

# An overview of integrated pest management (IPM) in north-eastern Australian grain farming systems: past, present and future prospects

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**Abstract.** The authors overview integrated pest management (IPM) in grain crops in north-eastern Australia, which is defined as the area north of latitude 32°S. Major grain crops in this region include the coarse grains (winter and summer cereals), oilseeds and pulses. IPM in these systems is complicated by the diversity of crops, pests, market requirements and cropping environments. In general, the pulse crops are at greatest risk, followed by oilseeds and then by cereal grains. Insecticides remain a key grain pest management tool in north-eastern Australia. IPM in grain crops has benefited considerably through the increased adoption of new, more selective insecticides and biopesticides for many caterpillar pests, in particular *Helicoverpa* spp. and loopers, and the identification of pest–crop scenarios where spraying is unnecessary (e.g. for most *Creontiades* spp. populations in soybeans). This has favoured the conservation of natural enemies in north-eastern Australia grain crops, and has arguably assisted in the management of silverleaf whitefly in soybeans in coastal Queensland. However, control of sucking pests and podborers such as *Maruca vitrata* remains a major challenge for IPM in summer pulses. Because these crops have very low pest-damage tolerances and thresholds, intervention with disruptive insecticides is frequently required, particularly during podfill. The threat posed by silverleaf whitefly demands ongoing multi-pest IPM research, development and extension as this pest can flare under favourable seasonal conditions, especially where disruptive insecticides are used injudiciously. The strong links between researchers and industry have facilitated the adoption of IPM practices in north-eastern Australia and augers well for future pest challenges and for the development and promotion of new and improved IPM tactics.

**Additional keywords:** area-wide management, bean podborer, corn, *Eretmocerus*, etiella, *Helicoverpa*, loopers, mirids, mungbeans, peanuts, podsucking bugs, silverleaf whitefly, soybean aphids, *Trichogramma*, western flower thrips, wheat.

## Introduction

### *Crops and geography*

This paper is an overview of integrated pest management (IPM) practices in north-eastern Australian grain farming systems. IPM strategies and tactics are discussed, as well as the underlying reasons for their success and adoption. Major grain crops include the coarse grains (winter and summer cereals such as wheat, barley, sorghum and maize), oilseeds (sunflowers and canola) and pulses (chickpeas, mungbeans, soybeans and peanuts). While soybeans and peanuts are often classed as oilseeds, in this paper they are regarded as pulses because of shared pests and their botanical (legume) classification. Seeds of both crops are now largely marketed for human consumption, their oil being a secondary market. Of the above crops, the coarse grains cover 92% of the total grain-cropping area (4.6 M ha) with only 4% (~0.2 M ha) each to oilseeds and pulses (ABARE 2008). From a

crop rotation perspective, the area sown to pulses and oilseeds falls well short of that for a more diversified sustainable farming system (Doughton and Holford 1997).

North-eastern Australia is defined as the area stretching northwards from central New South Wales (latitude 32°S, roughly the Dubbo/Taree area) to north Queensland (mainly the Atherton Tableland and the Burdekin region). Sorghum is reviewed elsewhere (Franzmann *et al.* 2008), but where appropriate, reference is made to IPM in this crop.

### *IPM definitions*

Throughout this paper the term IPM is used to refer to the integration of several tactics to manage pests, rather than a sole reliance on insecticides. Such tactics could include, but are not restricted to, the use of selective insecticides or biopesticides, cultural controls such as destruction of weed

host plants, conservation of natural enemies, economic thresholds (ETs), host plant resistance and regular crop sampling to monitor pest and beneficial activity. We also refer to area-wide management (AWM) strategies by which we mean strategies based on using an understanding of a pest's ecology, biology and host range to manage its abundance across a defined region.

### Challenges in managing field crop pests

IPM in north-eastern Australian grain farming systems is complicated by the diversity of crops, pests, market requirements and cropping environments. In general, the summer pulse crops with 20 major pests (Brier 2007) are at greater risk of economic pest damage than oilseeds and cereal grains, each with fewer than nine major pests (Franzmann 2007a, 2007b; Hopkins and McDonald 2007; Murray 2007).

Summer pulses are particularly at risk of economic pest damage because of stringent market quality requirements (Brier 2007). These crops are attractive to pests at any crop stage e.g. seedling spring-planted mungbeans to cereal thrips, *Thrips tabaci* Lindeman, vegetative soybeans to *Helicoverpa* spp. and various loopers including *Chrysodeixis*, *Thysanoplusia*, *Mocis* and *Pantylia* spp., flowering mungbeans to mirids, *Creontiades* spp., podborers, *Etiella behrii* (Zeller) and *Maruca vitrata* (F.) and *Helicoverpa* spp., and most podding pulses to *Helicoverpa* spp. and podsucking bugs (chickpeas excepted for the latter). Major podsucking bug pests include the green vegetable bug, *Nezara viridula* (L.), and the redbanded shield bug, *Piezodorus oceanicus* (Montrouzier), and the large and small brown bean bugs, *Riptortus* sp. and *Melanacanthus scutellaris* (Dallas), respectively. Pulses with an indeterminate growth habit e.g. mungbeans and adzuki beans, in the tropics and coastal subtropics are particularly attractive to *M. vitrata*, a specialised legume pest, larvae of which feed initially inside flowers before moving to adjacent pods. In contrast, winter-grown chickpeas are only troubled by *Helicoverpa* spp. Peanuts escape pod damage from podsucking pests because the pods are underground, but they are vulnerable to soil insects such as peanut scarabs, *Heteronyx piceus* Blanchard (Ward and Rogers 2006). Peanuts are also vulnerable to attack by *E. behrii* (also known as lucerne seed web moth), larvae of which are able to reach the underground pods through cracks in the soil in dry seasons (Brier *et al.* 1999). Because they are mostly grown for human consumption, product appearance is extremely important and most pulse crops have a very low pest damage tolerance, 2% seed damage usually being the maximum allowable before crop value is substantially penalised by  $\geq$ AU\$100/t (Lucy *et al.* 2005).

Pests that periodically inflict significant damage in oilseeds (primarily sunflowers, safflower and canola) include *Helicoverpa* spp. in all crops, diamondback moth, *Plutella xylostella* (L.), in canola, and Rutherglen bug, *Nysius vinitor* Bergroth, in sunflowers and safflowers. In heavier soils, cereals and oilseeds, and to a lesser extent pulses, are attacked by soil insects including false wireworms, *Gonocephalum* spp. and *Pterohelaeus* spp. and black field earwigs, *Nala lividipes* (Dufor) (Franzmann 2007a; Murray 2007).

The coarse grains (summer and winter) cereals have a much lower pest risk, being attacked less frequently by fewer pests. Winter cereals experience severe damage sporadically from

*Helicoverpa* spp. but are more frequently attacked by armyworms, usually the common armyworm, *Leucania convecta* (Walker) (Hopkins and McDonald 2007). Both maize and sorghum are regularly attacked by *Helicoverpa armigera* (Hübner) but this pest rarely causes economic damage in maize and is easily controlled with *Helicoverpa* nucleopolyhedrovirus (NPV) in sorghum. Because winter cereals are lower value bulk commodities, and because their damaged seeds are more easily graded out, seed quality is not the major issue that it is in summer pulses. Very sporadic but potentially serious threats in more inland regions are the Australian plague locust, *Chortoicetes terminifera* (Walker), spur-throated locust, *Austacris guttulosa* (Walker), and migratory locust, *Locusta migratoria* (L.) (Walker *et al.* 2007).

Many of the major or common grain crop pests in north-eastern Australia are truly cosmopolitan pests e.g. *N. viridula* and *M. vitrata*, or at least distributed widely throughout the Old World e.g. *H. armigera*. However, some such as the native budworm, *H. punctigera* (Wallengren) are endemic to Australia.

### Background to the current IPM era, including driving forces

IPM is frequently reported as having been first adopted globally as a framework for pest management in the early 1960s (Clement *et al.* 2000; Bajwa and Kogan 2003) after its conception by the IPM pioneers Stern and van den Bosch (1959). However, since the early 1900s, various tactics compatible with IPM have been employed in north-eastern Australia (and elsewhere) (Williams and Il'ichev 2003). Indeed some new or 'novel' approaches have previously been explored. For example, the use of molasses baits targeting *Helicoverpa* spp. moths by Atherton (1933) is in essence an early deployment of moth attractants. While this paper focuses on IPM from the late 1970s onwards, reference is made to earlier periods where required, to better place current IPM practices into context.

The late 1970s period was chosen deliberately as a reference point as it coincided with the introduction of the synthetic pyrethroids (SPs) in 1977, a key episode in Australian grain crop pest management. The SPs were attractive for pest management due to their low cost, relatively low mammalian toxicity, and the broad range of pests able to be controlled. However, SPs are also very toxic to many beneficial invertebrate species. Initially, the SPs were extremely effective and were widely adopted for pest control in Australian field crops (Forrester *et al.* 1993). However, within 6 years resistance had developed which dramatically reduced efficacy against their primary field crop target, *H. armigera* (Gunning *et al.* 1984).

