predators to the adjacent field. Stanley noted that the sampling design utilised, (plots equi-distant from the middle of the field) did not allow the detection of gradients towards the centre of the field.

An intensive sampling scheme (grid or transect) is required to answer questions about the spatial patterns of beneficial abundance within fields. Researchers, with limited resources, often cannot design such schemes. Intensive sampling can provide valuable information about pest and beneficial dynamics within the crop. In order to be confident about predicting beneficial abundance within a field from a set of samples taken randomly, we first must have a good understanding of the underlying population distribution. Furthermore, spatial data about beneficial populations can be combined with physical and environmental measurements to reveal a great deal about the ecological requirements of beneficials.

Variation between fields and between crops

The spatial abundance of beneficials is patchy between fields. Within a cropping region, an individual field is surrounded by other fields of the same crop, other crop types, as well as non-crop vegetation. The abundance of insects within a field is determined by the emigration and immigration of pests and beneficials to and from adjoining vegetation (crop or non-crop) as well as their within field reproduction and survival. The dynamic nature of a cropping system means that insect movement is continually occurring, often in response to the supply and removal of resources and other habitat variables.

Yee (1998) identified potential habitats of eight predator taxa in cotton in the Namoi Valley and Darling Downs by sampling vegetation and identifying pollen found in or on predators. Many predators utilised wheat, barley, sunflower, and uncultivated weeds and grasses such as turnip weed (*Rapistrum rugosum*). Further data comes from studies on the potential of alternative vegetation as trap crops for heliothis and other pests (Mensah & Harris 1996a) and refuges or nurseries for beneficials (Mensah & Harris 1996b, Mensah 1999b, Walker *et al.* 1996). Walker *et al.* (1996) investigated the presence or absence of cotton beneficials on alternate crops in the Namoi Valley. It was found that lucerne had the greatest diversity of beneficials followed by sunflowers and peanuts. Walker *et al.* (1998) evaluated the potential of seven crops [lucerne, cotton (Ingard®, unsprayed and conventional), sorghum, maize, pigeon pea and soybean] to harbour beneficials. Mensah (1999b) investigated sunflower, safflower, sorghum, lucerne and tomato as refugia for predatory insects of heliothis. Again lucerne provided the most dramatic results, with the number of predators being highest adjacent to the lucerne strip and decreasing with distance from the strip to 300m within the cotton crop. However, in this particular study predator abundance was generally low. Mensah (1999b) noted that despite the increase in predator numbers within the lucerne crop, the numbers moving into the adjacent cotton may not be high. In order to promote nursery crops or non-crop refuges for beneficials as a pest management strategy the movement of the insects from the source area into the target crop must be shown and quantified.

The movement of predators between adjacent and non-adjacent fields within a region is largely unknown. The majority of studies use only correlation techniques and fail to include mark-release-recapture experiments on beneficial insects to support their results. Apart from the traditional mark-release-recapture techniques, detection of pollen within and on the outside of beneficial insects may be used to determine the location and movement between their foraging habitats (Silberbauer & Gregg 1999, Yee 1998). The development of novel techniques for quantifying predator movement in the field requires greater attention given the importance of dispersal and aggregation patterns for pest suppression.

In contrast, numerous studies provide a more detailed picture of heliothis movement between fields (Fitt & Pinkerton 1990), between areas within a region (Drake & Fitt 1990) and between regions (Fitt *et al.* 1990,1992, Gregg *et al.* 1995, Rochester 1999ab). The information available suggests that there is substantial movement of pests between fields, with little regard to defined property boundaries. On the Darling Downs, data on heliothis egg density in two focal areas has been mapped for cotton and grain crops (Figure 2). Areas of high egg density (2.7 eggs/plant) may extend for up to 3 km and encompass more than one management unit (W. Rochester pers. comm.). This suggests that it is unrealistic for each property, or crop type, to be viewed as an independent unit in terms of the invertebrate assemblages present, and pest management practices implemented. Zalucki and Norton (1999) suggest that area wide, season long management plans are necessary for multivoltine, highly mobile, polyphagous pests, such as heliothis. Such area wide pest management programs are currently being evaluated (The Darling Downs, Qld), and the area wide management of heliothis insecticide resistance is commonly practised. Similar programs for the area wide conservation and mapping of beneficial abundance have not been attempted.

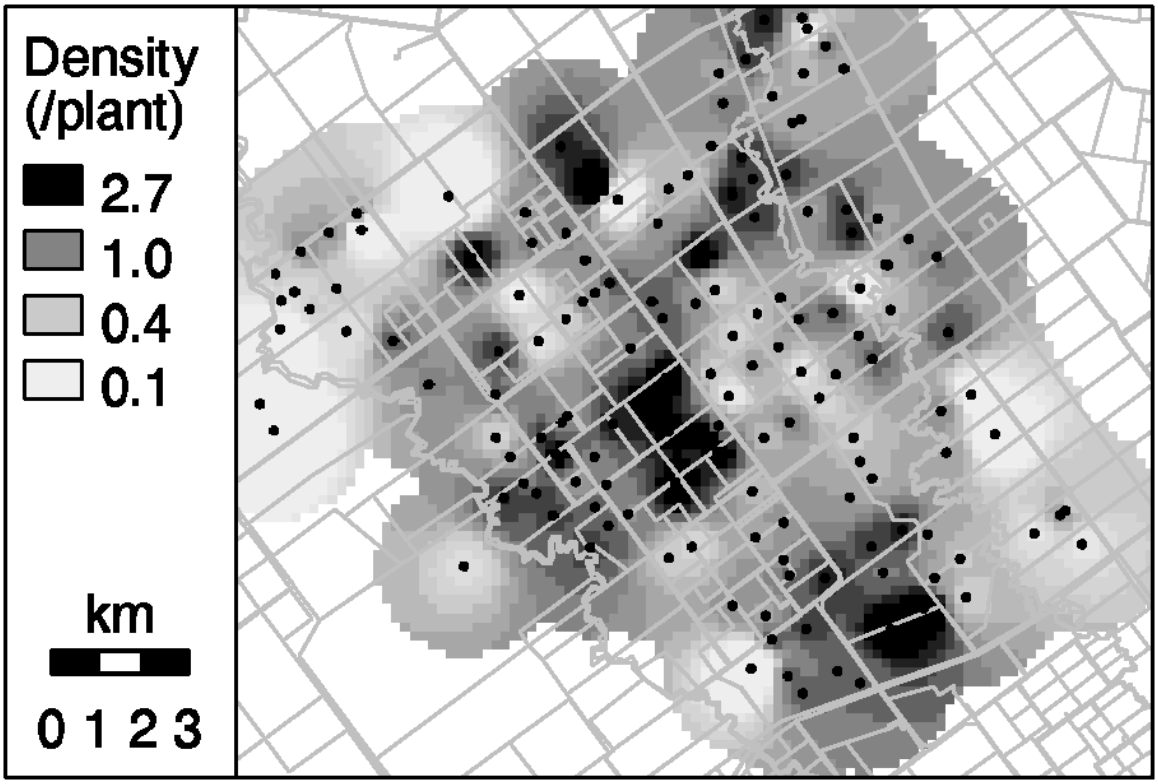

Figure 2. Distribution of heliothis eggs on cotton crops at Brookstead on the Darling Downs Qld. on 13 February 1998. Black dots represent the centre of management units (usually equivalent to a number of fields within one farmer's property that are managed in a similar fashion) (D. A. H. Murray and W. A. Rochester, unpublished data).

Surveys of beneficial populations in non-cotton fields have all found that different kinds of vegetation act as refugia and potential nursery areas for beneficial species and that there are distinct habitat preferences, or at least big differences in abundance. For example, green lacewing adults (*M. signata*) were relatively more abundant on eucalypts and sunflower; brown lacewings (*M. tasmaniae*) were most abundant on sorghum and damsel bugs (*N. kinbergii*) were most abundant on sunflower (Silberbauer and Gregg 1999). This suggests that (a) non-cotton vegetation is an important resource for predatory insects and (b) perhaps more importantly, that when thinking of agronomic measures to preserve predatory insects it is necessary to consider each species individually since measures that suit one may be less advantageous or detrimental to populations of another.

Walker *et al.* (1997, 1998) examined beneficial insects in more than 20 crop and non-crop habitats in the Namoi Valley, NSW. They found that irrigated lucerne crops supported the most diverse and abundant cotton beneficial community through most of the year, while sunflowers, sorghum and maize crops often supported high numbers of predatory Coleoptera and Hemiptera for short periods. Of the non-crop habitats, burr medic (*Medicago* spp.) supported reasonable numbers of predatory insects, but not for the length of time possible in lucerne (Walker *et al.* 1998). The ability of non-crop habitats to support predators varied widely through space and time and appeared to be linked to rainfall. Crops least suitable as nurseries for predators were grain legumes (Walker *et al.* 1998) and fallow wheat fields (Silberbauer & Gregg 1999).

Variation between regions

The agricultural practices of a region can influence the overall abundance of predators and parasitoids found within that region. Heliothis eggs parasitised by *Trichogramma* spp. are found commonly in crops throughout southeast Queensland (the Darling Downs, and Lockyer Valley regions)(B. Scholz pers. comm.). However, in the Namoi Valley of New South Wales egg parasitoids are rare (Schellhorn *et al.* 2000). Egg parasitoids have only recently been properly investigated in northern New South Wales, and in early studies of heliothis mortality they were largely ignored (Dillon *et al.* 1994). Schellhorn *et al.* (2000) found that egg parasitoids exist in the Namoi Valley, but the parasitism rate is low and variable within crops and among crops. Schellhorn *et al.* (2000) speculated on factors that may contribute to the low population density observed. Firstly, there may be a lack of habitats for *Trichogramma* spp. during autumn and winter. Most growers in the Namoi Valley grow cotton in the summer, and their fields are left fallow in the winter or planted predominately with wheat. The lack of diversity in crop types and large expanses of ground left bare during winter greatly reduces the area of suitable habitats for *Trichogramma*. Secondly, broad-scale insecticide use combined with the absence of refuge areas for parasitoids reduces population levels. Finally, the geographical distribution of certain *Trichogramma* spp. may reach its southern boundary towards the Namoi Valley.

Yee (1998) collected presence/absence data for a selection of predators from four sites, split between two regions, the Namoi Valley (NSW) and the Darling Downs (Qld). The relative presence of *M. signata*, *D. bellulus* and *D. notescens* differed significantly between sites. *Diomus notescens* presence (88%) was more consistent at the 'Milchengowrie' site within the Namoi Valley. The presence of *D. bellulus* at the other site within the Namoi Valley, 'ACRI' (49%), was not significantly different from the two Darling Downs sites ('Condamine Plains' 59%, 'Wamara' 45%). *Mallada signata* was only found once at 'Condamine Plains' (3%) and thrice at 'Milchengowrie' (6%), but was significantly more common at the other two sites ('Wamara' 26%, 'ACRI' 17%). *Diomus notescens* was most consistently present at 'Milchengowrie' but all four sites where significantly different from each other. These results suggest that variation between sites within a region can be at least as great as variation between regions. The other predators investigated (*C. transversalis, M. frenata, M. tasmaniae, H. conformis and H. octomaculata*) did not differ significantly between sites. Despite the limitations imposed when using presence/absence data this study provides valuable information on the inter- and intra-regional variation of predators. This type of data can only be collected when standardised sampling techniques to quantify beneficial abundance are employed across a number of regions. Due to logistic problems associated with such an undertaking this has rarely been attempted in Australia. As a result we have mostly anecdotal evidence on the variation in beneficial abundance between regions.

