Crop biotechnologies deployed worldwide primarily possess traits for herbicide resistance, insect resistance, or both. While the economic and environmental benefits of these traits can be significant, they are threatened by evolution of insect and weed resistance. Failure to develop successful resistance management strategies will, not only deprive current adopters of the benefits of crop biotechnology, it will also have a powerful negative demonstration effect on regions contemplating biotechnology approval. This paper reviews the features and performance of resistance management strategies for insect-resistant (IR) and herbicide-resistant (HR) transgenic crops. Key factors determining success are technology attributes and institutional capacity. Trangenic IR and HR crops will be more sustainably deployed if they are embedded in integrated pest management (IPM) and integrated weed management (IWM) with strong, outward extension linkages to farmers and backward linkages to research institutions. Public and private plant breeding can play a critical role in developing stacked traits that reduce overreliance on single chemical compounds. While extension plays an obvious role in disseminating information, it can also serve two other important functions. First, it can facilitate farmer collective action for area-wide resistance management. Second, it can provide government agencies with information needed to increase the flexibility and cost-effectiveness of resistance management regulations. The paper concludes by discussing current capacity constraints and future institutional capacity needs of developing countries for successful IPM and IWM.
Resistance Management and Sustainable Use of Agricultural Biotechnology

Introduction

Genetically modified (GM) crops first became commercially available in 1996. In countries where they have been approved, growers have rapidly adopted GM crops with herbicide resistant (HR), insect resistant (IR) traits, or both traits. In countries where approved, GM varieties accounted for 90% of soybean hectares, 78% of cotton hectares, 72% of canola hectares, and 60% of maize hectares by 2008 (Table 1). Crops with HR traits or IR traits account for more than 99% of GM crop hectares worldwide (James, 2009). Among HR crops, the dominant trait is resistance to the herbicide glyphosate.

Adoption of IR Bt crops and HR crops has generated significant economic benefits. For Bt crops, this has come from higher yields from greater insect control, reduced insecticide application costs, or both (Marra, 2001; Marra et al., 2002; Carpenter et al., 2002; Gianessi et al., 2002; Brookes and Barfoot, 2008; NRC, 2010; Price et al., 2003). Evidence of farm profit gains from HR crops has been more mixed (Marra, 2002 et al.; Lin, et al., 2001; Webster et al., 1999; Bonny, 2007). Several studies have considered harder-to-measure benefits of HR crops, such as simplicity, convenience, flexibility, and safety (Alston, et al., 2002; Carpenter & Gianessi, 1999; Marra et al., 2004). Fernandez-Cornejo et al. (2005) found HR crop adoption was associated with higher household, but not farm income. They posited, that HR crops are management labor saving, thus freeing time for other economic activities. Gardner, et al. (2009) found more direct evidence supporting this hypothesis. Other studies suggest non-pecuniary factors such as increased flexibility and simplification of weed control and ease of integration into conservation tillage are important sources of value (Bonny, 2007; Brookes & Barfoot, 2008; Piggott & Marra 2008; Sydorovych & Marra, 2007, 2008; Alston, et al., 2002; Marra et al., 2004; Hurley et al., 2009a).

GM crops also provide several environmental benefits. Adoption of IR Bt crops has led to movements to insecticides with lower toxicity and harmful environmental effects (Knox, et al.,
2006; Wossink and Denaux, 2006; Kleter et al., 2007; NRC, 2010). Similar results have been reported for HR crops resistant to the herbicide glyphosate. Glyphosate often substitutes for herbicides with higher toxicity and persistence in the environment (Brimmer et al. 2004; Fernandez-Cornejo, et al. 2002; Nelson & Bullock, 2003; Gardner and Nelson, 2008). Adoption of HR crops appears to encourage adoption of conservation tillage practices (Carpenter, et al., 2002; Fawcett & Towery, 2002; Fernandez-Cornejo & Caswell, 2006; Kim & Quinby, 2003; Marra et al., 2004; Trigo & Cap, 2003; Kalaitzandonakes, and Suntornpithug, 2003; Roberts et al., 2006; Frisvold et al., 2009a). This can potentially reduce soil erosion and attendant water pollution (Brookes & Barfoot, 2008; NRC, 2010).