While the SPs are incompatible with IPM, they and other older, non-selective pesticide groups have ultimately benefited IPM in north-eastern Australian grain crops. Indeed, the current awareness of IPM in north-eastern Australia has been driven largely by the insecticide resistance 'crisis' of the early 1990s, when *H. armigera* developed high levels of resistance to all insecticide groups available at the time – SPs, organophosphates, carbamates and endosulfan (Gunning *et al.* 1984, 1992, 1998; Forrester *et al.* 1993; Fitt 1994; Gunning and Easton 1994; Fitt and Cotter 2005). This crisis was exacerbated by the non-selectivity of most of these insecticides which decimated beneficial insect populations, allowing *H. armigera* populations

to resurge, requiring further control and selection for resistance (Murray *et al.* 1998).

The resistance crisis highlighted the vulnerability of the north-eastern Australian grain industry to the dangers of relying solely on insecticides for the control of *H. armigera*. This, and to a lesser extent, teething problems with transgenic cotton expressing the single Cry1Ac toxin from *Bacillus thuringiensis* Berliner (*Bt*), provided the impetus for the development of IPM recommendations, of AWM strategies and multi-pest strategies and the search for more selective insecticide/biopesticide options for grain crops (Murray *et al.* 1998; Duffield and Jordan 2000; Brier *et al.* 2005, 2007).

The other significant IPM driving force in north-eastern Australia was the arrival in 1994 of silverleaf whitefly (SLW), *Bemisia tabaci* (Gennadius) biotype B (Gunning *et al.* 1995). While not attacking all grain crops, this pest poses a significant threat to soybeans, sunflowers and navy beans, and to a lesser extent to peanuts (Moore *et al.* 2003; Brier 2007; Franzmann 2007a). As no effective or economically viable insecticides are currently available for control of SLW in these crops, the only management option is to maximise the effectiveness of natural enemies, particularly the newly-introduced SLW parasite *Eretmocerus hayati* Zolnerowich and Rose (Brier *et al.* 2007; De Barro and Coombs, in press).

### IPM objectives

A major objective of pest management in north-eastern Australian grain crops has been to replace older, less selective insecticides wherever possible, with newer, more selective products, with the expectation that native and introduced natural enemies will more effectively stabilise pest populations. Complementary IPM initiatives include threshold studies identifying pest/crop scenarios where, often contrary to industry perceptions, pests are not inflicting economic damage, and hence spraying is unnecessary, and the recommendation of agronomic and cultural practices to further reduce the risk of pest attack. The advent of SLW in particular has highlighted the need for multi-pest IPM approaches to minimise the impact of insecticides on natural enemies. The IPM value of such tactics or strategies are widely recognised internationally e.g. Lewis *et al.* (1997), and especially in cropping systems threatened by problematic pests such as SLW (Oliveira *et al.* 2001; Naranjo *et al.* 2003) and *Helicoverpa* spp. (Zalucki *et al.* 1986; Fitt 1989; Naranjo and Luttrell, in press).

Integral to IPM at both an AWM and individual field scale is insecticide resistance management (IRM), which includes tactics such as limiting the number of pest generations exposed to a pesticide, rotation of pesticide groups, and restricting the number of sprays of a pesticide group applied per season, either to a specified period of time, or the number applied to individual crops (Holloway 2002; Farrell 2007). These tactics have been well developed and widely implemented in cotton (e.g. Farrell 2007) and to a lesser extent in grains (D. Murray, pers. obs.).

### IPM tools (tactics) and strategies

#### Insecticides

Insecticides continue to play a key role (Bailey 2007) in pest management in north-eastern Australian grain crops. As

mentioned previously, the resistance of *H. armigera* to older insecticides has provided the impetus for the registration of some new generation insecticides in grain crops (Murray *et al.* 2005a). Products such as indoxacarb are now widely used for *Helicoverpa* spp. control in grain crops (G. Cornwall, DuPont Australia, pers. comm.) and other new generation insecticides are awaiting evaluation and registration (H. Brier and D. Murray, pers. obs.). These new products are generally less disruptive of beneficials than the older insecticides they replaced, particularly at the lower rates registered in grain crops compared with cotton. For instance, the rate for indoxacarb in grains is 60 g active ingredient (a.i.)/ha compared with 127.5 g a.i./ha in cotton; [see Wilson *et al.* (2007) for the relative effect of different rates on beneficials]. The registration of more selective insecticides in grain crops has been facilitated in part by the advent of *Bt* cotton (Ingard<sup>®</sup> and Bollgard II<sup>®</sup>). Many of the new generation caterpillar insecticides were originally intended for conventional cotton, but greatly reduced insecticide use in Bollgard II<sup>®</sup> crops has increased the interest of agrochemical companies in other markets, including grain and pulse crops (Murray *et al.* 2005a).

The move to more selective insecticides in grain crops has also been driven by the deregistration of some older insecticides, particularly those with residue, health and environmental concerns such as monocrotophos and endosulfan (APVMA 2008). However, this trend has sometimes had negative IPM impacts in the short term. For example, the removal of endosulfan for use on pulse and grain crops has left SPs such as deltamethrin, which are very disruptive of beneficial populations, as the only effective registered option for control of podsucking bugs in summer pulses (Brier *et al.* 2007).

In contrast to the new caterpillar insecticides, many of the potential new generation sucking pest insecticides, in particular the neonicotinoids and fipronil, are disruptive of key beneficials such as the parasitic hymenoptera, predatory bugs and ladybirds (Wilson *et al.* 2007). Coupled with the low cost of the SPs (~AU \$9/ha) and dimethoate (~AU\$4/ha), this has been a major disincentive for the registration of new insecticides for sucking pests (Hemiptera) in pulses and grains. Furthermore, the impact on beneficials of some older insecticides targeting sucking pests can be reduced with the addition of common salt to tank mix water as a 0.5% adjuvant. For example, with the addition of 0.5% salt, dimethoate rates can be reduced by up to 60%, with no reduction in efficacy against mirids but with a greatly reduced impact on predatory bugs and beetles and no salinity or phytotoxic risks (Brier *et al.* 2004). Salt adjuvants also have potential benefits for podsucking bug management, particularly for *P. oceanicus*. Interestingly, deltamethrin alone gives no control of this pest, but with the addition of 0.5% salt, up to 60% control can be achieved (Brier *et al.* 2007).

#### Biopesticides

Attempts in the 1970s to develop NPV as a mainstream product for control of *Helicoverpa* spp. were thwarted by the introduction of the effective and cheap SPs (Franzmann *et al.* 1996; Teakle *et al.* 1996; Holdom *et al.* 1996). However, since the mid 1990s, biopesticides have gained greater acceptance in grain crops, and can truly be regarded as having arisen from the ashes of Elcar<sup>®</sup> (an NPV product marketed by the American Cyanamid Company)

(Teakle *et al.* 1996). *Helicoverpa* NPV and *Bt*-based products are now widely used to control *Helicoverpa* spp. and loopers, respectively, especially in situations where modest efficacy is sufficient and offset by high selectivity against beneficials, such as in vegetative crops, or where *Helicoverpa* spp. pressure is low, or where there is high natural control but above-threshold pest pressure (Scholz *et al.* 1998).

Impetus for the development of biopesticides in north-eastern Australia has been provided by restrictions on the use of new generation selective insecticides (e.g. to one indoxacarb spray per crop) to slow the development of resistance in *H. armigera*. The other major driver for biopesticides has been the advent of SLW and the promotion of the 'go soft early' IPM strategy in soybeans to counter this pest by conserving its natural enemies, especially its newly introduced parasitoid, *E. hayati*. This strategy recommends using biopesticides (NPV or *Bt*) for control of *Helicoverpa* spp. and loopers in vegetative crops and to control loopers with *Bt* in flowering and podding soybeans, unless there is extreme pest pressure requiring a higher level of control (Brier *et al.* 2005). These recommendations are based on well established defoliation thresholds for soybeans (Thomas *et al.* 1974), *Helicoverpa* threshold studies in Australian soybeans (D. J. Rogers, unpubl. data), efficacy data for *Bt* against *Thysanoplusia* and *Chrysodeixis* spp. loopers in soybeans (Knight and Brier 2000), and the well documented flaring of SLW wherever non-selective insecticides are widely used, particularly in the earlier stages of crop development (Sequeira and Naranjo 2008).

Crops where the use of biopesticides against *Helicoverpa* spp. has been successful include sorghum (Murray *et al.* 2001; Franzmann *et al.* 2008), coastal soybeans (Brier *et al.* 2007), sweet corn (Scholz *et al.* 1998) and irrigated peanuts (P. Hattfield, Arachis Australia, pers. comm.). The efficacy of biopesticides in coastal soybeans is boosted by higher in-crop humidity, and the high spray volumes used (e.g. >200 L/ha), which improves coverage. Lower efficacy has been reported in post-vegetative mungbeans (D. Murray, unpubl. data), primarily because young larvae feed on flowers in preference to leaves, thereby reducing the likelihood of their contacting the biopesticide, before attacking pods (H. Brier, pers. obs.). In contrast, in post-vegetative soybeans and peanuts, young *Helicoverpa* larvae often feed on leaves (Brier 2007) and good control is obtained.

