A Future for IPM in Cotton: The Challenge of Integrating New Tools to Minimize Pesticide Dependence

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Abstract

Insect pests represent a severe limitation for cotton production in many cotton regions of the world. Key pests in many systems are Heliothine moths (*Heliothis* and *Helicoverpa* spp.) which are not only damaging but also very well adapted to exploit the production systems most often associated with cotton. The capacity of some species to readily evolve resistance to pesticides, a capacity derived from their population structure, serves to magnify their pest status. A diversity of minor and induced pests must also be managed. While integrated pest management (IPM) has been a catchcry for many years, it is difficult to honestly ascribe the term IPM to the practice of pest management in most intensive production systems. Many components of IPM are being used, eg., sampling systems, thresholds, cultural practices in some cases, however, the main intervention for the management of key pests remains pesticides. This is certainly true in Australia, USA, China, India, Pakistan and parts of South America where pesticides represent a significant component of the cost of production. In western economies at least the reliance on pesticides brings a significant environmental liability with increasing concern on issues of off-target drift, chemical residues in waterways, soils and livestock. The imperative to move away from reliance on pesticides is a strong one.

IPM must be founded on a thorough understanding of the ecology of pest and beneficial species and their interaction with the crop. There is little doubt that ecological understanding of pest dynamics is improving all the time, likewise our appreciation of beneficial insects and alternatives to pesticides. However, I will argue that the emerging era of insect resistant transgenic cottons (expressing Bt or other insecticidal proteins) offers real prospects to use these new tools as the foundation for more sustainable, economically acceptable IPM with less reliance on pesticides. Transgenics will not provide sustainable pest management alone; they must be supported with scientifically rigorous and well implemented resistance management strategies. However, transgenics do offer the opportunity to integrate a range of other tactics not easily compatible with the use of disruptive pesticides. The challenge for researchers, extension agents, consultants and growers will be to implement economically viable production systems which have reduced reliance on pesticides. A significant challenge for researchers and funding agencies alike is to recognize that work on a range of IPM components must continue alongside the increasing focus on biotechnology.

In this paper, a range of possibilities for enhanced IPM in the next decade and how these can build on a framework of transgenic varieties is discussed.

Introduction

Whether cotton production is in intensive systems such as those of the USA or Australia or small holder systems characterized by those of Africa or Southeast Asia, insect pests are a major constraint on production and their management imposes significant costs and environmental concerns. Integrated pest management has long been proposed as the future for cotton pest management. Many definitions of IPM can be applied from a minimal approach based on sampling systems and thresholds to better time the use of pesticides, through to a more inclusive approach which seeks to minimize pesticide use and includes components such as conservation or augmentation of beneficial insect populations, host plant resistance (HPR), use of selective insecticides, incorporation of the compensatory capacity of the plant and cultural techniques. Australian cotton production currently utilizes several of these components, and IPM has been extended beyond the crop phase to become a year-round strategy for pest management, fully integrated with the cotton farming system. Likewise in many other intensive production systems pesticides are a significant component of production costs and the main tactic for pest management. This dependence on pesticides is unlikely to be sustainable and brings with it considerable economic costs as well as ecological problems from pesticide resistance in *Helicoverpa armigera*, and environmental risks associated with pesticide residues in soil and water and drift of pesticides into non-crop environments. The imperative to reduce dependence on broad spectrum pesticides is strong.

New Generation Selective Chemicals

Although there is a need to reduce dependence on environmentally disruptive chemicals, it seems likely that future cotton production systems will require some pesticide use. In contrast to the broadspectrum compounds of the past, the new generation of pesticides are much more selective, less disruptive, more environmentally benign and introduce new modes of action to overcome established resistance problems (Holloway and Forrester 1998). These new compounds are more compatible with a holistic approach to IPM. They are also considerably more expensive, which should help to ensure they are used conservatively and so preserve their long-term usefulness. All new chemistry should be immediately integrated into resistance management strategies to target use to the most appropriate pest and time of season and limit use to reduce risks of resistance.