There are concerns, however, that the economic and environmental benefits of GM crops may not be sustainable because of the evolution of insect and weed resistance (e.g., Benbrook, 2001; Lemaux, 2008). Entomologists have documented three cases of field-evolved resistance to Bt crops. These are: (i) *Spodoptera frugiperda* (J. E. Smith) (fall armyworm) resistance to Cry1F toxin in Bt corn in Puerto Rico; (ii) *Busseola fusca* (Fuller) (maize stalk borer) resistance to Cry1Ab in Bt corn in South Africa; and (iii) *Helicoverpa zea* (Boddie) (cotton bollworm) resistance to Cry1Ac and Cry2Ab in Bt cotton in the U.S. Southeast (Matten et al., 2008; Van Rensburg, 2007; Tabashnik et al., 2008, 2009).

Tabashnik et al. (2009) completed a comprehensive analysis of resistance monitoring data from 41 studies across five continents for Bt cotton and maize. In addition to the three cases of resistance noted above, they report on five studies from China and India with ambiguous evidence of resistance of *Helicoverpa armigera* to Cry1Ac in Bt cotton. For seven target pests, however, they report strong evidence of no increase in the frequency of resistance to Bt toxins in GM crops. They also reported sustained susceptibility of some populations of *H. zea* and *H. armigera*. Despite the three cases of confirmed insect resistance to Bt crops, there have yet to be economically significant field control problems.
To date, weed resistance to herbicides that complement HR GM crops appears to be a more significant problem than insect resistance to Bt crops. Prior to 1998, there were no reported glyphosate-resistant weed species in the United States. By 2008, however, glyphosate resistance had been confirmed for 9 species in the United States (Figure 1) and 16 species worldwide (Heap, 2009). U.S. resistant weed species are spread across 19 states (Figure 1). Costs of herbicide resistant weeds can be significant, ranging from $5-$130 / hectare (Mueller et al., 2005; Scott and VanGessel, 2007; Webster and Sosnoskie, 2010). In severe cases, growers may opt to abandon fields altogether (Culpepper et al., 2008). Resistance to glyphosate has evolved in Palmer amaranth ($A.\ palmeri$) in glyphosate-resistant cotton fields throughout the southeastern United States (Culpepper, 2006; Steckel et al., 2008; Culpepper et al., 2008 and 2009; Nichols et al., 2008; Norsworthy et al., 2008; York et al., 2008). Regarding glyphosate-resistant Palmer amaranth, a University of Georgia extension publication warns, “there are no economical programs to manage this pest in cotton (Culpepper and Kichler, 2009).” By 2008, glyphosate resistant Palmer amaranth infested more than 240,000 hectares of land in Georgia, North Carolina, and South Carolina (Culpepper et al., 2009). An additional 87,000 hectares of cotton were infested in Arkansas (Doherty, et al., 2008).

Evolution of resistance to Bt crops and to herbicides that complement HR crops poses three risks. First, it would deprive agricultural producers of pecuniary and non-pecuniary benefits of these crops. Second, it would deprive society of environmental benefits of reduced chemical applications, movements toward less toxic and persistent chemicals, and conservation tillage. Third, it may have a powerful, negative demonstration effect on countries considering approval of IR and HR GM varieties for the first time. Despite their apparent benefits, many countries remain reluctant to approve GM crop varieties. Countries that have not approved GM crops with HR or IR traits account for 37% of cotton, 61% of maize, 63% of canola, and 26% of soybean hectares worldwide (Table 1).

**Aims and scope**
This paper reviews the features and performance of resistance management strategies for insect-resistant (IR) and herbicide-resistant (HR) transgenic crops. It attempts to explain why resistance problems have developed for HR crops but not for Bt crops. One key factor has to do with fundamental attributes of the two technologies and their compatibility with integrated pest and weed management. Another key factor was the institutional and regulatory setting where each type of technology was deployed. While resistance management for Bt crops was federally mandated with their initial introduction, resistance management practices for HR crops have been voluntary and decentralized. Regulatory requirements for managing resistance to Bt crops also spurred greater levels of research into the science of pest resistance. Consequently scientific understanding of resistance management strategies for Bt crops is relatively advanced.