Research continues to investigate fungal biopesticide options for sucking pests in grains and pulses. While initial trials have shown promise against *Creontiades* spp., subsequent evaluations have proved less promising against podsucking bugs, principally *N. viridula* (K. Knight, Monsanto Australia, pers. comm.). Reasons for this inferior performance may be due to in-crop humidity being too low to allow reliable conidiogenesis and subsequent host infection by fungi (Sosa-Gomez and Alves 2000), as well as imperfect coverage of plants in trials with small plot spray applicators (K. Knight, pers. comm.). Recent studies in cotton seem to confirm the potential of fungal biopesticides against *Creontiades* spp. (Mensah and Austin 2008).

### Resistance management

IRM strategies for *H. armigera* have been in place since 1983 (Forrester *et al.* 1993; Rossiter *et al.* 2007). Although primarily

aimed at cotton, the IRM strategy benefits grain crops as it restricts the use of key grain insecticides such as indoxacarb and spinosad on an area-wide basis throughout north-eastern Australia. In chickpea, their use is restricted by setting application cut-off dates, ensuring a gap of one *H. armigera* generation (~42 days) between their last use in chickpea and their first use in cotton, and by limiting the number of sprays per crop to one for indoxacarb and two for spinosad. In summer pulses, there are no time-of-use restrictions, but the number of sprays per crop is limited as for chickpeas. These restrictions benefit IPM because new effective selective insecticides are reserved for the control of *Helicoverpa* spp. at the later more critical flowering/podding stages. Biopesticide use is encouraged during the earlier vegetative stages when crops are better able to compensate for pest damage and when near total control is not necessary. While resistance monitoring indicates a recent stabilisation or decline in resistance levels for most conventional insecticides (Rossiter *et al.* 2007), there is an ongoing need for IPM systems to reduce reliance on insecticides and avoid a repeat of the *H. armigera* resistance crisis of the early 1990s (Forrester *et al.* 1993).

### Changes in the IPM fit of insecticides/biopesticides in grains

Since the 1970s, the IPM fit (i.e. high efficacy against target pests and low negative effects on beneficials) of many insecticides commonly used in grain and pulse crops has improved significantly. The overall impact of insecticides from each era can be quantified by using the impact ratings cited in Wilson *et al.* (2007), where the negative effect of insecticides (expressed as the percentage reduction in abundance compared with an untreated crop) on beneficial species is rated as very low, less than 10%; low, 10–20%; moderate, 20–40%; high, 40–60%; and very high, >60%.

Calculations based on the above ratings show a marked improvement on average in the IPM fit of caterpillar insecticides, from a high average rating of 51% in the 1970s and 1980s, to a low average rating of 16% in 2005–08, due to the availability of newer, more selective insecticides (indoxacarb and spinosad), and the greater use of biopesticides (Wilson *et al.* 2007). In cotton crops, analysis has shown that crops managed with products with lower ratings tended to have higher beneficial populations than those managed with higher ratings, thus supporting the validity of the concept that use of more selective insecticides will help conserve beneficial populations (Mansfield *et al.* 2006). A similar pattern could be expected in grains. In contrast, the IPM impact of sucking pest insecticides remains a high 51%, little different to their 55% rating in the 1970s.

While the impact of dimethoate has been reduced to medium–low for mirids by the use of low rates plus salt (Brier *et al.* 2004), the impact of podsucking bug insecticides has increased because endosulfan, with a medium–high impact rating, was de-registered, and replaced by deltamethrin with a very high impact rating. Note that the calculated impact ratings are the average for the insecticides most commonly used, and make no allowance for the relative quantities used of each pesticide.

IPM practitioners should note that the impact of particular insecticides can vary considerably between beneficial groups,

with indoxacarb having a low impact against *Trichogramma* (Scholz and Zalucki 1999), but a high impact against ladybirds (Wilson *et al.* 2007). Even the very high impact SPs are not universally high, having little impact at rates registered in pulse crops, on brown smudge bug, *Deraeocoris signatus* (Distant), an important aphid, mite and SLW predator (Brier *et al.* 2005; Mensah and Pyke 2007).

### Conservation of natural enemies

The conservation of natural enemies, both native and introduced, is one of the major IPM objectives in north-eastern Australian grain farming systems and takes advantage of species already present in the cropping environment (New 2002). This approach has the advantage of encouraging generalist predators which, if undisturbed, can survive in crops on less important pests or other non-pest prey until major pests such as *Helicoverpa* arrive – the ‘lie-in-wait’ approach (Chang and Kareiva 1999). For *Helicoverpa* spp. the objective is to reduce the frequency of pesticide intervention, and thus delay the development of insecticide resistance (Murray *et al.* 2005a). For SLW, conservation of natural enemies is critical because there are no registered or economically viable pesticide options available in grain crops (Brier *et al.* 2007). For crops at risk of SLW attack in particular, there is a multi-pest focus, where the most selective management of pests other than SLW is critical for the containment of SLW through the conservation of key natural enemies such as *E. hayati*.

Major predatory insects in Australian grain farming systems include predatory beetles, predatory bugs, lacewings, hoverfly larvae, ants (Awan *et al.* 1989; Johnson *et al.* 2000; Mansfield *et al.* 2003) and spiders (Pearce *et al.* 2004). Major egg parasitoids (in terms of incidence if not always effectiveness) include the introduced *Trichogramma* spp. (Scholz 1991; Parker and Scholz 2004; Davies and Zalucki 2008) and *T. basalis* (Clarke 1992). Major caterpillar and pupal parasitoids include native Hymenoptera; *Microplitis demolitor* (Wilkinson) (Murray and Rynne 1992; Franzmann *et al.* 2008), *Netelia producta* (Brullé), *Heteropelma scaposum* (Morley), *Agathis* sp., *Apanteles* sp., *Litomastix* sp., and native tachinids such as *Carcelia* sp. (Zalucki *et al.* 1986; Brier 2007). The tachinid parasite of *N. viridula* adults, *Trichopoda giacomellii* (Blanchard), is now well established (Coombs 2003). Unlike the egg parasitoids, most caterpillar and pupal parasitoids, with the exception of *M. demolitor*, do not kill their host until the pupal stage. As a result, they have little impact on damage inflicted by the generation of caterpillar pests observed in a crop, but as levels of parasitism are frequently very high, they can have a marked impact on the number of pests surviving to the next generation (Titmarsh 1992).

While beneficial refuges (mainly lucerne) have been employed on some cotton farms (Mensah 2002), this approach has been adopted on very few grain farms, largely because the majority are dryland rather than irrigated farms, and lucerne establishment under dryland conditions is more challenging. Pigeon pea might be a more attractive dryland alternative, with the added bonus of being a *Helicoverpa* trap crop. However, refuge crops may also act as beneficial sinks, an issue that needs to be better understood before their wider adoption (Mensah and

Sequeira 2004). Any moves towards habitat management will need to consider the effects of landscape composition and spatial configuration on pests and beneficials, and their movements within the landscape (Schellhorn *et al.* 2008).

The conservation of natural enemies has been greatly assisted by pest-threshold research that has identified pest–crop scenarios where (1) spraying is not warranted (Turner and Brier 1979) or (2) spraying for major primary pests can be delayed until the crop is at lesser risk from secondary pests such as SLW (Brier and Rogers 1991b; Brier *et al.* 2007). Despite promising studies (Grundy and Maelzer 2000; Nicholas and Coutts 2006), augmentative releases of natural enemies in Australian grain crops have not been widely adopted because of high costs, practical limitations of distribution in large fields, and/or because of sometimes doubtful efficacy (Twine and Lloyd 1982).

The contribution of natural enemies is arguably vastly underestimated in north-eastern Australian grain farming systems. Evidence of this is the rapidity with which pests such as *Helicoverpa* spp. can be flared by a single disruptive spray in pulse crops (Brier *et al.* 2005; Knight *et al.* 2007), and by anecdotal evidence of the stabilisation of soybean aphid, *Aphis glycines* Matsumura, and soybean looper, *Thysanoplusia orichalcea* (F.), populations (both exotic pests) by natural enemies (ladybirds, predatory bugs, hoverflies and caterpillar parasitoids) after the spectacularly high initial incursions of these pests (H. Brier, pers. obs; N. Moore, NSW DPI, pers. comm.).