Host Plant Resistance

Sustainable IPM will also need considerable input from the plant itself. The cotton plant is not simply a substrate for the interaction of pests and chemicals, it is the template on which a broad range of interactions occur between the pests and their environment. Cotton has a number of both morphological and biochemical traits which impart varying degrees of pest tolerance. Through conventional breeding some of these have been introduced into commercial varieties (eg. okra leaf types in Australia, Wilson 1994) and provide incremental gains in pest tolerance, but there remains much genetic variability in insect resistance traits and in the potential of cotton to compensate for damage (Sadras 1995, Sadras and Fitt 1997). This genetic resource has not been fully exploited by breeders, but should be in order to provide a more resilient plant background for pest management (Bottrell et al 1998).

Beneficial Insects

Cotton fields typically harbor a rich diversity of insects. In Australia up to 450 different species have been recorded in unsprayed fields (L. Wilson unpublished) and a significant proportion of these are beneficial. It is striking that the key beneficial groups in cotton are similar in many parts of the world (Hearn and Fitt 1992), but their impacts and value have often proven difficult to demonstrate. This is partly because of the difficulty of identifying which of a multitude of predators are providing significant value and partly because large scale unsprayed experiments, where natural controls can be quantified, are uncommon. One of the greatest impediments to development of IPM in cotton has been the lack of tools to control target pests without also disrupting these beneficial populations.

While predators and parasites are important components of IPM systems, in many cases their potential value can also be overstated. We need to recognize there are often severe limitations in the capacity of beneficials to control some pests, particularly the Heliothines. These pests are highly mobile, highly fecund, well adapted to exploit diverse cropping systems (Fitt, 1989, 1994) and capable of explosive infestations of crops. Beneficials are often not sufficiently abundant in cotton crops, at the times when *Helicoverpa* appear, to minimize damage. Since most beneficials are easily disrupted by pesticides (eg. Wilson et al 1998) and populations may be slow to recover, there is little evidence that beneficials can effectively control *Helicoverpa* spp. unassisted in intensive cotton systems. Consequently an important area of research, beyond simply minimizing the use of disruptive chemicals, has been to identify means to conserve and or augment beneficial populations. Conservation of natural enemies requires considerable ecological understanding of their seasonal phonology, habitat and prey requirements while augmentation is best exemplified by mass releases of egg parasitoids (Trichogramma), which has had limited success in most regions (Luttrell et al 1994).

Habitat Diversity

Increased habitat diversity is often advocated as a means to enhance biological control in agroecosystems. This could be achieved through intercropping or companion planting of particular plants with the crop of interest to act as trap crop for key pests, or to provide alternative prey or nectar sources to maintain populations of beneficials (Wratten and van Emden 1995). There is however, little evidence for cotton systems that reduced diversity per se leads to pest outbreaks (Hearn and Fitt 1992), particularly for generalist pests such as *Helicoverpa* spp. which can be more abundant in diverse, broadacre cropping systems where they exploit a suite of host plants and often manage to outpace the activities of predators and parasitoids (Fitt 1989). The use of trap crops for such species requires considerable caution to ensure the trap crops do not themselves become major sources of new populations.

What is required is the right quality of diversity, appropriately dispersed in the landscape. Increased diversity may be beneficial if it can make the cotton crop less apparent to pests and more difficult to locate (operates only at field level), provides diversionary hosts (more likely for extensive row crops), or maintains the abundance of beneficial species by providing food or refuges. Decreased diversity (increased monoculture) may dislocate the pests life cycle by removing alternative foods, diluting attack over an abundant crop, increasing edge effects, or reducing synchronization between pest and crop by altering planting dates.

In some tropical cotton systems small scale diversity of the cropping system does indeed provide value in pest management by maintaining beneficials. Cotton production in Vietnam is one example where a moratorium on the use of pesticides (reducing sprays from 15-20 per season down to 1 or 2) saw productivity maintained while major pests like *Helicoverpa* became minor problems due to the abundance of beneficials which flourished in the small plot intercropped system used there.