Beneficial species lists collected from studies in a number of regions within Australia have been compiled (see Tables 2, 3 and 4). From such studies it should be possible to draw conclusions about the beneficial assemblage in each region, and obtain an idea of the geographical range of some species. However, due to the different objectives of each of the studies, different collection techniques employed and samples sorted to different levels of taxonomic resolution generalised conclusions are not possible at this stage. Most studies sampled the foliage dwelling invertebrates using a vacuum sampler, but ground dwelling invertebrates were largely neglected. Spider species are often grouped together and presented along with species level data for the other invertebrate orders. From such lists we can get a good idea of which beneficial species are present within regions, and common to most regions. However, little can be said about which, if any, species are unique to a particular region. Standardisation of collection techniques and sampling times would add considerably to our understanding of the differences in beneficial assemblages between regions.

Research to date shows that predator abundance is highly variable at a number of spatial scales. A greater understanding of the factors which cause this variability is required in order to improve predictions on predator abundance for management purposes.

3.2 Pesticide effects on the abundance of beneficials

The availability of transgenic cotton (Ingard®), better selective pesticides such as *Bacillus thuringiensis* (Bt) and nuclear polyhedrosis virus (NPV; Gemstar®), and increasing adoption of area-wide pest management, has led to a decline in synthetic insecticide application for heliothis control that would otherwise disrupt key biological control agents such as predatory arthropods. As a result, there is now greater prospect and impetus to conserve and utilise beneficials of primary and secondary field crop pests. In order to achieve this task, it is essential to quantify pesticide impact on key beneficial species or groups. Unfortunately specific information is lacking for a range of beneficials and pesticides.

Typically, beneficial arthropods may acquire a pesticide dose via direct contact during application, residual contact after application, and consumption of contaminated material. Stevenson and Walters (1983) outline various test methods that reflect these different routes of pesticide uptake. Arthropod movement, droplet size, residue persistence and coverage influence the rate of uptake (Croft 1990). Pesticides may have lethal and sublethal effects on beneficial arthropods. Whilst assessment of lethal effects can be expressed as a change in survival or abundance, the impact of sublethal doses on survivors is less pronounced and therefore harder to quantify. These effects may take the form of altered physiology (fecundity, longevity, developmental rate, sex ratio) and behaviour (locomotion, searching, feeding, oviposition) (Croft 1990).

Besides the direct effects of pesticides, indirect effects include reduced diversity and density of primary and alternative prey/host species and disruption to the spatial and temporal synchrony of the predator/parasitoid with the prey/host (Croft 1990). Often these indirect effects are delayed and hard to recognise. They may be expressed as predator reduction through poor crop immigration/colonisation, and predator emigration. Early season control of cotton pests, such as aphids, thrips and mirids, with a selective insecticide may initially be only mildly disruptive to generalist predators. However, subsequent indirect effects may render biological control inadequate for the remainder of the season. As a result the crop may suffer from outbreaks of primary and secondary pests.

Wilson *et al*. (1996, 1998, 1999b) used insecticide applications to suppress predators and correlative analysis of abundance to evaluate the effect of early season insecticide applications on the ability of a predator guild to suppress mid-season outbreaks of cotton aphids and two-spotted mites. Outbreaks of two-spotted mites developed earlier and reached higher peak densities in insecticide treated cotton. Insecticide effects on the predators studied were variable between years, predatory groups, species and product. Drawing generalised conclusions from such results is difficult, but crucial for growers developing IPM strategies in cotton.

Croft (1990) reviewed information of pesticide effects on beneficials from 1950 to 1985. Data are drawn from 975 investigators working in 58 countries and represent more than 600 natural enemy species and 400 agricultural chemicals. Unfortunately this is the most recent generalised reference in the literature. A current, regularly updated database including newly developed pesticides would be an invaluable resource as a repository for existing information and a precursor for future work.

In Australian cotton, good progress is being made to present data on the impact of pesticides on beneficials. Tables are presented in the current cotton IPM guidelines in ENTOpak (Wilson *et al.* 1999a). They rate the impact of 26 insecticides and miticides applied as seed treatments, foliar or soil sprays on five arthropod groups (ants & wasps, beetles, bugs, spiders, thrips) and overall groups. The impact rating is based on the percent estimated reduction in abundance following pesticide application. It is unclear how the impact rating was derived and no data to substantiate the rating are presented. The extent to which this information has been utilised by industry also remains unquantified. It is reassuring that pesticide companies such as Aventis and DuPont are documenting quantifiable pesticide effects on beneficials according to a universal classification system such as that of Wilson *et al.* (1999a).

3.2.1 "Soft" pesticides for use in IPM

It has been the long-standing aim of numerous researchers to identify pesticides suitable for use in IPM programs. This is evident in the numerous research articles presented over the past 25 years. In Australian cotton farming systems recent examples of conserving predator abundance and activity by the use of selective pesticides such as Bt and NPV have been recorded (Murray *et al.* 1994b, Scholz *et al.* 1998, Scholz 2000 unpublished data).

Murray and Lloyd (1997) recorded arthropod pest and beneficial populations to compare the effect of a new insecticide (spinosad) with unsprayed and conventional insecticide managed cotton in a season long trial during 1995-96. Whilst overall predator densities were low (<1 per metre), spinosad treatment was considered non-disruptive to the abundance or diversity of three predator groups (true bugs, beetles and spiders) compared to the unsprayed control. In addition, spinosad controlled heliothis with resultant fruit damage equivalent to or less than conventional insecticide practice.

Wade (1999) studied the effects of 11 pesticides on the survival and development of first-instar assassin bug *Pristhesancus plagipennis* Walker. Exposure to residues of miticides (abamectin, diafenthiuron and propargite), fungicides (benomyl, iprodione, mancozeb, triadimenol) and insecticides (carbosulfan, naled and spinosad) were slightly toxic (<30% mortality) at the highest recommended rate. The insecticide lambda-cyhalothrin was harmful (80-99% mortality).

Grundy *et al.* (2000) examined the initial and residual toxicity of 11 insecticides from four groups to various stages of *P. plagipennis* under laboratory conditions. The initial toxicity of five selected insecticides was verified in the field. There were distinct differences in residual toxicity between products:

- slightly toxic (RT_{50} < 1 d) carbaryl, esfenvelerate, endosulfan
- low toxicity (RT_{50} 1-3 d) deltamethrin, methidathion, dimethoate, maldison, chlorpyrifos

- moderate toxicity (RT_{50} 3-6 d) methomyl
- highly toxic (RT_{50} >6 d) cypermethrin, monocrotophos.

Annetts *et al.* (1998) investigated the toxicity of ten insecticides to the parasitoid wasp *M. demolitor* under laboratory conditions. The external developing pupae were extremely tolerant of the insecticides tested, whilst adults had good tolerance to only three when applied topically to simulate direct spraying. Late instar endoparasitic larvae were tolerant of insecticides that acted primarily as a stomach poison, delayed host mortality allowing subsequent development), when applied topically to the heliothis host larvae. Egg and larval stages were susceptible to contact insecticides applied at any time. The reduction in parasite larval survival was mostly attributed indirectly to host mortality, but direct effects of the toxin to the larvae were possible.

Lytton-Hitchins *et al.* (1998) studied the effect of seven insecticides applied separately three times on predators in cotton. The abundance of ants in the foliage and on the ground was compared between the untreated and treated plots. The insecticide toxicity could be classified according to an impact rating, based on the percent reduction in average ant abundance compared to the control (Wilson *et al.* 1999a):

- very low toxicity (<10%): thiodicarb
- low toxicity (10-20%): emamectin benzoate
- moderate toxicity (20-40%): avermectin, imidacloprid
- high toxicity (40-60%): pyrrole
- very high toxicity (>60%): spinosad, fipronil

Johnson (2000) examined predator abundance in commercial cotton fields at Byee (Burnett District, Qld). Pesticide disruption was inferred by altered predator abundance following pesticide application. The relatively selective pesticides (*Bt*, endosulfan, NPV, petroleum oil and spinosad) caused no substantial reductions in predator density. However, interpretation of the pesticide effects was restricted by the overall very low predator abundance (<1 predator per metre) that varied little between the unsprayed and sprayed sites. Abundance may have been underestimated due to the use of a vacuum sampling technique.

Scholz *et al.* (1998) found that the application of deltamethrin in sweet corn reduced the numbers of wasps and predators. These plots suffered significantly greater cob damage and heliothis larval infestation. In a separate study, Scholz (2000 unpublished data) found that the numbers of predators on sweet corn plants declined from 2/plant to 0.5/plant in plots sprayed with deltamethrin.

3.2.2 Insecticide exclusion experiments: What can they tell us?

Stanley (1997) assessed reductions in beneficial abundance following an insecticide application in commercial cotton fields over two seasons by comparing seasonal abundance between different pest management strategies. Insecticide treatments had a marked effect on predator abundance. The untreated areas had consistently higher beneficial densities by a factor of 5-10. Effects were sometimes variable between sites and years (endosulfan less toxic, chlorfluazuron and thiodicarb more toxic than expected), and species and lifestages had different levels of susceptibility. This restricted formulating generalised statements about the products. Stanley (1997) remarked that predator numbers were quite low in the cotton growing area and declined mid-season, even in untreated areas. This decline coincided with the onset of regional insecticide use (see also section 5.3). The explanation implies regional depletion of predator sources (non-sprayed habitats), spray drift and possibly extensive movement of mobile stages. The low numbers of immature predators in the crops suggests that these life-stages were particularly susceptible to pesticides and/or are not being produced in the crop.

Scholz *et al.* (1998) and Scholz (2000 unpublished data) provide encouraging results that non-disruptive (selective) pesticides can be used to effectively manage heliothis in sweet corn where their action complements that of beneficials. The effect of applications of conventional and selective insecticides with or without *Trichogramma* releases against heliothis and beneficials were evaluated in experimental field trials over three seasons. Heliothis abundance, cob damage, beneficial abundance and activity on egg cards were compared between the different treatments. In a separate study the initial and residual effect of a similar range of insecticides applied in the field on *Trichogramma* survival were compared. The conventional insecticides deltamethrin and methomyl were highly disruptive to beneficial survival (density), and cobs suffered more damage from the higher heliothis larval infestation than in other treatments. The narrow spectrum insecticides Bt, HzNPV, indoxacarb and spinosad caused slight beneficial mortality and resulted in the least amount of cob damage and numbers of heliothis larvae. Scholz *et al.* (2000) provide evidence of initial contact and residual insecticide effects on *T. pretiosum* in cotton. The insecticides beta-cyfluthrin, imidocloprid and naled were highly disruptive (>80% mortality) when caged wasps were sprayed directly in the field. The other products tested (fipronil, novaluron and omethoate) caused less than 15% initial mortality. After three days of field weathering, residues of all products tested were of very low toxicity (less than 10% mortality).