### Classical biological control

Australian grain crop economics (i.e. relatively low crop values, large paddock sizes, and relatively high labour costs) preclude the rearing and inundative or augmentative release of exotic and native parasitoids, a tactic employed in countries with lower labour costs (Bueno and van Lenteren 2002). Also, the relatively small areas (on a global scale) of many of the more pest-susceptible crops, e.g. soybeans, make commercial investment more risky because of the small market size (D. Papacek, Bugs for Bugs, pers. comm.). Exotic biocontrol releases are usually restricted to a limited period of time (e.g. 3–4 years) at selected release sites. After their initial releases, exotic biocontrol agents are largely left to establish and spread to other regions unaided. Classical biocontrol agents for major Australian grain (and other crop) pests are discussed in detail by Waterhouse and Sands (2001) and include the following:

#### Parasitoids for *N. viridula*

*N. viridula* was first recorded in Australia in 1916 and is now a major polyphagous pest (Bailey 2007). Because it is rarely attacked by native parasitoids, *N. viridula* has been the target of several exotic parasitoid import and release programs (Waterhouse and Sands 2001). The egg parasitoid *Trissolcus basalis* (Wollaston) was introduced to Australia in 1933 initially from Egypt (Wilson 1960), and later from elsewhere (Waterhouse and Norris 1987). *T. basalis* has been reported as reducing the incidence of *N. viridula* in southern coastal Australia (Waterhouse and Norris 1987; Waterhouse 1998). However, in north-eastern Australia, *N. viridula* remains a major problem, particularly in grain legumes (Velasco and Walter 1992; Brier 2007), and the effectiveness of *T. basalis* as a biocontrol agent has

been questioned (Clarke 1990, 1992; Waterhouse 1998), as has its negative impact on predatory pentatomids (Loch and Walter 1999). Other introduced *N. viridula* egg parasitoids including *Trissolcus mitsukurii* (Ashmead) in 1962 and *Telenomus chloropus* (Thomson) in 1962 and 1981 (Waterhouse and Norris 1987) have either not been effective or have not established in Australia. Several introductions have been made of *Trichopoda* sp., tachinid parasitoids attacking adults and late-instar nymphs of *N. viridula*. While *Trichopoda pilipes* (F.) and *T. pennipes* (F.) failed to establish (Waterhouse and Norris 1987), *T. giacomellii* is now well established from north-eastern New South Wales to central Queensland (Coombs and Sands 2000; Coombs 2003, 2004; H. Brier, pers. obs.). Because of the protracted time to kill its hosts, *T. giacomellii* has a limited in-crop impact on *N. viridula*, but most likely plays a useful role in reducing survival and fecundity of overwintering *N. viridula* populations (Khan and Murray 2002).

#### Parasitoids for *Helicoverpa* spp. and other noctuids

A range of indigenous parasitic wasps and flies and predatory arthropods attack the eggs and immature stages of *Helicoverpa* spp. in crops (Zalucki *et al.* 1986; Johnson *et al.* 2000). However, they do not always achieve effective biological control and insecticides are widely used to control damaging infestations. Several noctuid pests and *Helicoverpa* spp. in particular, have physiological, behavioural, and ecological characteristics that elevate their pest status and make them difficult targets for consistently effective biological control. These attributes include wide host range, high mobility, high fecundity, and a facultative diapause (Fitt 1989).

Seven hymenopterous parasitoids have been introduced into Australia for biological control of *Helicoverpa* spp. (Waterhouse and Sands 2001). Of these introductions, only the egg parasitoid *Trichogramma pretiosum* Riley has proved to be very effective in some locations (Strickland and Lacey 1996; Parker and Scholz 2004; Davies and Zalucki 2008).

Several larval parasitoids have been introduced against cutworms, armyworms and semi-loopers, but none have proven particularly effective (Waterhouse and Sands 2001). Despite the apparent lack of success of introduced parasitoids, there are occasions when they can cause high mortality (up to 52.3%) of noctuid pests (Broadley 1986; Zalucki *et al.* 1986) and these contributions should not be ignored (Titmarsh 1992).

#### Parasitoids for SLW

Following the discovery of SLW in Australia in 1994 (Gunning *et al.* 1995), biocontrol candidates were considered for release in Australia to supplement native parasitoids (Goolsby *et al.* 2005). *E. hayati* was released in 2004, and while the outcome of this introduction is yet to be determined, preliminary surveys indicate rapid and widespread establishment throughout areas infested with SLW (De Barro and Coombs, in press).

#### Predators

While not specifically introduced under a classical biocontrol program, the generalist coccinellid predator *Hippodamia variegata* (Goeze) was first discovered near Gatton in Queensland in 2000 and quickly spread throughout north-

eastern Australia (Franzmann 2002). While benefits as a generalist aphid predator may be realised, it is not known to what extent *H. variegata* may adversely affect native ladybirds, as has been reported for the introduced *Coccinella septempunctata* L. in the United States (Elliott *et al.* 1996).

#### Economic thresholds (ETs)

ETs are one of the cornerstones of IPM (Stern 1973), as they help rationalise and hopefully reduce, the use of insecticides, thus reducing their impact on beneficial arthropods, selection for resistance and risk of environmental and/or health problems. ETs for many pests in north-eastern Australian grain crops have progressed from qualitative (subjective) recommendations such as 'spray when pests reach damaging levels or are present' (Caldwell 1945), to nominal (fixed) thresholds e.g. two *Helicoverpa* larvae per row metre in soybeans (Turner and Titmarsh 1979), to more recent empirical threshold models of the type described by Norton (1976). As a rule, major pests in major grain crops have better quantified thresholds than the same or lesser pests in minor crops, as research has focussed on major crops with a higher net worth. Thresholds for major pulse crop pests and for major oilseed and cereal crop pests are listed in Tables 1 and 2, respectively.

There has been considerable research to develop threshold models for major pests in the larger grain crops. Key pests targeted have been *Helicoverpa* spp., podsucking bugs, *Creontiades* spp. and *N. vinitor*. Threshold models are available for *Helicoverpa* spp. in chickpeas (Anon. 2007a), in navy beans (D. J. Rogers, unpubl. data), in mungbeans (Brier *et al.* 2008), in soybeans (D. J. Rogers, unpubl. data) and in sorghum (Twine and Kay 1982; Franzmann 2004). Threshold models are also available for podsucking bugs in mungbeans and soybeans (H. Brier, unpubl. data; Brier 2001), for *Creontiades* spp. in mungbeans and soybeans (Brier 2007), and for *N. vinitor* in sorghum (M. Miles, unpubl. data).

The abovementioned threshold models fall into two categories, those based on potential yield loss for *Helicoverpa* spp., *Creontiades* spp. and *N. vinitor*, all Norton (1976) type models, and those based on potential quality loss for podsucking bugs.

These two threshold types are fundamentally different in concept. The yield-based thresholds cited for flowering, podding and heading crops are Norton (1976) type models ( $ET = C/V \times D/1000$ ) where the 'break even' pest population is calculated for an array of control costs and crop values, and where C = cost of control (\$/ha), V = crop value (\$/t), D = potential yield loss (kg/ha per pest/m<sup>2</sup>) and 1000 converts yield loss in kg/ha to t/ha.

For the yield-based thresholds cited above, reductions in crop value due to yield loss are greater than downgrades due to reduced seed quality. However, the reverse holds for podsucking bugs, where thresholds are governed by potential reductions in seed quality. Because the penalties for even slightly exceeding critical seed damage levels (usually only 2%) are many times greater than the cost of control, action thresholds are typically set at 70–75% below the critical podsucking bug population likely to cause 2% damage (Brier *et al.* 2007). As quality penalties are based on % damage, potential crop size must be estimated, and small crops with fewer seeds are at greater risk of requiring spraying to

prevent economic loss, having thresholds as low as 0.3 bugs/m<sup>2</sup> (Brier 2001, 2007).

From an IPM perspective, the low quality-based threshold for podsucking bugs in summer pulses are problematic. The increased marketing of soybeans for human consumption, rather than for stockfeed (James and Rose 2004), and the pursuit of premium markets in all summer pulses, has seen increased spraying for podsucking bugs with the only effective registered insecticide, deltamethrin (I. Crosthwaite and J. Plath, Bean Growers Australia, pers. comm.; Brier *et al.* 2007). However, research has shown that spraying can be delayed until early podfill, thus reducing the risk of SLW attack (Brier 2007), without compromising seed quality (Brier 2001). Nevertheless, it would be preferable if the natural enemies present in crops at early podding were not disrupted but allowed to eventually disperse to other, later-maturing crops in the farming system.

The many podsucking bug species attacking some crops poses the challenge of accounting for multiple species. While individual species may be present at below threshold levels, their combined damage may be economically significant. Because all species inflict the same type of damage, the concept of 'injury equivalency' (Hutchins *et al.* 1988) has been applied to the podsucking bug complexes to help overcome this problem. Thresholds are expressed as *N. viridula* adult equivalents (Brier 2007), and the damage potentials of podsucking bug populations are adjusted for species and bug stages (nymphs and adults) with a computer model. The model incorporates data from species comparison trials in mungbeans and soybeans (H. Brier, unpubl. data), *N. viridula* nymph damage potentials collated by Brier (2001) from data generated by Todd and Turnipseed (1974), McPherson (1979) and Bowling (1980) and *N. viridula* nymphal mortality studies by Stam (1987). The bug-stage adjustment in particular benefits IPM, as the model suggests that most late infestations of young nymphs have insufficient time to inflict critical damage and thus spraying is not warranted.

Recent threshold studies have benefited IPM by identifying pest-crop scenarios where economic damage is not inflicted, despite previous industry perceptions, and/or despite highly visible damage symptoms at the time of pest infestation. Examples in north-eastern Australia where pests have been shown to have no impact on yield or harvest maturity include *T. tabaci* in spring mungbeans (Brier 2007), *Creontiades* spp.  $\leq 6/m^2$  in soybeans (Brier 2007), and *H. armigera*  $\leq 6/m^2$  in flowering mungbeans (Brier *et al.* 2008). In the first two examples, spraying is no longer recommended, the latter in particular benefiting SLW management in soybeans. Unpublished threshold studies (D. J. Rogers, unpubl. data) show that up to 7 *Helicoverpa* larvae/m<sup>2</sup> can be tolerated in vegetative soybeans without yield loss. This suggests that  $>7$  *Helicoverpa*/m<sup>2</sup> can be managed with biopesticides in vegetative soybeans, as populations have only to be lowered to 7/m<sup>2</sup> to maintain yield potential.