Increased field-level diversity is not easily accommodated in the large scale highly mechanized, intensive production systems. The often quoted example (Hare 1983) of interplanting strips of alfalfa in cotton to act as a trap crop for Lygus bugs, although effective has never been widely implemented because it was too disruptive to other management practices and not economic given the loss of productive cotton area and low costs of chemical control. Efforts are underway in Australia to extend this approach through a combination of lucerne strips, a predator food spray (Mensah 1997, 1998, Mensah and Khan 1997) and biological pesticides such as Bt and nuclear polyhedrosis virus. In this case lucerne strips planted in association with cotton provide a trap crop for a secondary pest, the green mirid *Creontiades dilutus*, and a nursery for generalist beneficials. Large scale field trials and area-wide management groups are showing the potential of this soft IPM approach. In combination with transgenic Bt cotton (next section), food sprays and virus have shown great potential to reduce conventional pesticide requirements .

Development and mplementation of Transgenic Bt Cottons

Biotechnology is rapidly producing a suite of new crops with enhanced insect and disease resistance among many other transgenic traits being developed. Genetically engineered cottons expressing delta-endotoxin genes from *Bacillus thuringiensis* sub spp. *kurstaki* (Bt) offer perhaps the most significant step forward in cotton pest management. Bt cotton varieties are being commercialized in many parts of the world (Fitt and Wilson 2000). These Bt cottons offer great potential to dramatically reduce pesticide use for control of the major Lepidopteran pests and offer a real opportunity to develop sustainable IPM systems for cotton production.

In Australia, Bt cottons (tradename INGARD®) have the potential to reduce pesticide needs for *Helicoverpa armigera* and *H. punctigera* by some 50-70%. Likewise in the USA, pesticide requirements for *H. virescens* have been dramatically reduced with BOLLGARD® cotton varieties. If widely adopted, Bt cottons should reduce environmental disruption, may reduce the incidence of some secondary pests, eg. mites, and should allow the implementation of other novel management strategies not compatible with existing pesticide usage.

Despite the potential benefits of Bt cotton technology and the demonstrated safety of Bt in conventional sprays, there have been a number of concerns related to the potential environmental and ecological impact of transgenic plants. Most of these have been addressed by thorough field testing and evaluation before commercial release (Fitt, Forrester, Wilson and Murray unpublished results, Llewellyn and Fitt 1997). Changes in pest status of sucking pests (eg. stink bugs) following the dramatic reduction in use of pesticides against Lepidoptera has been one concern (Turnipseed and Greene 1996).

However, the major challenge to sustainable use of transgenic cottons is the risk that target pests may evolve resistance to the engineered toxins. Resistance to conventional Bt sprays has evolved in a field populations of *Plutella xylostella* (Tabashnik, 1994). For this reason much effort has been devoted in developing and implementing pre-emptive resistance management plans to accompany the commercial release of transgenic varieties. The strategy adopted in Australia is targeted at *H. armigera* and based on the use of refugia to maintain susceptible individuals in the population (Roush, 1996, 1997; Gould, 1994). This strategy seeks to take advantage of the polyphagy and mobility of *Helicoverpa* spp. to achieve resistance management by utilizing gene flow to counter selection in transgenic crops**.**

Components include:

1. effective refuges on each farm growing INGARD cotton
2. defined planting window for INGARD cotton to avoid late planted crops
3. mandatory cultivation of INGARD crops to destroy most overwintering pupae of *H. armigera*
4. defined spray thresholds for *Helicoverpa* to ensure any survivors in the crops are controlled
5. monitoring of Bt resistance levels in field populations

The refuge strategy assumes that resistance to Bt is likely to be functionally recessive, that resistance genes are at low frequency in natural populations and that random mating occurs among individuals from refuges and Bt crops (Roush 1997, Gould 1998). These assumptions seem reasonable based on current knowledge of Bt resistance in field populations of *Plutella* and laboratory selection of resistance in *Heliothis/Helicoverpa* populations. However, there is some evidence that Bt resistance frequencies may be higher than expected in natural populations (Gould et al. 1997). Resistance management plans should therefore be conservative and deployment of transgenic cottons should proceed with caution as more information on the interaction of Bt crops with pest populations is gathered. Resistance management plans have also been devised for the USA, although much less comprehensive than in Australia, and will be needed in most countries where transgenic Bt cottons may be released. Another issue which will impinge on the long term sustainability of Bt cottons is the use of the same CryIA genes in other crops which are also hosts of *Helicoverpa*. These issues are addressed in Fitt (1997).