3.3 Relating the abundance of beneficials to pest mortality

In some cases, the correlation between presence of beneficial insects and a pest is thought to imply that predation will occur. Pyke (1980) estimated predator numbers per metre of cotton in IPM and conventional crops. Predators were ranked according to persistent presence and abundance. Peak abundance appeared mid December to late January (Pyke 1980). Damsel bugs (*N. kinbergii*) were considered the most consistent predator even in conventionally sprayed cotton. *Dicranolauis bellulus*, *C. transversalis*, *M. frenata* and *D. signatus* were also considered to be consistent predators. Pyke (1980) stated that work on *N. kinbergii* should be given priority in future research. Stanley (1997) showed a spatial correlation between the abundance of *C. transversalis* and heliothis eggs in cotton but found the majority of predators were correlated with the jassids (*Austroasca viridgrisea*) (Paoli) and *Orosius argentatus* (Evans). This perhaps was because they were present in high numbers consistently throughout the season. Bishop and Blood (1981) compared four spider species in cotton and found a numerical relationship between two of the species (*Chiracanthium diversum* Koch and *Oxyopes mundulus* Koch) and heliothis abundance.

Titmarsh (1992) suggested abundance of populations alone does not measure predator effects, especially if mortality due to abiotic factors has not been considered. He concluded that little mortality of heliothis could be attributed with certainty to beneficials. However, he did attribute a large proportion of "unknown disappearance" of brown eggs and early instars to predation. Scholz (2000 unpublished data) showed that, in sweet corn, though *Orius* sp. were present in high numbers they were not feeding on heliothis eggs. This implies that presence is not a basis to determine predation. It remains important to verify that if a predator species is present it is contributing to mortality of the target prey present. It is widely acknowledged that this is very difficult to do (Kyi *et al.* 1991, Seymour & Jones 1991, Stanley 1997, Johnson 1999).

Surveys alone are unlikely to answer the above questions. To determine the "importance" of a predator we need to know much more about the biology and ecology of all the predatory insect species we consider to be of value in cotton production. Without this very basic knowledge we cannot make predictions of population size or population movement. For many of the most common predators, we even lack information on life cycles. For example, the life cycle of the red and blue beetle (*D. bellulus*) in the field is virtually unknown, although the eggs, larvae and pupae have been described (Stanley 1997). It is thought that *D. bellulus* larvae probably develop in the soil (Room 1979). For other species, we lack basic knowledge on crucial facets such as the number of generations in a season, how and where the species over-winters in cotton regions, and migration/dispersal capabilities. In part, this is because most previous investigations have focussed on these insects as predators, not as model organisms for basic biological or ecological research. While this trend is understandable given the priorities of the research funding bodies, it is ironic that we now find ourselves in a position where, until basic biological and ecological questions like these are examined we cannot make recommendations regarding the habitat preferences of beneficial species, or the ways in which agricultural systems might be manipulated to favour them.

Other problems relate to survey methods themselves. The most commonly used survey methods in cotton, suction sampling (using D-vacs) and visual survey are subject to different biases and efficiencies and may not be comparable between different vegetation types. For example, Stanley (1997) found that suction sampling varied in its effectiveness depending on the size of the suction sampler being used, time of sampling and the placement of the nose of the device. Visual sampling has its own problems associated with the variable techniques of observers, the time-consuming nature of sampling and bias towards noticing larger, more visible insects that live towards the top of the plants.

4. Methods for evaluating beneficials

4.1 Theory

Whether a predator or parasitoid is considered to have potential as an effective biological control agent is partly influenced by its numerical and functional responses. The numerical response, a change in the localised abundance of a natural enemy, is a result of its' reproduction, immigration or a change in life stage survival. The functional response is the change in the number of prey consumed by a single predator at varying prey densities and is tied to predator survival and reproduction (Wratten 1987)

The relationship between the number of prey consumed and density varies because of the interaction between search time and handling time (the time taken to consume a prey). Handling time is influenced by gut saturation, search image formation, search arena, and emigration or interference from prey or other predators (Bell 1990, Wratten 1987). There are four types of models used to describe the functional response of a predator to prey density (Taylor 1984). A type I curve represents a linear relationship, type II a decelerating curve, type III a sigmoidal relationship and type IV a dome shaped response. If prey consumption fits a type III model then the predator is thought to be theoretically a good candidate for biological control as this response stabilises the prey population. This is because after an initial period of low consumption the predator's ability to search and find prey increases as a result of learning.

Many generalist predators are opportunists (Hagler *et al*. 1992) and have the ability to switch to the numerically dominant prey type as other sources of prey become depleted (Murdoch 1969). Other factors that influence predation (other than the searching ability of the predator and the number of prey available) include the patch size, the predators' behaviour towards prey numbers and prey stages as well as elements of the abiotic environment such as temperature, moisture, light and so forth. It is well known that these factors affect consumption rates (Coll *et al.* 1997, Frazer & Gilbert 1976, Lopez *et al.* 1976, Murray & Mensah 1996). Searching ability is an important consideration. The cost of searching to a predator is loss of time for reproduction, finding refuges and egg laying. Searching by the predator is likely to be affected by the first encounter event. Upon encounter or consumption of a prey the predator's behaviour may alter to cover a concentrated area. The predator may also increase its rate of searching (Evans 1976). Similarly if few prey are encountered the predator may increase it's searching area. The behaviour of the predator may occur due to its means of locomotion, perception of sensory information, prey resources available and the risks involved in finding resources. For example, low temperature is known to cause coccinellids to spend more time being inactive even when capable of searching (Frazer & Gilbert 1976).

Predator searching can differ amongst different plant species, plant surfaces and prey distributions within those plants (Coll *et al.* 1997, Treacy *et al.* 1987). Furthermore, searching in a patchy environment can influence how a low level of prey is maintained. For example, Congdon *et al.* (1993) showed that *Stethorus punctum picipes* Casey was able to locate and consume prey at low densities on plants. Conversely, an increase in heliothis survival in cotton late season was attributed to the loss of search efficiency of predators due to an increase in plant size (Congdon *et al.* 1993).

Prey numbers influence whether a predator is considered efficient. Numbers of prey are usually dynamic and, if the predator is to be used for biological control, the needs of the predator must be considered. These include knowing how many prey they need to consume to survive and reproduce (O'Neil 1988), whether they can find them and whether the target prey are the most dominant species in the crop. Hagler and Naranjo (1994) showed that the proportion of predators consuming pink bollworm, *P. gossypiella*, and whitefly, *Bemisia tabaci* (Gennadius), was fairly constant throughout the season despite some very low pest population levels. They suggest that the beneficials were still able to find target prey at very low numbers. Another important consideration is the number of prey a predator is required to consume to reduce prey numbers to below economic threshold.

4.2 Economic thresholds

Where predators are to be used as the main form of control they need to be able to find and consume the target prey and reduce their numbers to below economic thresholds (Luff 1983). They may also make a positive contribution, even when not used alone, to keep pests below an economic threshold. Economic thresholds are based on the pest density at which action must be taken to prevent assumed economic crop damage or crop maturity delay (Stern *et al.* 1959). Sterling *et al*. (1989) describes the concept of 'inaction' in a management program as the density of beneficials sufficient to maintain pests below the action level (economic injury level). This assumes an understanding of the beneficials' contribution to control over space and time. If this is understood a decision to act or not on a pest population can be made. The threshold is usually described as the number of prey per unit of habitat. In the 1999/2000 cotton season the most common threshold for heliothis was two small larvae per metre row. If predators are to be used as the main focus of control in cotton then they need to be able to reduce and/or keep heliothis below threshold levels.

Ideally we need to incorporate the abundance and action of beneficials into dynamic thresholds. For example, changing the size of larvae used as a threshold to say one medium healthy (not diseased or parasitised) larva per metre row may give beneficials and other mortality agents or factors more time to act. Evaluating the use of dynamic thresholds has yet to be considered.

4.3 Predators - methods of evaluation

The impact of predators on prey populations is often inferred by numbers of both predator and prey in the field. Although this may help to identify which predators are worth considering for further investigation it does not provide information on the direct impact of each predator species (Wratten 1987). Direct impact can be measured by exclusion studies of prey or predators in small arenas such as a Petri dish and large cages (in laboratory or field situations). Studies may be done with exclusion of prey or predators by pesticides, through direct observation of predation in the field and by serological or labelling techniques that detect predation of a specific prey. These methods, and their limitations, are described in detail in Kiritani and Dempster (1973), Luck *et al.* (1988), Seymour and Jones (1991), Sunderland (1988) and Wratten (1987). Boreham and Ohaigu (1978), Dempster (1960), Greenstone (1996) and Sunderland (1988) review serological techniques in greater detail.

To assess the effectiveness of a predator species we need to conduct a field survey on predator and prey populations, do direct observations on feeding, exclusion trials, behavioural studies and (if possible) serological trials. The efficiency of a predator species can then be ranked and used to aid in management decisions (Breene *et al.* 1990, Dent 1991, Mensah & Singleton 1998). Wherever possible all these aspects should be combined to assess a predator's use as a biological control agent. However, in reality resources often do not allow this. Given that most predators are small and difficult to see, the low abundance of prey and predators and the short duration of study time, means field studies on predation are difficult. For this reason, to date, much reliance has been placed solely on cage studies conducted in artificial or field environments.

Although cages are useful they do have distinct limitations and requirements, such as an understanding of prey and predator preferences towards oviposition and feeding sites, prey dispersion and predator searching behaviour. In addition cages change the microclimate on the plant surface which may alter predation behaviour (Hand & Keaster 1967). Further confining prey and predators is likely to increase predation rates (especially at low densities) as predators do not emigrate and therefore tend to re-search areas (Luck *et al.* 1988).

Despite these limitations, cages are useful in providing information on the preferred prey of the predator, potential consumption, the effect of search area on predation rates, and enabling the comparison of individual predator species (DeClercq & Degheele 1994, Isenhour & Yeargan 1981, Lingren *et al.* 1968, Lopez *et al.* 1976, Propp 1982).

Specific studies on predation of heliothis using cages in Australia include using two metre square cages (Titmarsh 1992), small one metre squared cages (Dillon *et al.* 1994, Stanley

1997), individually caged plants (Johnson 1999), small 400ml containers (Horne *et al.* 2000) and Petri dishes (Grundy & Maelzer 2000, Johnson 1999, Stanley 1997).

4.4 Parasitoids - methods of evaluation

The impact of parasitoids can be assessed, in part, because their activity results in a parasitised egg or larvae. Annetts *et al.* (1998) trialed a number of methods for assessing parasitoid population levels and found direct observation and percent parasitism the most practical for use in the field.

To measure parasitoid impact many studies use the arbitrary indication provided by percentage parasitism. It is important to include host and parasitoid absolute density and phenology when using percentage parasitism to indicate the impact of parasitoid activity on its host, as such processes can influence the determination and interpretation of percent parasitism records (Van Driesche 1983). Accurate indications of parasitoid impact could feasibly be observed by local removal or introduction of the parasitoid in order to assess host population dynamics in both situations

Two common techniques to assess parasitism rates in the field have emerged. The first involves the collection of artificially placed hosts from the crop, such as heliothis egg cards. The percentage of parasitised hosts is then recorded after a short time period (usually 48 hours) (Annetts 2000, Scholz 2000 unpublished data, Simpson & Cavallaro 1998, Walker *et al.* 1998). A problem with using egg cards is the singular nature of heliothis egg lays in real life situations. Scholz (2000) showed that heliothis egg card parasitism rates were related to naturally occurring egg parasitism rates, but that this is not always the case. Schellhorn *et al.* (2000) used bags on branches of cotton to contain egg lay to one area and 48-72 hours later assess percent parasitism. This simulated natural oviposition but a marked difference was found between parasitism rates on bagged compared to natural egg lays whereby the latter was negligible .