These studies have improved the grain industry's understanding of basic crop physiology, especially the crop's capacity to compensate for pest damage and of particular crop-damage risk factors. Ongoing *Helicoverpa* threshold studies in reproductive mungbeans (H. B. Brier, unpubl. data) show this

crop has a far greater compensatory capacity than is acknowledged by most agronomists, with no yield loss at any crop reproductive stage for up to 6.6 larvae/m<sup>2</sup> in an irrigated crop, and no yield loss at flowering at up to 8 larvae/m<sup>2</sup> in a well grown dryland crop. However, there was a significant reduction in yield at late podfill in the dryland crop. The data also indicate that moisture-stressed mungbeans are at greater risk of delayed or uneven harvest if suffering severe bud or flower damage, as a higher percentage of these structures will be eaten than in well watered crops with many more reproductive structures.

The impact of growing conditions on thresholds needs to be considered in all crops, as moisture stress has also been shown to increase the damage potential of pests in soybeans (Szmedra *et al.* 1990) and sunflowers (Forrester and Saini 1982), and is thought to be important in chickpeas (M. Miles, pers. obs.).

Despite the progress outlined above, Tables 1 and 2 show there are still many significant threshold gaps for north-eastern Australian grain crops. Pests requiring more refined thresholds include SLW in soybeans, *M. vitrata* in mungbeans, cluster caterpillar, *Spodoptera litura* (F.), in soybeans, loopers (various species which are more prevalent in new coastal grain-growing regions) in mungbeans and soybeans, and aphids, mainly corn aphid, *Rhopalosiphum maidis* (Fitch), and oat aphid, *R. padi* (L.), in cereals. While no insecticides are registered for SLW in soybeans, knowing the pest density/damage relationships for current cultivars would assist in SLW management, as SLW may be less damaging than is first estimated by growers (Bueno *et al.* 2005).

Future threshold studies should ideally evaluate the impact of crop cultivar on pest damage and thresholds. While this may seem onerous, most current threshold models assume rates of pest damage are constant across cultivars. However, this is not necessarily so, as recent studies (H. Brier, unpubl. data) show *N. viridula* damaging twice as many seeds in small-seeded Nato soybean cultivars, than in the large-seeded culinary cultivar Bunya. Given the marked physiological variation between cultivars in many Australian grain crops (C. Douglas; A. Cruickshank, QDPI&F; A. James, CSIRO, pers. comm.), it is highly likely there will also be differences in their ability to compensate for pest damage. The limitations of simple threshold models, which ignore cultivar and other important factors, have long been recognised (Szmedra *et al.* 1990). The challenge is to develop more realistic guidelines that are not so overly complicated as to be unacceptable by industry.

A weakness of many current thresholds is the underlying assumption of near 100% survival of pests. This assumption may lead to overestimation of the damage potential of many pest populations because the frequently very high natural mortality of eggs and earlier instar larvae or nymphs is overlooked, even though it has been well documented in cotton and grains (Titmarsh 1992). Mortality is factored into control decisions for *Helicoverpa* in chickpeas (Anon. 2007a) and podsucking bugs (Brier 2007). In practice in many crops, sampling inefficiencies as reported for *Helicoverpa* in soybeans (Duffield *et al.* 2005) may underestimate pest pressure, thereby cancelling out the reduction in the pest's damage potential due to larval mortality as reported by Titmarsh (1992). An approach developed to help incorporate beneficial abundance in threshold decisions is the beneficial-to-pest ratio concept of Mensah (2002),





|   |                             |                         |                          |                          |                          |                          |                          |
|---|-----------------------------|-------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Bean podborer<br>( <i>Maruca vitrata</i> )  | Value/Range                 | Not a pest in this crop | 3/m <sup>2</sup>         | 3/m <sup>2</sup>         | 3/m <sup>2</sup>         | Not damaging in soybeans | Not damaging in peanuts  |
|   | Type                        |                         | Nominal                  | Nominal                  | Nominal                  |                          |                          |
|   | Rate of damage <sup>B</sup> |                         | Not quantified           | Not quantified           | Not quantified           |                          |                          |
|   | Crop stage                  |                         | Flowering to podding     | Flowering to podding     | Flowering to podding     |                          |                          |
|   | Source                      |                         | Unknown                  | Unknown                  | Unknown                  |                          |                          |
| Flower thrips<br>[ <i>Franklinella schultzei</i> ,<br><i>Thrips imuginis</i> ,<br><i>F. occidentalis</i> ] <sup>C</sup> | Value/Range                 | Not a pest in this crop | 4–6/flower               | 4–6/flower               | 4–6/flower               | 4–6/flower               | 4–6/flower               |
|   | Type                        |                         | Nominal                  | Nominal                  | Nominal                  | Nominal                  | Nominal                  |
|   | Rate of damage <sup>B</sup> |                         | Not quantified           | Not quantified           | Not quantified           | Not quantified           | Not quantified           |
|   | Crop stage                  |                         | Flowering                | Flowering                | Flowering                | Flowering                | Flowering                |
|   | Source                      |                         | Unknown                  | Unknown                  | Unknown                  | Unknown                  | Unknown                  |
| Two-spotted mite<br>( <i>Tetranychus urticae</i> )  | Value/Range                 | Not a pest in this crop | 30% of leaves infested   | 30% of leaves infested   | 30% of leaves infested   | 30% of leaves infested   | 30% of leaves infested   |
|   | Type                        |                         | Nominal                  | Nominal                  | Nominal                  | Nominal                  | Nominal                  |
|   | Rate of damage <sup>B</sup> |                         | Extrapolated from cotton | Extrapolated from cotton | Extrapolated from cotton | Extrapolated from cotton | Extrapolated from cotton |
|   | Crop stage                  |                         | Flowering to podding     | Flowering to podding     | Flowering to podding     | Flowering to podding     | Flowering to podding     |
|   | Source                      |                         | Wilson (1993)            | Wilson (1993)            | Wilson (1993)            | Wilson (1993)            | Wilson (1993)            |

<sup>A</sup>The main pod-sucking bug species in north-eastern Australia are, in order of importance (damage and incidence), *Nezara viridula*, *Riptortus serripes*, *Melanacanthus* sp., *Piezodorus oceanicus*, and *Dictyotus caenosus*. Thresholds are in green vegetable bug (*Nezara viridula*) adult equivalents.

<sup>B</sup>Quality thresholds are based on pod-sucking bug population required to inflict 2% seed damage, a critical damage level above which pulses in north eastern Australia are downgraded by typically  $\geq$ \$100/t. Typically the action threshold is set at 70% of the critical bug population to ensure the critical 2% damage threshold is not exceeded.

<sup>C</sup>*Franklinella occidentalis* (western flower thrips) has been recorded in many pulse crops including peanuts and has the potential to be very damaging in the latter crop because of its ability to transmit tomato spotted wilt virus (TSWV). The quoted threshold does not apply as *F. occidentalis* is resistant to the current thrips pesticide (dimethoate<sup>®</sup>) and the number of thrips to initiate a TSWV outbreak in a crop is many orders of magnitude below that for the yield-based thrips per flower threshold (Brown *et al.* 1996).

**Table 2. Summary of thresholds for oilseed and cereal crops**

Grey shading indicates where the threshold model was based on regression data for that crop

| Pest  | Threshold                   | Sunflower                         | Canola                               | Winter cereals                                 | Maize                        | Sorghum  |
|---|-----------------------------|-----------------------------------|--------------------------------------|--|------------------------------|--|
| <i>Helicoverpa</i> spp.                                 | Value/Range                 | >2 small or >1 medium larva/plant | ≥5–10 mm long larvae/m <sup>2</sup>  | 4–10 larvae/m <sup>2</sup>                     | Not controlled in most crops | 1–3 larvae/head                                      |
|   | Type                        |                                   |                                      | Empirical model                                |                              | Empirical model                                      |
|   | Rate of damage <sup>A</sup> | Nominal                           | Nominal                              | 1.5 g grain loss/larva                         |                              | 2.4 g grain loss/larva                               |
|   | Crop stage                  | Budding                           | Mid-podding                          | Head emergence – harvest                       |                              | Post-flowering                                       |
|   | Source                      | Forrester (1980)                  | Hertel and Roberts (2007)            | Extrapolated from sorghum data                 |                              | Franzmann (2004)                                     |
| Diamond back moth ( <i>Plutella xylostella</i> )        | Value/Range                 | Not a pest in this crop           | 17–23 larvae/10 plants               | Not a pest in this crop                        | Not a pest in this crop      | Not a pest in this crop                              |
|   | Type                        |                                   |                                      |  |                              |  |
|   | Rate of damage <sup>A</sup> |                                   | Nominal                              |  |                              |  |
|   | Crop stage                  |                                   | Mid to late flowering                |  |                              |  |
|   | Source                      |                                   | Hertel and Roberts (2007)            |  |                              |  |
| Rutherglen bug ( <i>Nysius vinitor</i> )                | Value/Range                 | 10–25 adults/plant pre-flowering  | 10 adults or 20 nymphs/plant         | Not known to be a pest                         | Not known to be a pest       | 20–25 bugs/head                                      |
|   | Type                        |                                   |                                      |  |                              | anthesis <sup>A</sup> ; 25–40 bugs/head milky dough; |
|   | Rate of damage <sup>A</sup> |                                   |                                      |  |                              | 30–50 bugs/head soft dough                           |
| Aphids ( <i>Rhopalosiphum maidis</i> , <i>R. padi</i> ) | Value/Range                 | 20–50 adults/plant                | Nominal                              | 90% plants infested and <2 predators per plant | Not controlled in most crops | M. Miles (unpubl. data)                              |
|   | Type                        |                                   |                                      |  |                              |  |
|   | Rate of damage <sup>A</sup> | Post-flowering                    | Flowering, pod filling               |  |                              |  |
|   | Crop stage                  | Post-flowering                    | Hertel and Roberts (2007)            |  |                              |  |
|   | Source                      | Franzmann (2007a)                 | >50% of plants with clusters on stem |  |                              |  |
|   | Value/Range                 | Not a pest in this crop           |                                      |  |                              |  |
|   | Type                        |                                   |                                      |  |                              |  |
|   | Rate of damage <sup>A</sup> |                                   | Nominal                              |  |                              |  |
|   | Crop stage                  |                                   | Flowering, early pod set             |  |                              |  |
|   | Source                      |                                   | Hertel and Roberts (2007)            | Elder <i>et al.</i> (1992)                     |                              |  |