Transgenic Bt Cotton as a Foundation for IPM

The introduction of transgenic Bt cottons offers the possibility to substantially reduce the number of insecticide applications for *Helicoverpa* control. Despite the hype which often surrounds them, transgenic crops should not be perceived as a "silver bullet" solution to pest problems (Fitt and Wilson 2000). Experience in Australia has shown that efficacy of varieties expressing the CryIAc Bt protein is not consistent through the growing season and can be highly variable (Fitt *et al* 1994, Fitt 1998, Fitt et al 1998). Efficacy against *Helicoverpa* spp. typically declines through the boll maturation period, to the point where survival of larvae is little different to that in non-transgenic cotton (Fitt *et al*. 1994, Fitt 1998, Fitt *et al* 1998), although growth rates of survivors on the INGARD crops are still dramatically reduced (Fitt unpublished). This decline in efficacy begins during flowering and supplementary *Helicoverpa* control has been necessary on INGARD crops, particularly in the last third of the growing season. Despite this INGARD crops have reduced the need for pesticide sprays by at least 50% (Pyke and Fitt 1998) — a spectacular achievement for any IPM technology.

Rather than silver bullets, Bt cotton varieties should instead be viewed as a foundation on which to build IPM systems which incorporate a broad range of biological and cultural tactics. Research has shown little effect of INGARD cotton on non-target species, including non-lepidopterous pests, beneficial insects, and other canopy dwelling and soil dwelling species (Fitt *et al*. 1994; Wilson, Fitt and Forrester, unpublished data). Survival of beneficials should therefore be higher than in conventionally grown sprayed cotton. These beneficials should in turn provide control for some secondary pests, particularly those such as mites and aphids which are induced pests in sprayed cotton. This potential will be further enhanced as more efficacious transgenic varieties are released. In Australia, Bt cottons expressing two independent Bt proteins (Cry IAc and CryIIA) show much more consistent efficacy and will greatly enhance the sustainability of resistance management (Roush 1996). Other possibilities for insecticidal genes are also being researched (Llewellyn and Higgins 1998, Hanzlik and Gordon 1998). Were no pesticide required for *Helicoverpa* it is possible that only mirids would require control with foliar insecticides (Wilson et al., 1998).

Reduced use of disruptive pesticides will allow more emphasis on the management and manipulation of beneficial species, using nursery crops and food sprays described earlier, or other means of conservation and augmentation. Predation may be of even greater significance in INGARD crops as those larvae that do survive have markedly reduced growth rates (Fitt unpub. data) and are thus exposed to predation for a longer period at stages when they are smaller and less damaging. Furthermore, since many of the beneficial insects in cotton are generalists (Hearn and Fitt 1992; Wilson et al. 1998), their increased abundance can minimize the risk of outbreaks of a range of secondary pests. Beneficial activity should be explicitly considered in pest management decisions in the future.

Selective chemicals used only when essential will be an important component for IPM systems based on transgenic cotton. These options are discussed fully in Wilson et al. (1998). Highly selective biological insecticides will also have a role in pest management at the cropping system level. Formulations of Nuclear Polyhedrosis Virus (eg. GEMSTAR), will provide alternative control options for *Helicoverpa* which may survive on transgenic crops or on other crops in a farming system. Genetically modified viruses with enhanced speed of kill are also being developed (Richards and Christian 1998). These will provide options for Lepidopteran control in cotton IPM systems, but may have a better place in management of Heliothines on other crops (eg. sorghum and legumes) grown in agro-ecosystems where cotton is grown. In this way they will provide an alternative management tactic to transgenic Bt cotton in those crops.