The second part of the paper draws policy lessons from the US experience. First, GM IR and HR crops will be more sustainable if they are embedded in integrated pest and weed management programs with strong, outward extension linkages to farmers and backward linkages to research institutions. Second, public and private plant breeding plays a critical role in resistance management by developing varieties with traits that reduce over-reliance on any single toxin or chemical compound. Examples include pyramiding of Bt traits or development of crops resistant to multiple herbicides, encouraging rotation of compounds with different modes of action. Third, developing varieties with such “stacked” or “pyramided” traits will be more effective if implemented as a complement to, rather than a substitute for, active, collective grower participation in IPM and IWM programs. Fourth, while extension plays an obvious role in disseminating information, it can also serve two other important functions. It can facilitate farmer collective action for area-wide resistance management. Extension can also provide government agencies with information needed to increase the flexibility and cost-effectiveness of resistance management regulations.

The paper concludes by discussing current capacity constraints and future institutional capacity needs of developing countries for insect and weed resistance management.
Resistance management: a tale of two technologies

HR weeds have begun to pose economically important problems for use of GM HR crops, while insect pest resistance has yet to pose similar problems for Bt crops. Next, I consider how resistance management has been affected by differences in (i) the basic features of these technologies, (ii) how they have been integrated into production systems, and (iii) how they have been regulated. Understanding how these differences contribute to success or failure of resistance management will be crucial for developing effective resistance management policies in the future.

Narrow-spectrum vs. broad-spectrum control

The Bt toxin has a narrow spectrum of toxicity to a limited number of Lepidopteron pests. Bt stands for Bacillus thuringiensis, a soil bacterium. The Bt cells produce crystal-like proteins that disrupt midgut membranes, killing particular insect pests that ingest them. Normally the proteins are not active against humans, other vertebrates, and most beneficial insects (Mendelsohn, et al., 2003; Naranjo, et al., 2008). Foliar spray applications of Bt are one of the most important insecticides used in U.S. certified organic crop production (Walz, 1999; Hutcheson, 2003; Walker et al., 2003). Under U.S. federal standards, crops using low-toxicity insecticides – such as neem, pyrethrum, sabadilla, insecticidal soaps, such as diatomaceous earth (D.E.), and Bt sprays – can be certified as organic.

Because Bt cotton works continually, Cannon (2000) raised concerns that it might discourage insect scouting and monitoring, key elements of IPM. The shift to narrow-spectrum control, however, meant that growers had to consider pest population dynamics more, not less, carefully. Rather than spraying broad-spectrum insecticides and counting on collateral control of other insects, growers now had to monitor non-target pests more closely for supplemental control. Bt cotton also appears to exhibit little activity against natural cotton predators and non-target species, especially compared to cotton sprayed with insecticides (Head et al., 2005; Naranjo, 2005; Torres and
Ruberson, 2005; Naranjo, et al., 2008). Reducing impacts on natural predators is another key element of an IPM strategy.

While there is no single definition of integrated pest management (IPM) – Bajwa and Kogan’s (2002) compendium lists 67 definitions – an over-arching theme is the substitution of knowledge and information for insecticides. IPM requires an understanding of factors influencing pest populations, such as pest predators, host plant resistance, and choice and timing of cultural practices. This, in turn requires integration of agronomy, plant genetics, economics, pest population dynamics, and ecology.