<sup>A</sup>Data are preliminary and require field validation.

which established a ratio of beneficials to pests above which pests (*Helicoverpa* spp.) in cotton were unlikely to require control. This approach may also have application in grain crops.

### Sampling

Since the late 1970s, sampling protocols for many key grain pests have been steadily refined and widely promoted and adopted (Anon. 2007b, 2007c, 2007d). The adoption of beat cloth sampling, and the standardisation of beat sheet dimensions and sampling protocols in row crops, has significantly improved sampling reliability and accuracy for *Creontiades* spp., pod sucking bugs, *Helicoverpa* spp. and beneficial invertebrates (Wade *et al.* 2006; H. Brier, D. Murray, unpubl. data). Having a standardised sampling method has facilitated the implementation of empirically derived threshold models, particularly in pulses (G. Cumming, Pulse Australia, pers. comm.).

Impetus for the development and promotion of improved sampling protocols has been provided by the emergence of previously unrecognised pests such as *Creontiades* spp. in mungbeans (Anon. 2007c), the expansion of grain crops into new production regions with little to no previous sampling experience (AOF 2005), and an increased awareness of the need to detect pests such as *H. armigera*, before they are too large to control with current insecticides and biopesticides (D. Murray, pers. obs.; G. Cumming, pers. comm.). Recent sampling research in grain crops has demonstrated the superiority of beat-cloth sampling over suction sampling and sweep netting in terms of efficiency and precision (Anon. 2007c) for most pest and beneficial insects (H. Brier, unpubl. data), matching the findings of Wade *et al.* (2006) in cotton. For *Creontiades* spp., this research has exposed the unreliability of visual sampling in mungbeans, as previously employed by many cotton consultants.

Wherever possible, pest distribution data have been collated and analysed using Taylor's power law to develop sequential sampling plans for key pests, including *Creontiades* spp., pod sucking bugs and *Helicoverpa* spp. (Anon. 2007c, 2007d), and to justify minimum sampling requirements for these pests. These data have highlighted to industry the need for intensive sampling to accurately assess populations of younger *N. viridula* nymphs ( $\leq$  early 4th instar) whose spatial distribution is extremely clumped (Anon. 2007d), and which are usually the most abundant bug stage present at early podfill, the recommended time for spraying above-threshold pod sucking bug populations in pulses (Brier 2007).

Further sampling research and development is required for problematic pests such as *M. vitrata* in mungbeans, which feed in flowers before attacking pods (Anon. 2007c), and for SLW in soybeans. A 'quick' but reliable SLW rating scheme in soybeans would allow for industry self rating and, with appropriate calibration and ground truthing by scientists, would facilitate the gathering of long-term abundance data, critical for assessing the efficacy or otherwise of IPM tactics aiming to manage this pest in susceptible crops.

### Cultural controls

Various cultural controls have figured prominently as pest management tools in broadacre cropping. Examples of tactics

adopted by grain and cotton growers include cultivation to destroy overwintering *H. armigera* pupae (Fitt 1994), the use of disease-free seed to minimise the spread of disease by insect vectors (M. Ryley, QDPI&F, pers. comm.), adjusting the time of planting to avoid periods of peak pest pressure (Franzmann *et al.* 2008), crop rotations and weed management to reduce the availability of alternate or successive hosts of problematic pests such as thrips [which are also vectors of tobacco streak virus (Anon. 2006)], two-spotted spider mite, *Tetranychus urticae* Koch (Wilson 1993), and white fringed weevil, *Naupactus leucoloma* Boheman, a damaging pest of peanuts and other legumes (Anon. 2007d). Some less widely used tactics, or those currently being evaluated include adjusting sowing rates to compensate for pest damage or make the crop less attractive (Berlandier and Bwyne 1998; J. van Leur, NSW DPI, pers. comm.), the use of press wheels to increase soil density and reduce soil insect access to seed (Radford and Allsopp 1987), and irrigation management to maintain surface soil moisture to minimise *E. behrii* infestations of peanut pods (Brier *et al.* 1999). In extreme circumstances, the ultimate cultural practice has been to avoid crops susceptible to the pest in question, as occurred in the Emerald Irrigation Area with a switch from soybeans to less susceptible grain crops (Moore *et al.* 2004) following the major SLW outbreak of 2002 (Sequeira and Naranjo 2008). However, lower SLW activity in recent years may see a reversal of this trend with renewed interest in soybeans (S. Maas, QDPI&F, pers. comm.).

### AWM: *Helicoverpa* and SLW

For the most part, insect pests of broadacre farming have been managed field-by-field or farm-by-farm, with little or no regard for issues on neighbouring properties that may have consequences for the individual's own farm, or the consequences of individual management actions on neighbours' pest management strategies. However, there have been examples where regional or AWM strategies have been developed to help in the management of particular pests. For instance, Sequeira (2001) developed a regional management program for *Helicoverpa* spp. in the Emerald Irrigation Area in 1997 because of the need to have a preemptive resistance management strategy for the area to facilitate the introduction of *Bt* cotton. In these areas, chickpea trap crops were used as a sink for *H. armigera* populations that developed through winter on other crops and weeds. This was complemented by use of a late summer pigeon pea trap crop, which is highly attractive to *H. armigera* emerging from the soil beneath finishing cotton crops. These moths may carry genes for insecticide or *Bt* resistance, and concentrating them into pigeon pea trap crops allows them to be controlled by destruction and cultivation of the crop.

Another example of an area-wide approach to pest management comes from the mixed cropping (cotton and grains) region of the Darling Downs where, in the late 1990s, insect pest management was in crisis. Overwhelming pest pressure, combined with widespread insecticide resistance and secondary pest outbreaks pushed seasonal insecticide costs in cotton up to AU\$1000/ha. Murray *et al.* (2005b) implemented an AWM strategy on the Darling Downs in response to a

deteriorating *Helicoverpa* spp. management situation. Poor communication between growers of different crops meant that there was no coordinated effort to manage this pest across crop types. The AWM approach provided a framework in which to coordinate efforts to manage the pest across the region by using understanding of the pest's ecology to reduce abundance. For example, attempts were made to concentrate the spring generation onto chickpea trap crops where they could be controlled by crop destruction (Ferguson *et al.* 2000; Ferguson and Miles 2002). The major achievement of this project was to create an understanding among the grain and cotton growers that *H. armigera* needed to be managed at a regional level. The understanding centred on the principle that an area-wide approach was necessary for the successful management of pests that breed locally and have a wide host range, as advocated earlier by Zalucki *et al.* (1986).

This appreciation of the benefits of an area-wide approach have flowed on to shape the approaches taken with SLW and potentially other pests that meet the above criteria. For example Knight and Gurr (2007) canvass the possibility of using sacrificial trap crops to concentrate podsucking bugs in areas away from main crop plantings, as well as the use (when they become available) of softer insecticides to foster parasitoids attacking *N. viridula*. Finally, the profitability of adopting IPM on an AWM scale has been demonstrated in a 3-year study of a cotton and grains farming system in north-western New South Wales (Hoque *et al.* 2002).

#### Host plant resistance (HPR)

##### HPR to insect pests

HPR to sorghum midge, *Stenodiplosis sorghicola* (Coquillett), has been an outstanding Australian IPM and plant breeding success (Franzmann *et al.* 2008). However, HPR to insect pests has not been adopted or pursued in other grain crops. Despite considerable interest in HPR to *Helicoverpa* in soybeans in the 1980s, this research based on Asian soybean lines PIs 171451, 227687 and 229358 has been abandoned, both in the United States and Australia. The reason is that the leaf antibiosis recorded by Brier and Rogers (1991a) merely prolonged larval development, thereby placing crops at greater risk of yield loss. Prasadja (1993) showed that because larvae feeding on 'resistant' lines reach a damaging size ( $\geq 4$ th instar) later in the crop's reproductive development, plants are less able to compensate for damage, and that supposedly 'resistant' lines suffer greater yield losses than 'susceptible' lines. For pests such as *B. tabaci* and *A. glycines*, HPR is a potential future IPM tactic with significant resistance reported in soybeans to *B. tabaci* (Valle and Lourencao 2002) and to *A. glycines* (Hill *et al.* 2004; Li 2007).