The other common method is to collect naturally occurring hosts from the field and record percentage parasitism in the laboratory after hatching-emergence. Accurate identification of a parasitoid is also possible at this stage (Titmarsh 1992, Walker *et al.* 1998, Schellhorn *et al.* 2000). Biases in this method include the variation in larval distribution and persistence as a result of parasitism, as parasitised larvae accumulate due to their slower rate of development. Bias can be minimised by collecting samples from the whole plant. Note that not all life stages are targeted by a given parasitoid species.

Although often not included, assessing the effectiveness of parasitoids should include measurements of larval densities, species and crop damage. The immediate benefits of parasitism are often underestimated as parasitised larvae cause relatively minor damage to the crop. *Helicoverpa armigera* larvae parasitised by *M. demolitor* cease feeding after a few days resulting in 88.5% less damage than their non-parasitised counterparts (Annetts 2000 unpublished data).

4.5 Recent advances in methods for studying beneficials

Recent studies by Scholz (2000 unpublished data) and Schellhorn *et al.* (2000) used heliothis egg cards or potted plants infested with eggs to determine parasitism and predation. Predation is determined by classifying the egg damage according to the number of missing eggs (ants), collapsed eggs (true bugs and lacewings, or spiders if a brown stain was present), or partially chewed eggs (beetles) after 24-72 hours field exposure. During this time field observations provide direct qualitative evidence of parasitism and predation. Including alternative prey is also a more recent consideration when studying generalist predators (Johnson 1999, Stanley 1997).

Johnson (1999) used serological assays to determine which beneficial species feed on *H. armigera* directly in the field. Serological assays are useful for direct assessment of predation by populations of beneficials. They enable comparisons of predation activity between beneficial species, life stages, crop types, and seasonal changes within populations. Their only limitations are that they are rarely able to provide a measure of actual numbers of prey consumed per individual (but see Sigsgaard 1996) and, preparation of antibodies and assay techniques is very time consuming. Overseas, to date, one of the most useful studies on predation of *H. armigera* has been by Sigsgaard (1996) in India using serological studies. She identified key predators using serological assay and rated their importance.

4.5.1 Rapid diagnostics

To make better use of beneficials in decision-making requires a number of rapid diagnostic techniques. From sample counts we would like to know how many predators are present in the crop and whether they are eating the prey. If pest larvae or eggs are found it would be useful to know if they are diseased or parasitised. Crop scouts cannot spend time rearing and or dissecting. Molecular diagnostic techniques may hold promise here. If one could use a simple squash test [as is done to assess the presence of *H. armigera* eggs with the Lep Ton™ kit (Trowell *et al.* 1994)], to determine the disease or parasitism status of pest eggs and or larvae then savings on pesticide application, with concomitant advantages for real IPM, are a possibility.

5. Impact of beneficials

5.1 Survival of pests to damaging stages - life table studies in the field

Life table studies of pests and beneficials facilitate the identification, timing and action of key mortality agents. There has been no attempt to calculate partial or complete life table studies for beneficials in the field in Australia. In contrast partial life table studies exist for the pest heliothis, where the natural mortality of heliothis eggs and young larvae in the field has been attributed to weather, competition, host patch size, host plant phenology, predation, cannibalism, feeding habits, disease and parasitism (Dillon *et al.* 1992, Fitt 1989, Kyi *et al.* 1991, Titmarsh 1992, Twine 1973). Weather, as well as the direct effects of temperature on development and survival can include indirect effects such as rain induced drowning and soil splash (Titmarsh 1992). Dillon *et al.* (1992), Kyi *et al.* (1991) and Titmarsh (1992) all conclude that a large proportion of egg and neonate mortality can be apportioned to abiotic factors. Titmarsh (1992) showed that the variation in mortality of each stage of heliothis found in a field was more important for determining survivorship than the actual numbers of eggs laid. The exception to this was sunflower crops where natality was important. He concluded that plant phenology along with weather were the most likely cause of high mortality in heliothis eggs and neonates. Of these, plant traits were considered the initial and greatest cause of mortality of larvae as, if unsuitable, they caused the larvae to drop off the plant. It is likely that in early stages "drop off" from a plant equates to mortality at high soil temperatures (>29^{o}C) (Terry *et al.* 1989). The survival of larvae at lower soil temperatures remains to be tested.

Dillon *et al.* (1994) showed that a large proportion of heliothis eggs laid on cotton never hatch. They attributed this to predation and abiotic factors such as wind, rain and extreme climate (see also Quyyum and Zalucki 1987). Infertility was also seen as a cause of non-hatching. The total possible hatch rate was between 22 and 42% depending on the time of season in cotton. Even in closed cages survival of eggs was only 35%. Neonate larvae were thought to have high mortality rates but the cause of this is yet to be fully investigated.

Similarly overseas studies attribute mortality of *Helicoverpa zea* (Boddie) to abiotic factors such as wind, rain and abrasion (Nuessly & Sterling 1994). Duffield (1993) found greatest mortality (84%-94%) in the egg stage in pigeon pea and sorghum in India. Cannibalism was considered one of the major contributors to this loss (Sigsgaard 1996) although laboratory experiments and some limited field tests found only low levels of cannibalism.

On a regional level, survivorship of each stage of heliothis has been estimated from data collected over several seasons and crop types. Initial life table statistics on a regional management trial area at Brookstead (Queensland) show that survival of eggs and very small larvae on cotton decreases over the season whereas in other stages of larvae survivorship increases. The reason for this is unknown but may have to do with less contact of sprays in the canopy and greater searching areas for beneficial insects. Overall survivorship of eggs was 11%, very small to small larvae 82%, small to medium larvae 48% and medium to large larvae 40% in the first year of this trial (M. Miles & W. Rochester pers. comm.).

Analysis of long term light trap data (Maelzer *et al.* 1996, Maelzer & Zalucki 1999, 2000) indicate the predominant effect of weather and in some cases crop area on changes in abundance at a regional scale, at least as assessed by light trap records. Maelzer and Zalucki (1999) found that during the period 1973/74 to 1986/87 areas of sorghum had a negative impact on subsequent increases in *H. armigera* in the Narrabri district. This may indicate a negative effect of beneficals in this crop. On the other hand areas of lucerne and maize had a positive effect on the abundance of *H. armigera* and the former on *H. punctigera* also. This is contrary to expectations as lucerne is meant to have a large component of beneficials. As insecticide use on a regional basis was historically very high in the Narrabri region it would be difficult to detect the influence of beneficials in such an analysis.

5.2 Impact of predators and parasitoids on pest abundance

Australian studies have shown that beneficials contribute to heliothis mortality in the field (Seymour & Jones 1991). Teakle (1977) lists the use and effectiveness of pathogens. Most studies that report the impact of beneficials generally combine both predators and parasitoids as a group. However, there has been ongoing research in the sole use of parasitoids as biological control agents. Several species have been studied. The native *M. demolitor* is thought to contribute to mortality of heliothis larvae, when included as part of IPM (Annetts *et al.* 1998). Levels of around 70% parasitism by *M. demolitor* have been recorded in cotton on the Darling Downs between 1996/7 and 1997/8 (D.A.H Murray and R. Annetts, unpublished data). Two larval parasitoids (*H. didymator* and *C. kazak*) were introduced into Western Australia in 1983 and in eastern Australia in 1991, but their impact has been minimal (Murray *et al.* 1995). Minimal impact from parasitoids was also recorded by Titmarsh (1992) with only 3.6, 3.2 and 1.4% of III-VI instar larvae parasitised by braconids, ichneumonids and tachinids respectively on the Darling Downs between 1985/6-1987/8.

Twine (1973) found the parasite *Telenomus* sp. nr. *triptus* Nixon accounted for 97% of sampled heliothis eggs found parasitised in the cotton growing areas of New South Wales and southern Queensland. He also found *Trichogramma* sp. accounted for some of the parasitism. Research into *Trichogramma* species has been explored for some 60 years (Scholz & Zalucki 1998). Through the application of inundative releases, some *Trichogramma* species are known to be effective biological control agents of heliothis (Oatman *et al*. 1983). Their performance within Australia has been variable (Scholz & Zalucki 1998). Scholz (2000 unpublished data) suggests that the inconsistent levels of control from *Trichogramma* mass release are due to a poor understanding of parasitoid ecology, suitable release strategies and evaluation methods. With the exception of the above trials, most research to date on effective control in Australian cotton has been based on using a parasitoid agent to reduce heliothis to below current economic thresholds.

Trichogramma are ideal biological control agents as they eliminate egg hatching and hence larval feeding damage (Wajnberg & Hassan 1994, Scholz 2000 unpublished data). The use of *Trichogramma* in biological control generally involves their augmentation in agro-ecosystems for the suppression of target pest insect species (Li 1994). Scholz (2000 unpublished data) points out that successful *Trichogramma* augmentation involves hosts that demonstrate one or few ovipositional flights per season and lay their eggs in masses that generally take more than three days to hatch. Once egg lay is detected in a crop, *Trichogramma* release is initiated providing ample search time for aggregated host eggs. An example is the successful use of *Trichogramma* spp. to suppress the European corn borer, *Ostrinia nubilalis* Hübner overseas (Bigler 1986, Yu & Byers 1994). In contrast, Australian heliothis are multi-voltine and lay single eggs intermittently in cotton, then hatch in 2-3 days (Fitt 1989, Zalucki *et al.* 1986). Further, heliothis moth catches in pheromone and light traps are not an accurate method of predicting heliothis oviposition (Gregg & Wilson 1991) thus rendering them ineffective for scheduling potential *Trichogramma* release times. This suggests it would be difficult to successfully manage heliothis with inundative releases of *Trichogramma* in cotton. Alternatively conservation of indigenous *Trichogramma* populations may prove more useful

Parasitism of pupae also depletes the pest population. In the Darling Downs, average parasitism of field collected overwintering pupae was 37%, and ranged from 8% in chickpea to 62% in pigeon pea (Murray & Zalucki 1994). In the Namoi and Gwydir districts Fitt and Mares (1992) reported pupal parasitism rates of 7% in spring, 8% in summer, 21% in autumn and 16% during winter. They recorded similar levels of parasitism in chickpea (10%) and pigeon pea (60%) as found on the Downs. In addition 45% parasitism was noted in faba beans, 25% in linseed and sorghum, 15% in cotton, 12% in sunflower 10% in maize and 5%

in adzuki beans. Fitt and Daly (1990) reported similar levels of parasitism in cotton with 10% of pupae collected parasitised, of these *I. promissorius* had parasitised 31%. In autumn sunflower and pigeon pea crops, *I. promissorius* was rare or absent. In maize *I. promissorius* was recorded only one year in five. Overall parasitism in maize was recorded at 10%, of which *I. promissorius* contributed 40%.