Fitt (2008) notes the challenge of producing Bt crops is that they are “living crops” with greater abundance of both beneficial insects and secondary pests. While the first-generation, single-Bt toxin varieties were highly effective against tobacco budworm (*Heliothis virescens*) and pink bollworm (*Pectinophora gossypiella*) their effectiveness was limited against cotton bollworm (*H. zea*). Growers often continued to use sprays to control *H. zea*. In addition, there has been some increase in secondary pest activity as growers reduced broad-spectrum sprays for pests that Bt controls. Results from Australia and the United States suggest that despite secondary pests, Bt cotton adoption has led to a reduction in total insecticide applications (Fitt, 2008; Frisvold and Pochat, 2004; Frisvold 2009). Reductions in sprays for Bt’s target pests have outweighed increases in sprays to non-target pests. Studies have found similar results in parts of China (e.g. Huang et al., 2002; Wang et al. (2009). Secondary pest outbreaks have posed more serious problems in elsewhere in China (e.g., Wang et al., 2006) and in India and South Africa (Lemaux, 2008; Fitt, 2008; Naranjo, et al., 2008).

The performance of Bt crops may have more to do with the technical and institutional capacity of the regions where they are deployed than with the technology itself (Fitt, 2008). Moving from broad-spectrum sprays to a diversity of narrow spectrum control targeting different pests requires greater knowledge of entire pest complexes. Successful deployment of Bt technology will require complementary provision of education and training about these complexes.
Sustainable use of Bt crops will be a management- and knowledge-intensive endeavor. However, its narrow spectrum makes it compatible with many aspects of IPM – protection of natural predators and beneficial insects, reduced use of chemical insecticides, matching specific treatments to specific pests, avoiding over-reliance on any one compound to control multiple pests. These features of IPM, in turn, are critical for delaying resistance.

In contrast to Bt crops, HR crops are resistant to broad-spectrum, non-selective herbicides such as glyphosate and glufosinate. While Bt crops complement management-intensive IPM strategies, a reported benefit of HR crops is their ability to simplify decisions and reduce management time (Bonny, 2007; Gianessi, 2008). Glyphosate controls more than 300 weed species (Green et al., 2008). Growers can control many broadleaf and grass weeds effectively using one herbicide instead of many different ones (Fernandez-Cornejo & McBride, 2002). Adoption of HR crops appears positively associated with off-farm work of farm households and to be household labor saving (Fernandez-Cornejo et al., 2005 and 2007; Gardner et al., 2009). In addition, HR crops increase flexibility by expanding the window when growers can apply herbicides (Bonny, 2007). This reduces sensitivity to weather and timing of operations. There is evidence that small-scale, part-time farm operations are less likely to be aware of resistance problems or to adopt resistance management practices (Johnson and Gibson, 2006; Johnson, et al., 2009).

A crucial part of delaying the evolution of weed resistance is diversifying control strategies (Duke and Powles, 2009). This can be achieved by using combinations of chemical (herbicides) and non-chemical (e.g. tillage, crop rotations) tactics (Beckie, 2006; Beckie and Gill, 2006). Within chemical control, it is also important to avoid over-reliance on herbicides with the same site of action (Beckie, 2006; Beckie and Gill, 2006; Green, 2007; Green et al., 2008).

Adoption of HR crops in the United States, however, appears to have contributed to movements away from these resistance management practices. Since introduction of glyphosate-resistant crops, glyphosate applications have risen substantially at the expense of other compounds (Kim & Quimby, 2003; Fernandez-Cornejo & McBride, 2002; Bonny, 2007). Rapid
adoption of HR crops has led to vast areas of the American South relying heavily on glyphosate in extensive monoculture. Beckie (2006) argues this has encouraged, “simplified cropping systems favoring a few dominant weed species and frequent use of single site-of-action herbicides. (p. 809).” Complementary adoption of reduced- and no-till practices has accompanied HR crop adoption, reducing erosion and water pollution. However, this has reduced the diversity of weed control measures and increased reliance on single-site compounds. While crop rotation is another way break weed cycles and switch reliance on the same compounds, continued use of HR varieties of different crops can subvert the effectiveness of crop rotations as a resistance management strategy. In a survey of more than 1,200 growers, Hurley et al. (2009b) report about two thirds of corn and cotton growers and nearly half of soybean growers planned to rotate their current HR crop with another HR crop. Rotating the use of herbicides with different modes of action or using herbicide mixtures are other strategies to delay resistance (Beckie and Reboud, 2009; Green, 2007). These too appear to have declined. In a survey of agricultural professionals and growers, Harrington et al. (2009) found that 54% of respondents reported a decrease in rotation between herbicides with different sites of action, while 46% reported a decrease in use of crop rotations. (Interestingly, survey responses suggest that adoption of IR crops has not led to movements away from IPM practices). Frisvold et al. (2009b) found a significant negative association between planting of glyphosate-resistant crops and use multiple herbicides with different modes of action among corn, cotton, and soybean producers (they did, however, find increased use of new seed free of weeds and compliance with label rates). Thus, while adoption of Bt crops has proven compatible with IPM practices that delay resistance, adoption of HR crops appears to have encouraged behavior that has rapidly increased selection pressure.