##### HPR to insect-transmitted diseases

While not targeting insects directly, HPR is an effective strategy to combat many diseases transmitted by insects. In north-eastern Australia, the HPR approach has been proposed for tobacco streak virus in chickpeas, mungbeans and sunflowers (M. Ryley, pers. comm.) and for tomato spotted wilt virus in peanuts (G. Wright, Peanut Co. of Australia, pers. comm.), both of which are transmitted by thrips. Targeting the disease rather than the vector reduces the spraying of thrips vectors, an approach

which is of dubious efficacy and cost effectiveness, and which selects for resistance in the vector (Brown *et al.* 1996).

#### Genetically modified (GM) crops

To date, there has been strong consumer resistance to the introduction in Australia of GM grain crops of any type, particularly for human consumption (A. Boundy, Blue Ribbon Seeds, pers. comm.). This has been influenced by perceptions in countries importing Australian products (particularly Europe and Japan), as much as by perceptions in Australia. There are currently no examples of GM grain crops to control insect pests in Australia, which is in stark contrast to the United States where large areas of *Bt* maize and soybean are grown.

As mentioned previously, the advent of *Bt* cotton (Ingard<sup>®</sup> containing Cry1Ac and Bollgard II<sup>®</sup> containing Cry 1Ac and Cry 2Ab) has had a marked impact on IPM in grain and cotton farming systems throughout north-eastern Australia, by greatly reducing the number of insecticide sprays applied to cotton, thereby conserving beneficial insects and reducing secondary pest problems (Pyke and Doyle 2006; Pyke 2007). Alternatively, the reduction of broad-spectrum *Helicoverpa* spp. sprays in *Bt* cotton has favoured the survival of sucking pests such as *Creontiades* spp. and podsucking bugs which were previously controlled in cotton crops by sprays applied against *Helicoverpa* spp. (Lei *et al.* 2002).

#### Conveying the IPM message – development and extension

Pivotal to the adoption of IPM and AWM in north-eastern Australia have been the strong 'grass-root' links between researchers, extension officers, consultants, growers and key industry bodies such as Pulse Australia. These links have (1) allowed the rapid dissemination and adoption (as industry preferred practice) of the latest research findings, (2) provided researchers with feedback regarding the practicality of their IPM tactics and (3) highlighted IPM issues of greatest concern to industry. Importantly, IPM extension in north-eastern Australia has been underpinned by Australian research data from a continuum of IPM research, development and extension projects in both grains and cotton.

Recent examples of development and extension IPM initiatives include (1) AWM grower groups formed on the Darling Downs in the early 2000s (Murray *et al.* 2005b), (2) the accredited Chickpea and Mungbean Agronomist courses (Anon. 2007b, 2007c), and (3) the Coastal Soybean/Pulse Break Crop IPM courses (Anon. 2007d, 2008). The latter course has been adapted for summer pulses grown in Southern Australia. As well as providing detailed information on specific issues e.g. identification, thresholds, sampling, beneficials, pest ecology, pesticide selection and application, the above courses explore the basic principles and theory of IPM, and the dangers of relying solely on insecticides. Importantly, these courses promote multi-pest IPM strategies that aim to maximise the effectiveness of native and introduced natural enemies, especially those targeting *H. armigera* and SLW. Through the Grains Research and Development Corporation's (GRDC) National Invertebrate Pest Initiative (NIPI), experience gained in conducting these IPM courses in north-eastern Australia is being shared with IPM practitioners in grain crops in southern Australia, and course

formats adopted and adapted where appropriate (G. Fitt, CSIRO; J. Bellati, SARDI, pers. comm.).

These courses have identified major gaps in IPM capacity in north-eastern Australia, e.g. 75% of consultants were not able to immediately recognise 50% of the most common insects in summer pulses (H. Brier, unpubl. data), highlighting the need for ongoing training. However, the courses have resulted in a marked reduction in pest damage and corresponding increase in crop quality and value, particularly in coastal soybeans (Rule *et al.* 2007). Complementing the above development and extension is the written and visual documentation of most of the major and minor north-eastern Australian grain pests (Brier 2007; Franzmann 2007a, 2007b; Miles *et al.* 2007; Murray 2007). Major outbreaks of sporadic pests such as soybean moth, *Aproaerema simplexella* (Walker), have been documented (Brier 1998) as have new pests occurring in new production areas e.g. *Mocis* and *Pantylia* spp. loopers in coastal soybeans (Brier *et al.* 2007). As such, the above development and extension initiatives have an important biosecurity role. Other examples of IPM that have been developed and widely extended in north-eastern Australia include IPM for lucerne aphids (Turner and Franzmann 1978), IPM for false wireworms in central Queensland (Robertson 1993) and IPM for sweet corn (Scholz *et al.* 1998).

### Conclusions and future IPM developments in north-eastern Australian grain farming systems

IPM strategies discussed above are summarised in Table 3 and gaps in knowledge are also emphasised. In general, IPM in north-eastern Australian grain farming systems has progressed significantly since the 1970s, primarily due to the registration of new, more selective insecticides and biopesticides for caterpillar pests (Murray *et al.* 2005a; Franzmann *et al.* 2008), increased recognition of the significant role of beneficials, the development and validation of sampling techniques, the development of validated threshold models that have raised the action thresholds for *Helicoverpa* spp. (Franzmann 2004; Anon. 2007a; Brier *et al.* 2007, 2008), and have identified pest-crop scenarios where pest control is not required due to plant compensation (Brier 2007; Brier *et al.* 2007). These developments have reduced the disruption of native and exotic beneficial insect populations, which may lead to fewer pest outbreaks. However, the impacts of the recent drought and the widespread adoption of Bollgard II<sup>®</sup> on pest populations in grain crops are just two factors that require further investigation, particularly regarding their effect on *Helicoverpa* spp. populations at a landscape level (Maelzer and Zalucki 2000; Zalucki and Furlong 2005).

The capacity to implement IPM effectively in north-eastern Australia has been further strengthened by at least two classical biological control events, notably the establishment and spread (natural and inundative release) of *T. pretiosum* to control *Helicoverpa* sp. (Parker and Scholz 2004; Murray *et al.* 2005b) and *P. xylostella* (Liu *et al.* 2004) and the importation of *E. hayati* to control SLW (De Barro and Coombs, in press). The arrival of SLW in Australia has been a major incentive for the uptake of IPM, as its track record for rapidly developing insecticide resistance emphasises the need for non-insecticide multi-pest IPM.

However, many important IPM gaps are yet to be filled (Tables 1–3). Perhaps the most pressing IPM gap is the lack of highly selective but effective insecticides or biopesticides for podsucking bugs and *Creontiades* spp. Because of the low thresholds for podsucking bugs, it is likely that intervention tactics will always be needed for these pests in pulse crops. As mentioned previously, none of the new chemistry evaluated to date in grains or cotton for control of these pests has an IPM fit. While biopesticides targeting podsucking bugs have not been promising to date, this tactic should not be abandoned and success may come with more virulent strains and/or more robust formulations better suited to the rigours of commercial application (K. Knight, pers. comm.).

An effective insecticide or biopesticide option is also required for *P. oceanicus* which cannot be effectively controlled with current insecticides, as well as to elucidate why the addition of salt lifts the performance of some insecticides against this and other pests. There is also a pressing need to find a dimethoate replacement for mirid and aphid management, because there is a high probability that organophosphate products such as dimethoate will be de-registered in the near-to-mid future (APVMA 2008).

The podborers *M. vitrata* and *E. behrii* remain problematic pests, with no selective registered insecticides to counter heavy infestations. While the feeding of both species inside flowers and pods precludes the use of biopesticides, novel products such as Magnet<sup>®</sup> (Ag Biotech Australia, Richmond, NSW), a moth attractant developed for the management of *Helicoverpa* spp. in cotton (Del Socorro *et al.* 2003), are a potentially less disruptive option, as only a proportion of the crop is treated (Grundy *et al.* 2006). While trials show that both species are attracted to Magnet<sup>®</sup> (H. Brier, unpubl. data) further research is required to determine if this or similar products can reduce moth populations sufficiently to significantly reduce pod damage, and (by default) to also determine their ETs (Grundy *et al.* 2006).

While a range of effective insecticides are currently available for control of *H. armigera* in Australian grain crops, the risk of resistance is ever present, and further evaluation of new insecticide groups is justified. Selection pressure on existing moderately selective insecticides (indoxacarb and spinosad) could be further reduced by using thresholds to further extend the biopesticide envelope. For example, current *Helicoverpa* thresholds mostly assume a constant rate of damage at all crop reproductive stages. Research in mungbeans (H. Brier, unpubl. data) suggests crops can compensate for early reproductive damage but this needs to be tested under a range of growing conditions, particularly where soil moisture is limited. Similarly, Prasadja (1993) in studies in the United States, has shown soybeans can compensate for damage to the crop's early reproductive stages, but this is contradicted by Australian data (D. J. Rogers, unpubl. data) and also requires clarification. Nonetheless, data to date suggest thresholds in many crops could be raised sufficiently to make biopesticides a viable option during flowering and early podding.