Evaluation of parasitoids as a tool to aid in reduction of the target pest under IPM situations has not been widely considered. However, there are a few examples of their efficiency in conjunction with other control methods such as predators and alternative spray systems. In comparisons of unsprayed, biological systems (Bt spray, natural enemy conservation and release of parasitoids), reduced pesticide systems and conventional cotton systems, Murray *et al*. (1994ab) showed that beneficials can be used to manage heliothis in some seasons in rain grown cotton. Yield was used to infer that beneficials reduced heliothis damage. Natural enemy activity was considered higher on unsprayed and biological systems. Furthermore, Scholz *et al*. (1996) showed that use of the naturally occurring parasitoids *Trichogramma sp*., other beneficial insects and NPV were sufficient to prevent numbers of heliothis exceeding economic thresholds in dryland cotton. This level of control was largely attributed to parasitoids.

The majority of studies do not single out specific beneficial species as efficient control agents but show that the natural enemy complex helps to control heliothis. Mensah and Singleton (1998) showed that beneficial insect numbers are higher when Envirofeast® or IPM plots are used, and the number of pesticide sprays is reduced in cotton managed with Envirofeast® food spray and lucerne strip crops. Although no direct evidence was provided on the relationship between beneficial insects and heliothis numbers, the number of eggs and larvae was consistently lower in plots where IPM was practised (Mensah & Singleton 1998). In a comparison between open and caged cotton plants Titmarsh (1992) showed that predation on heliothis eggs was between 14 and 44% and on first instar larvae between 15 and 44%. This contributed in part to an explanation of unknown disappearance of heliothis eggs and instar stages from life tables on mortality of heliothis. Conversely, Dillon *et al.* (1994) found that unknown disappearance was not attributed to predation when comparisons were done in open and closed cages. In the case of brown eggs, predation accounted for 83% of unknown losses in the field (Titmarsh 1992). Titmarsh and McColl (1992) suggest beneficials provide a valuable, although variable resource.

5.2.1 Impact of individual predator species in Australia: locally within a crop

Using a field cage study Stanley (1997) found that when five *D. bellulus* adults were present in one metre of cotton, mortality of *H. punctigera* was 7% on eggs and 22% on larvae. This increased to 31% on eggs with 30 beetles per metre. The larvae of the lacewing, *M. signata* were found to have a similar impact.

Johnson (1999) found that *D. notescens* and *H. conformis* were the two dominant predators of heliothis eggs in cotton late in the season; 86% of *D. notescens* and 54% of *H. conformis* had eaten eggs over 24 hours. Scholz (2000 unpublished data) showed removal of heliothis eggs from egg cards in lablab and Ingard® cotton was predominantly by spiders and ants, with spiders being the main predator. Between 47 and 91% of eggs were removed each week. Grundy & Maelzer (2000) showed the number of heliothis larvae in cotton was reduced with augmentative releases of the predator *P. plagipennis*.

Many of the species listed above are generalist predators known to feed on other pests within cotton (Grundy & Maelzer 2000, Johnson 1999, Stanley 1997, Wilson *et al*. 1998). Their contributions to the management of other pests apart from heliothis have not been widely assessed.

5.2.2 Within a growing season

Early season control of heliothis in cotton was implied by measures of abundance of both predators and prey by Deutscher and McKewan (1996). Recent work by Scholz (2000 unpublished data) showed the numbers and impact of beneficials was much higher in summer corn than spring corn. Dillon *et al.* (1994) showed that visible predation (egg parts left behind) accounted for between 10 and 25% of loss of hatch depending on the time of the season. Predation was greater in the late season. This is low, however predation categorised as disappearance was also included in data that accounted for between 70 and 55% loss of hatch depending on the time of season. Early season disappearance was greater. Evans (1987) showed a correlation with larvae of *S. litura* as a result of decreased beneficial numbers in soybeans in southeast Queensland. She found peaks of beneficial insects usually coincided with peaks of phytophagous larvae (including heliothis). Spiders and hemipterans appeared to play a role in keeping larval numbers down whereas beetles and parasitoids were not considered effective.

5.2.3 Regionally

From samples of heliothis eggs taken from crop and non-crop hosts throughout the Namoi valley over three seasons natural parasitism was found to be negligible with rates of 1.1, 1.4 and 2.3% (Walker *et al.* 1997). Rates of parasitism from studies on naturally occurring populations of parasitoids in Australia are tabled in Scholz (2000 unpublished data) within different crops by different parasites. Overall in each crop type rates varied from 0-80% in cotton, 0-34% in lucerne, 8-51% in maize, 15-65% in potatoes, 0-97% in sorghum, 0-38% in sunflowers, 80-95% in sweet corn and 15-90% in tomatoes. Schellhorn *et al.* (2000) found predation on eggs laid in bagged cotton branches varied between 9 and 95% but predicted a median value of 76% predation at 15 locations in the Namoi valley. The presence of pupal parasites such as *I. promissorius* is possibly important for reducing regional populations of heliothis (Fitt & Mares 1992, Fitt & Daly 1990).

5.3 Limitations to our understanding of predator impact

The lack of detailed information on the direct impact of beneficials of heliothis can be partly attributed to the fact that it is very difficult to do such studies. One reason for this has been the negative impact of spray drift (associated with pesticides) onto experimental plots of unsprayed cotton (Gibb 1998, Mensah & Harris 1996a, Murray & Mensah 1996, Stanley 1997, Wilson *et al.* 1996). Also until recent studies by Walker *et al*. (1996), Yee (1998) and Silberbauer and Gregg (1999) the ecology of most beneficial species has not been studied outside the cotton field. This is important when considering the potential impact on a regional level of a natural enemy (Metcalf & Luckmann 1994). As Matthews (1997) states, research into IPM requires interdisciplinary action and co-operation on a regional basis, a view shared by Zalucki *et al.* (1998). There remains a need for both growers and researchers to develop methods to allow the impact of beneficials to be studied without these limitations.

6. Cost benefits of beneficials in pest management

Farmers and consultants have access to a large amount of extension material (below and Appendix 3) that provide photographs and information on the beneficials of common pests such as heliothis. Through this type of readily available extension material farmers are becoming more aware of what insects within their crops are "good" and should be conserved. However, for farmers to expend time and resources on regular sampling of beneficials the benefits in terms of pest reduction (impact) must be clear. We are currently unable to determine what predator abundance levels equate to in terms of pest mortality, and therefore we are unable to incorporate predator counts into spray thresholds.

Nevertheless, recent economic studies have begun to quantify the benefits of preserving beneficials. Using 154 cotton fields on twelve adjoining farms in northern NSW over two years, Hoque *et al*. (2000) demonstrated that "soft" spray regimes decreased insecticide costs by 17-44%, had no consistent effects on yields, and increased gross margins by 5-6% for conventional cotton and 5-25% for Ingard® cotton. These results were obtained in a high pressure insect season (1998/1999) and a low-pressure season (1999/2000). Moreover, when the gross margin for each field was plotted against its "hardness index" based on the ratings given to insecticides in the IPM Guidelines for Australian Cotton (Mensah and Wilson 1999), statistically significant negative correlations were obtained. It should be noted that the numbers of beneficial insects were not recorded, and it was not clear how much of the gains in gross margins could be attributed to them. Other factors, such as plant compensation and differential survival of heliothis due to resistance, might have been involved. However, Hoque *et al.* (2000) focused on beneficial insects as the most likely explanation for their results. Though these studies do not directly give us cost:benefit ratios for conserving beneficial insects, either as individual species or as a group, they do indicate that such ratios are likely to be favourable, and they will encourage growers towards greater utilisation of beneficials in their pest management strategies.

Research to date has rarely considered the cost savings or economic benefits of using beneficial insects as part of a management program for control of heliothis and other pests. Scholz (2000 unpublished data) showed that whilst heliothis parasitism rates from *Trichogramma* were high in sweet corn this mass release strategy was not cost effective at release rates of 1-2 million females per hectare. Lower release rates failed to have an immediate impact on heliothis. Locally established populations of *T. pretiosum* caused up to 90% mortality in unsprayed sweet corn. This action was complemented with Bt and HzNPV. Thus additional costs would involve initial treatment until such a time that parasitism rates were high, scouting costs and the use of biopesticides.

Whilst the economics of using beneficials for heliothis control have not been widely addressed, there are some examples where costs attributed to rearing and release of beneficial insects for mass release have been calculated (King & Coleman 1989). Larvae of *Chrysopa carnea* at 123,000/ha can provide effective control of heliothis (Ridgway & Jones 1969). *Chrysopa carnea* cost US$12.50 per 4000 larvae, equating to a cost of $400 per hectare, which was not considered economically viable. Van Lenteren *et al.* (1997) lists costs of buying commercially reared predators and parasitoids. They list several generalist predators (some of heliothis) that are commercially available. Interestingly none are listed as available for the control of heliothis. Scholz (2000 unpublished data) tables the evaluations of *Trichogramma* against heliothis on many crops world wide and highlights that no conclusive evaluations of commercial potential have been done.

Grundy (2000 unpublished data) recently evaluated the feasibility of mass rearing the assassin bug *P. plagipennis*. Costs for producing the predator were estimated to be $3.52 per 100 nymphs. This equated to $704 per ha of cotton, a cost that was seen as barrier to the adoption of using the predator in management of heliothis. Grundy (2000 unpublished data) lists the problems associated with the success of mass rearing as inconsistent availability, high costs of production, high release rates, low correlation of release rates with suppression of the target pest and incompatibility with pesticides. Knipling (1979) developed theoretical models for appraising the value of augmentative releases of beneficial insects. Suppression of heliothis was considered technically feasible but in reality results are often inconsistent.

Savings to the industry, as a result of using beneficial insects, need to be assessed in several ways. Obvious savings to on farm management costs can be calculated from the reduction of applying a chemical. These often need to be offset with scouting costs. A saving may be seen as using a soft chemical rather than a broad spectrum. For example Scholz (2000 unpublished data) showed that, in corn, with the presence of beneficials, soft biopesticides could be used to compliment control of heliothis rather than using chemicals that were less selective against Hymenoptera spp. The savings attributed to increased yield, cleaner environments and industry reputation as a result of using beneficial insects are factors that should be included in assessing the economic feasibility of using beneficial insects.

The recent work of Hoque *et al.* (2000) provides a basis for roughly estimating both the savings resulting from the exploitation of beneficials (which permits the use of soft chemicals), and the benefit:cost ratios for the research which has allowed this to occur. Average increases in gross margins of 15% for Ingard® cotton and 5.5% for conventional cotton were obtained. Assuming that original gross margins were $2000 per hectare for both Ingard® and conventional cotton (Hoque *et al.* 2000, Michael Boyce & Co., 1998), and that the total Australian area of 550,000 ha contains 30% Ingard®, then some simple calculations show that if the soft option strategy is uniformly applied, the industry can annually save approximately $49.5m on Ingard® and $42.5m on conventional cotton. These potential savings amount to $A0.94 billion over a ten year period, a term which is frequently used to amortise the costs of biological control research (Tisdell 1990). Compared with the estimate of $20 - 25 million spent on research on beneficials in the last decade (Section 1), this yields a benefit:cost ratio of approximately 40:1. This ratio compares favourably with benefit: cost rations calculated for classical biological control projects involving the introduction of new beneficials. These range from 10:1 to 100:1 (Tisdell 1990, Van Driesche and Bellows 1996).