Regulatory environment

Another critical difference between Bt and HR crops was that resistance management was federally regulated and mandatory for Bt crops, but not for HR crops. Why the difference? In part this
was due to the value of microbial Bt sprays in organic agriculture. As transgenic Bt crops were being developed, organic grower groups became concerned that widespread use of the Bt toxin on vast acres of major U.S. field crops would hasten resistance to Bt. In response to this concern, the EPA found that preventing Bt resistance was in the “public good” and that steps to prevent resistance should be established (Walker, et al., 2003). Because the Bt toxin was embodied in the crop itself, Bt crops were regulated as pesticides under FIFRA (the Federal Insecticide, Fungicide and Rodenticide Act). Environmental and organic groups were unhappy with EPA’s initial registration of Bt crops in the mid-1990s. They first petitioned (in 1997) then filed suit (in 1998) against the EPA to block Bt crop deployment (Vogt and Parish, 2001; Fox, 2000). While these groups withdrew their suit in 2000, they continued vocal critiques of EPA biotechnology throughout the re-registration process for these crops.

EPA requires integrated resistance management (IRM) programs for Bt cotton to delay resistance and maintain its efficacy. IRM strategies have been developed in consultation with federal environmental and agricultural agency staff, university, public interest groups, grower groups, and Monsanto Company (the first developer of Bt cotton) (Matten and Reynolds, 2003). The EPA regularly convenes Scientific Advisory Panels to review underlying science and evidence regarding pest resistance and to revise IRM regulations (U.S. EPA, 2001, 2006a, 2006b). For IRM, EPA requires: (i) mandatory refuge requirements; (ii) resistance monitoring; (iii) remedial action plans to address resistance problems; (iv) IRM compliance monitoring; (v) grower education; (vi) grower agreements, and (vii) annual reports.

The requirement of resistance management plans for Bt crop registration was unprecedented in pesticide regulation. Resistance management plans have not been required for conventional pesticides (Matten, 2008). To delay resistance, EPA requires growers who plant Bt cotton to also plant non-Bt cotton on a minimum percentage of their total cotton acreage. These non-Bt acres serve as a refuge for susceptible pests, allowing them to survive and mate with adults that have become resistant to the Bt toxin and thereby delay the development of resistance in the pest popu-
lation. Experimental evidence and results from entomological simulation models suggest that refuges can significantly delay the onset of resistance (Carrière and Tabashnik, 2001; Gould, 1998; Heckel, et al., 1997; Tabashnik et al., 2003).

The EPA used its authority under FIFRA as a vehicle to require science-based development and implementation of specific resistance management regulations. EPA relied on recommendations from the National Academy of Sciences and Science Advisory Panels (SAPs) convened by its authority under FIFRA to spur further research on resistance management (NRC, 2000; US EPA, 2001). This led to significant advances in Bt resistance modeling and empirical analysis. This greatly increased the knowledge base concerning how and how well the refuge strategy might work. Results in the field have been consistent with entomologists’ theoretical predictions (Tabashnik 2009).