Further research is also required to quantify looper (*Trichoplusia*, *Chrysodeixis* and *Mocis* spp.) damage in pulses, particularly in mungbeans where loopers are known to attack flowers. The current nominal looper threshold is not much greater than the new validated mungbean threshold for *Helicoverpa*,

**Table 3. Pest x IPM tactic reference table for selected common grain crop pests in north eastern Australia as at mid 2008**  
 Grey shading is the IPM gap or problem. SP, synthetic pyrethroid; OP, organophosphate insecticide; ?, unknown or debatable effectiveness

| Pest (Species, Order: Family)   | Crops attacked            | Pest status <sup>A</sup> , frequency and origin | Thresholds (See also Tables 2, 3)           | Effective predators | Effective parasitoids    | Selective pesticides               | Effective biopesticides | Resistance and groups   | Greatest risk period                 |
|---|---------------------------|---|---|---------------------|--------------------------|------------------------------------|-------------------------|-------------------------|--------------------------------------|
| <i>Helicoverpa armigera</i> , Lepidoptera: Noctuidae  | Cereals, oilseeds, pulses | Major, regular, global                          | ET <sup>B</sup> models for most major crops | Yes                 | Yes, <i>T. pretiosum</i> | Yes                                | Yes                     | SP, OP, Carbamates      | All but prefer flowering and podding |
| <i>Helicoverpa punctigera</i> , Lepidoptera: Noctuidae  | Oilseeds, pulses          | Major, regular, native                          | ET models for most crops                    | Yes                 | Yes                      | Yes                                | Yes                     | No                      | All but prefer flowering and podding |
| Armyworms: <i>Leucania</i> and <i>Spodoptera</i> spp., Lepidoptera: Noctuidae                   | Cereals, pasture          | Moderate, regular, native                       | Nominal <sup>C</sup>                        | Yes                 | Yes                      | No                                 | No                      | No                      | Grain ripening                       |
| <i>Morua virata</i> , Lepidoptera: Pyralidae  | Pulses                    | Major, irregular, global                        | Nominal                                     | ?                   | ?                        | No                                 | No                      | No                      | Flowering and podding coastal crops  |
| <i>Etiella behrii</i> , Lepidoptera: Pyralidae  | Pulses mainly peanuts     | Major, irregular, native                        | No  | No                  | Not in peanuts           | No                                 | No                      | No                      | Late podfill in drought years        |
| Loopers: <i>Chrysodictis</i> , <i>Thysanoplusia</i> & <i>Mocis</i> spp., Lepidoptera: Noctuidae | Pulses, oilseeds          | Moderate, irregular, native, exotic             | Nominal                                     | Yes                 | Yes                      | Yes                                | Yes                     | No                      | Flowering and podding                |
| <i>Spodoptera litura</i> , Lepidoptera: Noctuidae   | Pulses                    | Moderate, irregular                             | Nominal                                     | Yes                 | ?                        | No                                 | No                      | No                      | Podding                              |
| <i>Approaerema simplexella</i> , Lepidoptera: Gelechiidae                                       | Soybeans                  | Minor but sporadic major outbreaks, native      | No  | Yes                 | Yes                      | No                                 | No                      | No                      | Podding                              |
| <i>Nezara viridula</i> , Heteroptera: Pentatomidae  | Pulses, oilseeds          | Major, regular, global                          | ET models for most crops                    | Yes                 | ?                        | No                                 | No                      | No                      | Podding to harvest                   |
| <i>Piezodorus oceanicus</i> , Heteroptera: Pentatomidae   | Pulses, oilseeds          | Major, regular, endemic                         | ET models for most crops                    | Yes                 | ?                        | No                                 | No                      | Tolerant to SPs         | Podding to harvest                   |
| <i>Crematodes</i> spp., Heteroptera: Miridae  | Pulses                    | Major, regular, native                          | ET models for mungbeans and soybeans        | ?                   | No                       | Moderately selective               | No                      | No                      | Flowering and early podding          |
| <i>Nysius vinitor</i> , Heteroptera: Miridae  | Oilseeds, cereals, pulses | Major, regular, native                          | ET models for sorghum                       | ?                   | No                       | No                                 | No                      | No                      | Grain and podfill                    |
| <i>Bemisia tabaci</i> , Homoptera: Aleyrodidae  | Pulses, oilseeds          | Major, irregular, exotic                        | No  | Yes                 | Yes                      | No                                 | No                      | SP, OP, Carbamates      | Flowering and podding                |
| <i>Aphis glycines</i> , Homoptera: Aphididae  | Soybean                   | Major, irregular, exotic                        | US based thresholds (for soybeans)          | Yes                 | No                       | Permit for pirimicarb <sup>D</sup> | No                      | No but always potential | Flowering and podding                |

|   |                  |                                       |                |     |    |                         |    |  |   |
|---|------------------|---------------------------------------|----------------|-----|----|-------------------------|----|--|---|
| <i>Thrips tabaci</i> ,<br>Thysanoptera:                               | Mungbean         | Minor, irregular,<br>global           | Not applicable | ?   | ?  | No                      | No | No   | Seedling spring<br>crops                      |
| Thripidae<br><i>Franklinella schultzei</i> ,<br>Thysanoptera:         | Pulses           | Moderate, irregular                   | Nominal        | ?   | ?  | No                      | No | No   | Flowering                                     |
| Thripidae<br><i>Franklinella occidentalis</i><br>(WFT), Thysanoptera: | Pulses           | Potentially major,<br>regular, exotic | No             | ?   | ?  | No                      | No | SP, OP,<br>Carbamates                                  | Peanuts at risk<br>from TSWV<br>spread by WFT |
| Thripidae<br><i>Tetranychus urticae</i> ,<br>Acarina: Tetranychidae   | Pulses, oilseeds | Major, irregular,<br>global           | Nominal        | Yes | No | Moderately<br>selective | No | OP,<br>SP, Potential<br>for<br>abamectin<br>resistance | Podding to late-<br>podfill                   |

<sup>A</sup>Major, having a major impact on yield and/or crop quality, because of the type of damage and/or sheer weight of pest numbers; Moderate, damage usually less severe and having less impact on yield and quality than that inflicted by major pests; Minor, damage usually inconsequential except in rare instances.

<sup>B</sup>ET models incorporating crop value and control costs, as well as quantified pest damage.

<sup>C</sup>Nominal non-validated fixed values.

<sup>D</sup>Emergency permit for primicarb available as at mid 2008, but permit renewal required from APVMA for 2009 and beyond.

which is regarded as a far more damaging pest. For similar reasons, *S. litura* damage should be quantified and the registration pursued of a NPV reputedly effective against this pest (P. Grundy, pers. obs.).

Additional biological control agents for aphids are required. While *A. glycines* populations have generally stabilised since their first arrival in Australia, severe outbreaks in coastal soybeans in 2008 had a severe impact on yield (A. Dougall, Maryborough Cane Productivity Services, pers. comm.). A permit has been secured for the selective and highly effective insecticide, pirimicarb, against this pest, but a more sustainable IPM option would be the importation of a suitable aphid parasitoid to complement the predatory beneficials which have mostly kept soybean aphid in check in recent years. Additional non-insecticide options are desirable given the ever-present risk of insecticide resistance developing very rapidly in soybean aphids as it has in cotton aphid (Herron *et al.* 2002).

The expansion of grain crops into coastal regions, with a greater surety of rainfall and irrigation (AOF 2005), presents new challenges for IPM, with the likely greater abundance of pests such as *M. virata* and *B. tabaci* (Brier 2007), and the year-long availability of host crops, particularly in the tropics. The latter factor is especially important for *B. tabaci* where cotton, grain and horticulture crops provide successive host availability. AWM strategies are required for *B. tabaci* and other key pests, as is the capturing of base-line and ongoing pest and beneficial insect incidence data, to measure the effectiveness of IPM tactics and any changes in pest incidence. In the future, landscape management may be an important AWM tactic to reduce the impact of pests such as *B. tabaci*, and to assist in the conservation of beneficial insects (Schellhorn *et al.* 2008).

Finally, whatever new IPM tactics are explored, it is vital that the current strong collaborative development and extension links between researchers, extension personnel, growers, consultants and industry associations are maintained. This will ensure that changes in pest incidence can be monitored and documented, and that problems can be addressed before they reach a crisis point. In particular, there should be continued emphasis on the development of multi-pest IPM and AWM strategies to lessen industry's dependence on insecticides wherever possible, and to stabilise populations of problematic grain pests, especially SLW and *H. armigera*. This will require the maintenance of both broadly-based research, development and extension groups, as well as more specialised IPM expertise in particular fields e.g. classical biological control, biopesticides, molecular technology, and predictive modelling.

While modelling may be critical in testing the effectiveness of IPM and AWM strategies and predicting changes in pest incidence due to climate change, models need to be tested against independent data, including long-term abundance data (Zalucki and Furlong 2005). The conundrum is that such data are less likely to be available (Zalucki and Furlong 2005), so the challenge for IPM in north-eastern Australia is to ensure that existing, unpublished data are not lost, and that new approaches to capture such data (traditionally very labour intensive and costly) are devised and implemented. In an era of decreasing resources, the support of GRDC for increased collaboration between IPM researchers throughout Australia, via the NIPI, will be invaluable

in the development of IPM guidelines for mixed cropping systems.

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