This calculation might be criticised for its assumption that all the soft option technology described in the IPM Guidelines for Australian Cotton and implemented in the study area of Hoque *et al.* (2000) is immediately applied across the entire cotton acreage. While it is clear that achieving this will require a substantial effort in extension, we believe it is not unrealistic to expect quick adoption given the clear economic benefits. Moreover, our calculations contain two other very conservative assumptions. The first assumption is that no further soft option technologies are developed and implemented during the next ten years, which seems unlikely. The second assumption is that indirect benefits (which often accrue to the wider community as well as growers) are not valued in our calculations. Pimentel *et al.* (1993) have shown that for US agriculture as a whole, the indirect benefits of reduced insecticide use, including reduced environmental contamination and reduced impacts on wildlife and human health, are approximately double the direct benefits of reduced pesticide costs to farmers.

7. What outcomes has the research on beneficials achieved?

The information on beneficials has over the years found its way into extension material available to pest managers and decision makers in a number of different forms (Appendix 3). The information essentially lists a "gallery of good guys" in various forms, from books (e.g. Shephard *et al.* 1983) and pamphlets produced by State government extension workers, magazine and newspapers articles and more recently "uteguides" and various computer packages (cottonLOGIC, BugMatch) (see Appendix 3 for details). In particular the Pest and Beneficial Guide (Pyke and Brown 1996) has proved most popular with a distribution of around 6,500 copies. These information materials all aim to provide ways of identifying the main predatory species for key pests such as heliothis, aphids and mites. Although this may well inform decision-makers that not all insects on crops are "bad", it is not widely known if this information has changed management practices.

Perhaps the most sophisticated packages available are computer programs and multimedia tools: CottonLOGIC (the successor to SIRATAC), and BugMatch Cotton. Both are widely distributed, the former to over 1000 growers and pest managers, and the latter to over 1400 users. Both CottonLOGIC and BugMatch Cotton provide a database of information and photographs on known cotton pests and their various predators and parasitoids. CottonLOGIC provides a means for counts of predators to be entered from vacuum samples or visual counts, as well as the percentage of parasitised eggs and larvae collected and pest:beneficial ratios (see below). Models then predict heliothis populations for three days following an insect check and adjust survival by taking beneficial numbers into account (see below).

We assume that although most growers/consultants/scouts are aware of what some beneficials look like and record them, they are not yet using them to answer the question: What is the impact of n number of benefícals x, y, and z on likely survival of pests a, b and c?

7.1 Impact - Have beneficials been incorporated into real time pest management?

There are four basic ways to use beneficials. These are via conservation, inoculation, augmentation and inundation. They can be used independently or integrated as part of decision making on spray programs in the form of IPM (Dent 1991). To date, the main thrust in cotton has been to conserve beneficials, especially early in the season. Examples of using these strategies as part of pest management are limited in Australia but do exist. Predator conservation was part of a management strategy in sprayed cotton on a property in southeast Queensland in the late 1970s (Pyke 1980). Here, predator numbers influenced both the type and timing of the spray. Decisions were based on the abundance of key predators. In another more recent program the reason for not spraying in the early season was attributed to predator presence and using a threshold of two small heliothis larvae per metre (Deutscher & McKewen 1996). The use of predator: prey ratios were recommended as early as 1992 where, if larvae were close to thresholds and 3-4 predators per metre were present, no action was taken until another check was done up to two days later (Murray & Mensah 1996).

Mensah and Harris (1995, 1996ab), Mensah *et al*. (1996) and Mensah (1997) incorporated predators into pest management decisions through the use of predator: prey ratios and conservation of beneficials by using lucerne as refugia and Envirofeast® food sprays to encourage beneficial insects into crops. This work has contributed considerably towards preparing growers in the adoption of biological control as part of an IPM strategy in Australian cotton. However, the predator: prey ratios are not yet based on knowledge of the effects of individual predator species and their lifestages (Mensah 1999a).

In sweet corn, the predator: prey ratio, when used on parasitoids, was found to be a weak predictor of damage to sweet corn cobs from heliothis ($r^2 = 0.586$) (Scholz 2000 unpublished data). He also found the number of parasitised eggs was a better predictor ($r^2 = 0.991$) and suggests *Trichogramma* numbers (=parasitised eggs) be used to determine when to spray and what type of spray to use. These provide a 'soft' way to manage heliothis in sweet corn. In sweet corn naturally occurring beneficial insects (predators) have recently been ranked as low, moderate or high contributors to heliothis mortality. These rankings can be taken into consideration when selecting insecticides and making management decisions on spraying. How widely these strategies will be adopted by growers is not known. Best management practices currently include recording beneficial numbers but whether these numbers are used for management decisions has not been quantified.

Augmentation and inundation of beneficials through mass reared insects has been scarce in Australia. One of the most recent examples has been the inundative release of the predator *P. plagipennis* in soybean, sunflower and cotton (Grundy & Maelzer 2000). They showed that as a result of augmentation heliothis larval numbers were lowered in cotton for most of the season. Wade (1999) also examined the potential of inundative release *P. plagipennis* in grain sorghum and concluded they have only moderate potential due to the high rates of disappearance shortly after release. Stanley (1997) reports augmentative release of the green lacewing, *M. signata* in sorghum strips inter-planted in cotton. The best known example of mass rearing parasitoids for augmentative releases is *T. pretiosum* used for suppression of heliothis in Australia, Russia, China and Latin America (King *et al.* 1985). To date inundative releases of *Trichogramma* have not been considered widely successful in Australia (Scholz 2000 unpublished data). This has been attributed to the lack of understanding of the release rates, ecology of the parasitoid, quality control on mass reared parasitoids and possible mortality from chemical sprays (Scholz 2000 unpublished data).

The most recent framework for the application of research on beneficials is the IPM Guidelines for Australian Cotton, formulated by Mensah and Wilson (1999). This information is supplied to growers along with information previously contained in annual Cotton Pesticides Guides, in a publication called the Cotton Pest Management Guide (Shaw 1999). It will be incorporated in CottonLOGIC and other extension material. The IPM Guidelines form the basis of the soft option strategies used in the economic study of Hoque *et al.* (2000). The results from this study are likely to encourage the widespread adoption of beneficials.

8. Review of beneficials in cotton farming systems – conclusions

This review has documented major research effort on beneficials in cotton and other crops in the cotton system, extending over 30 years. These studies are now beginning to bear fruit. Although we still often lack precise information on how best to manipulate individual species of beneficials, evidence from economic studies of "soft" versus "hard" insecticide options is providing growers with confidence to rely on them.

The challenge for the new millennium is twofold. The first is to capture the economic and environmental benefits that have been made possible by past research, and then to develop new and more specific techniques which explicitly incorporate beneficials into pest management systems, rather than just attempting to preserve them.

The second of these objectives confronts researchers with significant technical and intellectual challenges. The only way we are going to be able to predict (and eventually manipulate) populations of predators in cotton and other vegetation types is through a process of gathering: (1) detailed knowledge of the habitat preferences of all life stages of the predators

in question (2) information on the daily and seasonal movements of the mobile stages of the predatory species (this will link into variables like whether the abundance of prey, or other factors influence predator presence) and (3) computer modelling of the likely areas of high predator density. Needless to say, with our current state of knowledge this will be a challenge.

To date the literature suggests that beneficials can impact on heliothis populations and most researchers agree that it is important to conserve beneficials in order to aid control of heliothis. The fundamental limitation to their incorporation into IPM programs at present seems to be a lack of understanding of the management and role of beneficials. Many researchers have suggested, over many years, that until we know more about the impact of beneficials they cannot be effectively incorporated into management programs. Broadley (1980) suggested that manipulation of natural enemy populations can minimise or eliminate pesticide application but an understanding of the predator complexes must be clear before they can be used in management. Murray and Mensah (1996) stated that there is little known about the role of individual species of beneficials in Australian cotton. This was earlier suggested by Murray (1992) who stated that "we don't have confidence to rely on natural enemies because we don't know enough about them". Strickland *et al*. (1996) suggests that one of the key focuses on the future of IPM should be maximising the use of beneficials. Even more recently Alexander (1998) wrote "farmers should be looking for beneficials when making heliothis decisions" and Wilson *et al*. (1998) states that "clarifying the role of predation … is essential for developing integrated pest management systems". Fitt (1989) also noted "until the efficacy of beneficials is quantified, their potential is unlikely to be utilised efficiently". These are just a few examples of many references that argue for the need to better conserve and understand beneficial insects. However, as Seymour and Jones (1991) point out there remains very little evidence on the direct impact of beneficials on heliothis in Australia. If they are to be incorporated into management programs we need to know considerably more than the current literature provides on their role in mortality of heliothis, including the role of individual beneficial species within Australian cotton.

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APPENDIX 1 insert

Reasearch expenditure

APPENDIX 2
Sampling recommendations

Recommended crop inspections per week for *Helicoverpa* spp. (from CropLink notes, FSI, QDPI)

	Seedling	Vegetative	Flowering	Grain/Pod Fill
Soybeans	1	2	2-3	2-3
Navy beans	2	2	2-3	2-3
Mungbeans	1	1	2-3	2-3
Chickpeas	1	1	2	2
Sunflowers	1	1	2	2
Sorghum	1	1	7	1
Cotton	2	2	2	2

Soybean: * Visual sampling – *Helicoverpa* spp.
Inspect tops of leaves, stems and reproductive structures
Check 5m of row at 6 widely spaced sites
* Beat cloth (1m row) – *Helicoverpa*, podsucking bugs, mirids
Take 5, 1m samples from 6 widely spaced locations, (CropLink, FSI)

Mungbean: * Beat cloth (1m row) – *Helicoverpa* spp., podsucking bugs, mirids
Take 5, 1m samples from 6 widely spaced locations
* Suction sampler (20m row) – mirids
Take 1, 20m suction sample at 10 locations (account for sampling efficiency of 0.3) (Brier 1997)

Sorghum: * Plant shake – midge, *Helicoverpa* spp.
Shake plant head into bucket or bag
* Visual sampling - heliothis
Inspect plant terminals
Check 5m of row at 6 widely spaced sites, (CropLink, FSI)

Cotton: * Visual sampling – *Helicoverpa* spp., predatory insects

Sample 60 plants with no less than 3 entry points
* Suction sampler – *Helicoverpa* spp., predatory insects

Drawn from top to base of each plant in 20m row.

At two locations within field.

Predator : Pest ratio (Mensah, ENTOpak)

Lloyd St (PO Box 282) Narrabri, 2390 Ph (02) 6792 4088 Fax (02) 6792 4400
Email: crdc@crdc.com.au

APPENDIX 3
Pest management extension material available to field crop farmers and consultants

Computer programs / multimedia tools

- CottonLOGIC (integration of entomoLOGIC and nutriLOGIC)

A Database of information and photographs of 120 cotton pests and their predators, showing various stages of life cycles. Predator data can be entered from vacuum samples or visual counts, as well as the percentage of parasitised eggs and larvae collected. Pest/beneficial ratio can be calculated . Models predict *Helicoverpa* populations for three days following insect check. Means of recording agronomic data such as pesticides and fertiliser applications, insect pressure and field operations.