EPA initially registered Bt crops at roughly five-year intervals and required extensive information on resistance management science and compliance as a condition of re-registration (Mendlesohn et al.). This maintained pressure on Monsanto and on growers to demonstrate compliance with the refuge strategy. From growers’ perspective, the threat of EPA cancellation may have felt more real than the risk of Bt resistance. The environmental economics literature suggests that voluntary adoption of environmental practices is more likely if there is an underlying threat of regulation (Davies and Mazurek, 1996; Ribaudo, 1998; Khanna and Damon, 1999; Alberini and Segerson, 2002; Lyon and Maxwell, 2002).

One may think of the susceptibility of weeds or insects to pesticides as public goods. While it is in the long-term collective interest of growers to maintain this susceptibility by adopting resistance management practices, such adoption is individually costly. Individual growers have an incentive to free ride (i.e. to undersupply resistance management while counting on others not to). Refuge requirements are a government mechanism to prevent such free riding for the growers’ collective benefit. In a survey of corn growers, Alexander (2007) found that among Bt corn adopters, 75% agreed that refuges would maintain the technology’s effectiveness, 68% agreed that refuges benefited all growers, and less than 19% agreed that the benefits of refuges were not worth
the time and effort. However, only 40% of growers agreed that they would plant a refuge if not required. This suggests the challenges of resistance management through voluntary behavior.

While resistance management practices for Bt crops are federally mandated, management of weed resistance for HR crops has been de-centralized and voluntary. Bt crops have pesticidal substances incorporated into them and are thus regulated under FIFRA. HR crops do not include pesticidal compounds themselves, however, so EPA has no clear authority to regulate HR crop varieties directly (Horne, 1992). In principle, EPA could exert influence over weed resistance management in two areas. First, under FIFRA, EPA has authority to regulate uses of herbicides that complement HR crops. Second, EPA could (again, in principle) require resistance management procedures to be implemented as a condition of granting Section 18 exemptions. The Emergency Exemption Program mandated by Section 18 of FIFRA gives EPA authority to authorize emergency, non-registered uses of pesticides. States often make requests for Section 18 exemptions in response to pest or weed resistance that reduces the usefulness of registered compounds.

Even if EPA decided they had authority to regulate weed resistance management, the rationale and scope for such intervention is less clear than in the case of Bt crops. Because microbial Bt sprays have been valuable for insect control in specialty crop and organic farming, there was greater scope for external costs. The loss of pest susceptibility to Bt sprays would hurt organic and specialty crop growers, but these costs would be external to Bt crop seed sellers and corn and cotton growers.

Miranowski and Carlson (1986) seminal work on the economics of resistance management for chemical pesticides is useful for understanding why very different resistance management regimes arose for HR and Bt crops. They developed a framework to assess how economic and biological conditions affected the forms resistance management might take. If pests are highly mobile, then management of resistance can suffer from common pool externalities. Individual farmers would have an individual incentive to deplete the common pool of pest susceptibility. Individual incentives to delay resistance may not coincide with long-term benefits of growers collec-
tively. If pests are not especially mobile, however, resistance management is an inter-temporal management problem. Growers must still weigh short run costs of resistance management against long-term costs of the evolution of resistance. However, without pest mobility there are no externalities, so resistance management is a matter of private incentives. Without mobility, the useful role of government in resistance management is confined to extension and education to improve grower awareness of resistance management trade-offs. With highly mobile pests, however, there are social benefits to encouraging growers to manage pest resistance cooperatively for their long-term collective benefit. Direct government regulation of resistance management as it is applied to Bt crops may be warranted. Frisvold and Reeves (2008) have calculated that if current U.S. resistance management regulations were responsible for preventing field-level failures from resistance to Bt cotton, then the regulations have “paid for themselves” – growers’ long-run profits were higher because of the benefits from delayed resistance outweighed the short-run costs of regulation.

Grower cooperation can also be achieved through methods falling short of direct government regulation. As with other agricultural cooperative and with pest eradication programs, growers could vote to collectively implement practices. For example, for boll weevil and pink bollworm eradication programs in the U.S. growers impose assessments on themselves to fund activities, restrict certain behaviors, and mandate others (such as requiring after-season plowing to prevent pest over-wintering). The role of government here is indirect, imposing penalties on growers who might free ride and diverge from collective decisions.