A combination of insecticidal transgenes with other HPR characters through classical plant breeding may also enhance the stability of IPM systems. In Australia, the INGARD gene has been incorporated in okra leaf varieties to provide enhanced resistance to both *Helicoverpa* and mites (Fitt 1994, Wilson 1994). A range of insecticidal secondary compounds are also found in *Gossypium hirsutum*. For instance the terpenoid aldehydes such as gossypol or the related "heliocides" reduce survival and growth rates of *Helicoverpa* spp. (Fitt et al. 1995). Sachs et al. (1996) showed synergism between Cry IAb protein and high gossypol levels and some efforts are underway to combine these traits in commercial cultivars. On the other hand there is some evidence that tannins may reduce the efficacy of Bt transgenes (Daly and Fitt 1998).

Cotton varieties have a considerable capacity to compensate, even overcompensate, for insect feeding damage (Sadras 1995). Much greater use could be made of this capacity through the application of appropriate thresholds. On Bt cotton crops thresholds for *Helicoverpa* must allow time for larvae to feed sufficiently to ingest a lethal dose of the insecticidal protein, yet still allow intervention while larvae are of a size where they can be controlled effectively with insecticides (generally less than 6 mm) and before economic loss occurs. Thresholds for other pests remain largely unchanged. Cotton genotypes vary in their ability to compensate for pest damage (Sadras and Fitt 1997). Selection for genotypes with higher compensatory ability in combination with Bt genes could allow the use of higher thresholds for all pests with less risk, therefore reducing the need to intervene with disruptive insecticides.

Cultural techniques will integrate easily with Bt cottons. These will include cultivation to destroy any surviving *H. armigera* pupae in the soil through winter (Fitt and Daly 1990) — a mandatory requirement of the Australian strategy, as well as the use of trap crops to concentrate *Helicoverpa* populations as part of area-wide approaches to population management. Areawide management was devised as a concept in the USA where several successful campaigns have led, for example, to the eradication of bollweevil in much of the eastern U.S. cotton belt (Smith 1998). Areawide management of *Heliothis/Helicoverpa* in the USA through the use of virus sprays to reduce the first generation (Streett *et al* 1998), has been more problematic. Early experiments with areawide approaches to *Helicoverpa* management in Australia, based on trap crops and sacrifice crops, have shown promise and are being expanded.

Management of pests through behavioral disruption with pheromones may also be feasible with transgenic cottons. Pheromones for many species have been identified and are in widespread use for mating disruption of some species (Ridgway *et al* 1990), particularly pink bollworm (Kehat et al. 1998). Because of their mobility and limitations of conducting sufficiently large scale experiments it has been more difficult to show the potential for mating disruption with Heliothines (Betts *et al* 1993).

Finally, the current reliance on Bt genes in transgenic cotton varieties represents only the first wave of insecticidal proteins for pest management. While Bt genes are the most advanced commercially much research effort is focussed on alternative transgenes with activity against the major Lepidopteran and Hemipteran pests of cotton (Llewellyn and Higgins 1998). These offer possibilities for pyramiding with Bt genes to provide more sustainable resistance management (Roush 1998) or control of minor pests with some of the lectin genes. Few of these alternatives are close to market but they include highly novel options such as expression of a simple and specific RNA virus (*Helicoverpa armigera* stunt virus) in plants (Gordon et al. 1998, Hanzlik and Gordon 1998).

Conclusions

IPM systems for future cotton production will, of necessity, be more complex than the pesticide based systems currently in place, and will require greater effort on the part of crop managers whether they be professional consultants or farmers themselves. Transgenic cottons expressing insecticidal proteins with activity against one or more key pests offer great scope to dramatically reduce pesticide dependence and to allow the integration of a wide range of IPM compatible tactics. Provided they are supported with well researched resistance management strategies transgenic cottons should provide a foundation for sustainable IPM systems. The real challenge for researchers is to achieve this integration of approaches and for extension agents, consultants and growers to successfully implement economically viable production systems. A significant challenge for researchers and funding agencies alike is to recognize that work on a range of IPM components must continue alongside the increasing focus on biotechnology. Transgenic insecticidal cottons will not be sustainable technologies alone; they must be supported with other approaches which will require continued research.

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