Produced by CSIRO Plant Industry, CRC for Sustainable Cotton Production, CRDC

1,021 copies supplied in response to requests (D. Larsen pers. comm.)

- BugMatch Cotton

Information on integrated pest management in cotton. Includes colour images and digital video.
Produced by Centre for Tropical Pest Management and Aventis
1,400 supplied to cotton growers, corporate farm agronomists, reseller agronomists, consultants and their scouts, Department of Ag. staff, educational institutions and Aventis staff in Australia and overseas (D. Tomlinson, Aventis, pers. comm.)

Periodicals

- Groundcover - Quarterly newspaper that reports on research results of relevance to grain growers.

Produced by GRDC (hardcopy, internet)
Approx. 55,000 subscribers (W. Page, pers. comm.)
- Australian Grain

Bimonthly journal (hardcopy)
19,200 readers (Greenmount Press pers. comm.)
- TOP of the country

Quarterly newsletter which highlights TOPCROP activities
- The Australian Cotton Grower

Bimonthly journal (hardcopy)
1,800 subscribers (approx. 200 more readers) (Greenmount Press, pers. comm.)
- Australian Cotton Outlook
- Heliothis Stateline - Monthly newsletter

Books/Publications

- Insects: The Ute guide

Pocket-sized booklet on insect identification in cereal, pulse and canola crops
Produced by GRDC and TOPCROP Australia

- Cotton Pest Management Guide 1999-2000

Provides information on management of insect pests in cotton and their resistance to insecticides and transgenic plants. Provides IPM guidelines, and a guide to cotton pesticides
Produced by NSW Agriculture and Australian Cotton CRC, author A.J. Shaw

- The Cotton Pest and Beneficial Guide

Provides colour pictures and information on major pests, occasional pests, predators, parasites, pathogens and other common insects of cotton crops.
Produced by CRDC, CTPM, and CRC for Sustainable Cotton Production (1996), editors B. A. Pyke and E. H. Brown

Agronomic Notes

- CropLink (Farming Systems Institute, QDPI), Farm Notes (QDPI), AgFacts (NSW Ag)

Crop management notes available on internet (DPI web site) or as hardcopy
Produced by State Government Agricultural bodies

- ENTOpak - Compendium of material relevant to IPM and insect control in Australian cotton fields

Produced by CRC for Sustainable Cotton Production (hardcopy, internet)
95 distributed

Information from Agricultural retailers

- In-house publications, production notes e.g. IAMA, CSD, Aventis

Other resources

- Conference Proceedings

Australian Cotton Conference, Australian sorghum conference.

- Industry Expos and field days

APPENDIX 1

Research expenditure related to biological control of invertebrate pests: excludes inkind contributions by the research organisation for facilities, supplies and permanent wages and external funding contributions

Funding Body	Project Code	B/C Category a	Title	Start Date	End Date	Duration (yrs)	$ Yr 1	$ Yr 2	$ Yr 3	$ Yr 4	$ Yr 5	$ Total
GRDC	DAQ1F	1	Evaluation of *Microplitis* and exotic parasitoids for biological control of *Helicoverpa* spp. (joint CRDC)	Jul-90	Jun-93	3	26940	23337	26325	n/a	n/a	76602
GRDC	CSE8F	1	The development of a mycoinsecticide based on *Metarhizium anisopliae* for the control of scarabs, *Heteronyx* spp. in peanut crops	Jul-90	Jun-93	3	23692	29239	32223	n/a	n/a	85154
GRDC	DAQ30	1	Microbial control of heliothis on chickpea and other grain legumes	Jul-91	Jun-94	3	12460	12700	15960	n/a	n/a	41120
GRDC	DAQ60	2	Interaction with sunflowers, pest status and egg parasitoids of *Nysius* spp.	Jul-91	Jun-94	3	30000	32000	36700	n/a	n/a	98700
GRDC	DAQ81	1	The role of egg parasitoids for heliothis management in chickpea and pigeon pea	Jul-92	Jun-94	2	9000	9500	n/a	n/a	n/a	18500
GRDC	DAV89	2	Impact and management of invertebrate pests & beneficials in conservation tillage systems	Jul-92	Dec-95	3.5	26370	45959	48644	24462	n/a	145435
GRDC	DAQ125	2	Ecology of the grain legume bug complex: host range and natural enemies of pod and sap sucking insects	Jul-92	Jun-95	3	10500	12000	12360	n/a	n/a	34860
GRDC	DAQ228C	1	Heliothis biocontrol in midge-resistant sorghum using parasitoids and a specific heliothis virus	Jul-93	Jun-94	1	38950	n/a	n/a	n/a	n/a	38950
GRDC	CSE79	1	The isolation of *Bt* strains for the control of beetle pests of stored grain	Jul-93	Jun-96	3	91527	86452	85316	n/a	n/a	263295
GRDC	DAQ193	1	On-farm evaluation of the insect pathogen *Metarhizium anisopliae* for the biological control of the peanut scarab *Heteronyx piceus*	Jul-93	Jun-98	5	24050	38620	38930	36120	22656	160376
GRDC	CSE77	1	Biological control of Mediterranean snails in southern Australia	Jul-93	Jun-96	3	61887	65219	20324	n/a	n/a	147430
GRDC	DAQ160	1	Larval parasitoids for biocontrol of *Helicoverpa* spp.	Jul-93	Jun-96	3	31890	30860	32640	n/a	n/a	95390
GRDC	DAW371	1	Evaluation of predators and parasites for IPM of the native budworm in lupins	Jul-94	Dec-97	3.5	43506	46145	48049	22239	n/a	159939
GRDC	UA242	1	Nematodes as biocontrol agents of helicid snails (joint RIRDC)	Jul-94	Jun-97	3	34163	34789	44388	n/a	n/a	113340
GRDC	JRF40	1	PhD: Investigations into the biological control of GVB on soybean and other host plants	Feb-96	Feb-99	3	10833	26000	26000	15167	n/a	78000
GRDC	CSE108	1	Biological control and management of pentatomid bugs in soybean and pulse crops	Jul-96	Jun-99	3	51798	119502	122548	n/a	n/a	293848
GRDC	CSE109	1	Biological control of mediterranean snails in southern Australia	Jul-96	Jun-99	3	57400	59383	35328	n/a	n/a	152111
GRDC	DAQ364	2	Heliothis management for IPM in grain crops	Jul-96	Jun-01	5	150000	153870	157860	161470	163700	786900
GRDC	CSE118	3	Travel to attend international *Bt* meeting	Aug-96	Sep-96	0.04	4000	n/a	n/a	n/a	n/a	4000
GRDC	JRF45	1	PhD: Development of better IPM systems and applied biological control	Apr-97	Mar-00	3	6500	26000	26000	19500	n/a	78000
GRDC	CSE111	2	Pest management for grain crops of southern NSW	Jan-97	Jun-00	3.5	60320	119950	118990	126580	n/a	425840
GRDC	CSE136	2	Heliothis management for grains- strategic initiative	Jul-97	Jun-02	5	238577	240757	n/a	n/a	n/a	479334
GRDC	UQ100	1	Heliothis management for grain- Project 3 development of fungal biopesticides for *Helicoverpa* management	Jul-97	Jun-00	3	54846	64224	67911	n/a	n/a	186981
GRDC	UQ118	1	Baculovirus biopesticides for heliothis control- UQ component	Oct-97	Jun-02	4.75	190000	161760	248240			600000
GRDC	CSE155	1	Baculovirus biopesticides for heliothis control- CSIRO component	Oct-97	Jun-02	4.75	107611	212435	130000	237086		687132
GRDC	UA418	1	Nematodes as biocontrol agents of helicid snails (joint RIRDC)	Nov-97	Oct-98	1	32182	12791	n/a	n/a	n/a	44973
GRDC	DAQ440	2	A regional management strategy for heliothis mgt on the Darling Downs	May-98	Jun-98	0.13	25000	n/a	n/a	n/a	n/a	25000
GRDC	DAQ442	2	Regional management of heliothis on the Darling Downs	Jul-98	Jun-01	3	64550	63100	129000	n/a	n/a	256650

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GRDC	UA454	1	Biological control of redlegged earth mite using imported predators	Jul-98	Jun-01	3	44775	93301	70912	n/a	n/a	208988
GRDC	UQ122	1	The role of ascovirus in biocontrol of heliothis in grain crops	Nov-98	Nov-01	3	62681	64818	62326	n/a	n/a	189825
GRDC	UHS38	1	Honours: Potential of the assassin bug as a biological control agent of *Helicoverpa* spp in coarse grain crops	Jan-99	Dec-99	1	3000	3000	n/a	n/a	n/a	6000
GRDC	DAQ370	1	Biological control of the corn aphid on sorghum panicles	Jul-99	Jun-01	2	42000	42000	n/a	n/a	n/a	84000
GRDC	DAS300	2	Integrated snail management in the southern region	Jul-99	Dec-02	3.5	145112	148966	n/a	n/a	n/a	294078
GRDC	DAQ481	2	Integrating IPM for heliothis and other major pests of pulses, peanuts, soya	Jul-99	Jun-02	3	110000	115506	n/a	n/a	n/a	225506
GRDC	GRS32	1	PhD: Increasing the effectiveness of the natural enemies for the biological control of crop pests	Jan-00	Feb-03	3	15000	30000	30000	15000	n/a	90000
GRDC	CSE163	2	The regional management of *Helicoverpa* spp. in farming systems in southern NSW and northern Victoria	Jul-00	Sep-03	3	71519				n/a	71519
GRDC	UQ140	1	Development of fungal biopesticides for *Helicoverpa* management	Jul-00	Jun-01	1	67779	n/a	n/a	n/a	n/a	67779
CRC	UQ5	1	Biological mite control in cotton	Oct-83	Jun-84	0.75	8642	n/a	n/a	n/a	n/a	8642
CRC	UQ6	1	Investigation of *Vairimorpha necatrix* (Kramer) for the control of *Heliothis* spp.	Sep-83	Jun-85	1.75	4000	20878	n/a	n/a	n/a	24878
CRC	DAN22L	1	An evaluation of the potential for egg parasites in the control of heliothis in cotton	Jul-85	Jun-87	2	26655	30781	n/a	n/a	n/a	57436
CRC	CS22L	2	Investigation of mite abundance, economic injury and management	Jul-85	Jun-89	4	52460	73111	n/a	n/a	n/a	125571
CRC	DAQ32L	3	Overseas travel grant to attend symposium on *Trichogramma*	Nov-86	Nov-86	0.02	3500	n/a	n/a	n/a	n/a	3500
CRC	DAQ35L	1	Evaluation of chemical microbial pesticide combinations against heliothis	Jul-87	Jun-90	3	10115	12065	17306	n/a	n/a	39486
CRC	DAQ39L	1	Egg parasites for heliothis control in cotton	Jul-87	Jun-88	1	44000	n/a	n/a	n/a	n/a	44000
CRC	DAQ41L	1	A field evaluation of the potential of egg parasites for the control of *Heliothis* spp.	Jul-88	Jun-92	4	40000	44732	47896	28900	n/a	161528
CRC	DAQ42L	3	Travel to USA to study insect pathology, microbial control and insect rearing	Jul-88	Oct-89	0.25	2500	n/a	n/a	n/a	n/a	2500
CRC-CRDC	DAQ48C	1	Evaluation of *Microplitis* and exotic parasitoids for biological control of *Helicoverpa* spp. (joint GRDC)	Jul-90	Jun-93	3	17700	15908	17700	n/a	n/a	51308
CRC-CRDC	CSP21C	2	Ecology and management of spider mites on cotton	Jul-90	Jun-93	3	132756	128387	136248	n/a	n/a	397391
CRC-CRDC	DAQ53C	3	USA study tour to examine development of biocontrol agents	Jul-90	Jun-91	1	3375	n/a	n/a	n/a	n/a	3375
CRDC	DAQ54C	3	Travel to symposium on *Trichogramma*	Sep-90	Jun-91	0.75	5430	n/a	n/a	n/a	n/a	5430
CRDC	CSE25C	1	Factors influencing egg survival and larval establishment of heliothis on cotton	Jul-91	Jun-95	4	59997	59776	63431	61099	n/a	244303
CRDC	DAQ58C	2	IPM in raingrown cotton	Jul-92	Jun-96	4	110000	109500	109500	49000	n/a	378000
CRDC	UNE13C	1	Assessing the effectiveness of predators of *Heliothis* spp. (operating for J. Stanley's PhD)	Jul-92	Jun-95	3	9650	22749	11537	n/a	n/a	43936
CRDC	DAQ68C	2	Optimal early season insect control strategies	Jul-92	Jun-95	3	54162	74350	75084	n/a	n/a	203596
CRDC	NCQ1C	1	Use of *Bt* for the management of *Heliothis* in cotton	Jul-92	Jun-95	3	136528	203696	180173	n/a	n/a	520397
CRDC	CSP46C	2	Improved PM for mites and thrips on cotton	Jul-93	Jun-96	3	150553	144308	150016	n/a	n/a	444877
CRDC	CSE35C	3	Travel to Canberra for 2nd *Bt* meeting	Jul-93	Sep-93	0.25	4294	n/a	n/a	n/a	n/a	4294
CRDC	CRDC1C	2	Organic pest management in cotton	Jan-94	Jun-94	0.5	30000	n/a	n/a	n/a	n/a	30000
CRDC	DAN89C	2	Pest management in organic cotton	Jul-94	Jun-95	1	35000	n/a	n/a	n/a	n/a	35000
CRDC	CRDC3C	2	The cotton pest and beneficial guide	Jul-94	Jun-95	1	11910	n/a	n/a	n/a	n/a	11910
CRDC	UN29C	1	PhD operating: Seasonal abundance and diversity of soil fauna in the principal cotton growing valleys of NSW	Jul-94	Jun-97	3	4205	4205	4205	n/a	n/a	12615
CRDC	CSE47C	3	Travel: Invertebrate pathology and microbial control	Jul-94	Jun-95	1	3950	n/a	n/a	n/a	n/a	3950

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CRDC	CSE48C	3	Travel: Invertebrate pathology and conference on *Bt*	Jul-94	Jun-95	1	3716	n/a	n/a	n/a	n/a	3716
CRDC	CTPM1C	1	Assessment of *Bt* formulations on cotton	Jul-94	Jun-95	1	31750	n/a	n/a	n/a	n/a	31750
CRDC	DAQ88C	3	Travel: Symposium on *Trichogramma* and other egg parasitoids	Jul-94	Jun-95	1	4000	n/a	n/a	n/a	n/a	4000
CRDC	CSE43	1	The dynamics of beneficial insect communities in cotton agroecosystems and the role of alternative crops in producing pests and beneficials	Jul-94	Jun-95	1	50000	n/a	n/a	n/a	n/a	50000
CRDC	UNE27C	1	PhD: Comparing predatory insects of *Helicoverpa* spp. In Australian cotton: approaches to measuring prey consumption (Impact of predators on *Helicoverpa* spp.)	Jan-95	Jun-98	3.5	11552	23590	25477	15080	n/a	75699
CRDC	DAN98C	1	Conservation and utilisation of beneficial insects in the cotton agroecosystem for IPM in conventional, transgenic and organic cotton	Jul-95	Jun-98	3	110074	110750	111259	n/a	n/a	332083
CRDC	CSE51C	1	The dynamics of beneficial insect communities in cotton agroecosystems and the role of alternative crops in producing natural enemies in cotton	Jul-95	Jun-98	3	101111	110898	112422	n/a	n/a	324431
CRDC	CTPM2C	1	Field assessment of heliothis viruses on cotton	Jan-96	Jun-97	1.5	13900	n/a	n/a	n/a	n/a	13900
CRDC	CSE60C	2	Pre-emptive research into the biology and biological control of *Bemisia tabaci* biotype B (joint CRCSCP)	Jul-96	Jun-99	3	49303	65845	64386	n/a	n/a	179534
CRDC	DAQ79C	2	Seasonal phenology, hosts and natural enemies of the SLWF in cotton areas of Queensland	Jul-96	Jun-98	2	12500	11600	n/a	n/a	n/a	24100
CRDC	CSP74C	2	Management of mites and early season sucking pests on transgenic cotton	Jul-96	Jun-99	3	151628	164128	171783	n/a	n/a	487539
CRDC	AWA1C	2	Field evaluation of Ingard cotton varieties and integrated pest management (IPM) systems in the Kimberly	Jul-96	Jun-99	3	70000	81360	81562	n/a	n/a	232922
CRDC	CSE61C	3	Travel to IOBC conference	Jul-96	Sep-96	0.25	3000	n/a	n/a	n/a	n/a	3000
CRDC	CSE69C	3	Travel to *Bt* and IOBC conference	Jul-96	Jun-97	1	3000	n/a	n/a	n/a	n/a	3000
CRDC	CSE89C	3	Identifying the key groups of soil fauna in cotton agroecosystems (joint CRCSCP)	Jul-97	Jun-00	3	85590	67230	73789	n/a	n/a	226609
CRDC	DAN114C	2	Ecology and management of apple dimpling bugs on cotton	Jul-97	Jun-00	3	59464	63815	70126	n/a	n/a	193405
CRDC	CSE65C	3	A reappraisal of sampling relationships and *Helicoverpa* parasitoid populations in cotton	Jul-97	Jun-00	3	54911	64740	60953	n/a	n/a	180604
CRDC	DAQ85C	2	CRDC contribution to GRDC1C Regional management of heliothis on the Darling Downs	Jun-98	Jun-01	3	64550	63100	72953	n/a	n/a	200603
CRDC	DAQ83C	2	Monitoring SLWF and its natural enemies in cotton areas of Queensland	Jul-98	Jun-01	3	25500	30000	30000	n/a	n/a	85500
CRDC	CSE76C	1	Augmentation and conservation of *Helicoverpa* parasitoid populations in cotton	Jul-98	Jun-01	3	108229	110882	111993	n/a	n/a	331104
CRDC	DAN119C	1	Conservation and utilisation of beneficial insects in the cotton agroecosystem for IPM in conventional and transgenic cotton 2	Jul-98	Jun-01	3	125185	135734	137074	n/a	n/a	397993
CRDC	CRDC71C	2	Discussion paper: Why are cotton plants attractive to insects?	Jul-98	Jun-99	1	5000	n/a	n/a	n/a	n/a	5000
CRDC	DAQ 96C	1	IPM in dryland cotton	Jul-99	Jun-02	3	125000	125000	125000	n/a	n/a	375000
CRDC	UQ29C	1	PhD: Biology, ecology and utilisation of the damsel bug as a predator in cotton	Feb-00	Mar-03	3	12083	29000	29000	16917	n/a	87000
CRDC	UQ26C	1	Ecology of *Trichogramma* egg parasitoids in the ORIA and their role in cotton IPM	Jan-00	Jan-03	3	14100	14310	14310	n/a	n/a	42720
CRDC	UQ28C	1	PhD: Ecology of the *Trichogramma* egg parasitoids in the ORIA and their role in cotton IPM	Jan-00	Feb-03	3	14500	29000	29000	14500	n/a	87000
CRDC	UNE34	1	Review of research into the role of beneficial insects in cotton farming systems	Mar-00	Jun-00	0.25	7000	n/a	n/a	n/a	n/a	7000
RIRDC	DAQ?	1	Culture methods for larval parasitoids of *Helicoverpa* spp.	Jul-91	Jun-93	2	4950	5150	n/a	n/a	n/a	10100
RIRDC	DAQ130A	1	A field evaluation of egg parasitoids for heliothis in sorghum	Jul-91	Jun-94	3	10000	9500	9500	n/a	n/a	29000
RIRDC	UA31A	1	Nematodes as biocontrol agents of helicid snails (joint GRDC)	Jul-94	Jun-99	5	34163	34929	36078	32857	18461	156488

CRCSCP	2.2.4	1	Improving the efficacy of heliothis predators	Jul-93	Jun-94	1	10000	n/a	n/a	n/a	n/a	10000
CRCSCP	2.2.3	1	Integration of parasites into pest management programs	Jul-94	Jun-96	2	3000	3000	n/a	n/a	n/a	6000
CRCSCP	2.2.3	1	Integration of parasites into pest management systems (Stipend for R. Annetts' PhD)	Jul-94	Dec-97	3.5	26000	26000	26000	13000	n/a	91000
CRCSCP	2.2.9	2	Pre-emptive research into the biology and biological control of Bemisia tabaci biotype B (joint CRDC)	Jul-96	Jun-99	3	24200	20000	19300	n/a	n/a	63500
CRCSCP	2.2.17	1	Pollen markers for beneficial insects in cotton (Honours scholarship M. Yee)	Jul-97	Jun-98	1	4000	n/a	n/a	n/a	n/a	4000
CRCSCP	2.2.15	1	Identifying the key groups of soil fauna in cotton agroecosystems (joint CRDC)	Jul-97	Jun-00	3	37500	34500	35000	n/a	n/a	107000
CRCSCP	2.2.16	1	Sources of beneficial insects colonising cotton fields	Jul-98	Dec-00	2.5	66300	71200	n/a	n/a	n/a	137500
CRCSCP	4.9.3	1	Summer scholarship	Dec-98	Jan-99	0.13	4000	n/a	n/a	n/a	n/a	4000
CRCSCP	4.9.3	1	Summer scholarship- Effect of temperature, time, and meal size on the detectability of *H. armigera* larvae in the guts of the earwig *Labidura truncata*	Dec-98	Jan-99	0.13	4000	n/a	n/a	n/a	n/a	4000
CRCSCP	4.9.3	1	Summer scholarship- Augmenting parasitoids of *Helicoverpa* spp.: does nectar feeding increase parasitoid abundance and parasitism rate?	Dec-98	Jan-99	0.13	4000	n/a	n/a	n/a	n/a	4000
CRCSCP	4.9.3	1	Summer scholarship: Predator ecology in the South Burnett district	Dec-99	Jan-00	0.13	4000	n/a	n/a	n/a	n/a	4000
CRCSCP	1.2.1AC	2	Integrated pest management systems for sustainable transgenic cotton production in the west Kimberly	Dec-99	Jun-02	2.5	76000	n/a	n/a	n/a	n/a	76000

a: 1=B/C only project; 2=B/C related project; 3=B/C related travel