Miranowski and Carlson also considered the role of the supplier of the pest control technology. If the supplier had monopoly control of the product and it were sufficiently valuable, then the supplier would have an incentive to manage pest susceptibility to the product as an exhaustible resource. A monopolist would have greater incentive to delay resistance than if the product were sold in a competitive market. In the case of Bt crops, the insect pests they target are highly mobile (generating one type of externality) while resistance could also harm growers relying on microbi-
al Bt sprays (a second externality). Although Monsanto held the patent on the initial transgenic Bt crop varieties, patent length is limited and new competitors have entered the market with other Bt varieties. In contrast, weeds have generally been considered highly immobile and glyphosate sales remain a large source of income for Monsanto.

Finally, Miranowski and Carlson consider the role of price signals in farmer decisions to manage resistance. They point out that if new pest control products are being developed and commercialized regularly, then farmers will have little incentive to manage resistance to existing products. They find that from the early 1960s to early 1980s, prices of pesticides rose more slowly than other agricultural inputs. They argued that this signaled to growers that resistance was not making effective pesticides scarce.

This picture has continued, at least up to the last few years. From 1997 to 2007, prices of herbicides rose more slowly than those for other production inputs (Table 2). Since 2007, prices of herbicides have risen relative to other production items (Figure 2). Prices of glyphosate in particular have risen compared to all production items only since 2008. Thus, price signals up until recently appear to have encourage a “no resistance management” approach to herbicides. In contrast, because of the unique features of Bt sprays and Bt incorporated in plants, it has been more widely felt that there are no close substitutes for Bt.

Hence, resistance management for glyphosate resistant crops has taken the form Miranowski and Carlson’s framework would predict. Actual resistance management has been left to individual growers, while the pest control product supplier has coordinated with grower associations and extension to educate growers about resistance and its management. Herbicide price signals have not signaled scarcity of effective weed control products, until perhaps recently.

Externalities in weed resistance management may be greater than previously believed, however. Mobility of resistant weed seeds may be greater than previously believed (Marsh et al., 2006). HR Palmer amaranth now appears to be quite mobile. Weed seeds are also transported via custom harvest and other custom machinery operations. Custom operators currently lack incen-
tives to internalize external costs of spreading resistant seed. Moreover, HR crop varieties complement conservation tillage, a practice with many external benefits, which include reduced soil erosion and water sedimentation, reduced fossil fuel use for plowing, and soil carbon sequestration. If resistant management leads to significant movements away from conservation tillage (as it has in some parts of the southeastern United States), external benefits of conservation tillage would be lost. Glyphosate resistant weeds could also lead to reversion to herbicides with more negative environmental impacts. Thus, there are broader social costs to movement away from glyphosate and conservation tillage (Marsh et al., 2006).

Even if herbicide resistant weeds are more mobile and generate greater externalities than previously appreciated, a regulatory response would be difficult to implement. First, for weed resistance management it is less clear what would constitute “compliance” with resistance management. For Bt crops, one can assess whether refuges are of the appropriate size, configuration, and proximity to Bt fields. While growers have often found these requirements confusing (e.g., see Alexander) they involve one-time, seasonal planting decisions. There are additional restrictions on which insecticides can be sprayed on refuges, but growers and pest control advisors in the United States are familiar with crop and purpose restrictions on insecticide applications. Some studies have examined the extent to which growers have complied with refuge requirements (Carriere et al., 2005; Goldberger, et al., 2005).

In contrast, for HR crops, there are multiple crop, herbicide, tillage, and machinery-cleaning choices one could make that may delay resistance to varying degrees. But, given that multiple strategies are important, how does one measure adoption? Some empirical studies have developed indexes characterizing the intensity of integrated weed management (IWM) adoption. Hollingsworth and Coli (2001) developed a scoring system based on a weighted sum of practices adopted. Hammond et al. (2006) and Frisvold et al. (2009b) used indices that were unweighted counts of the total number of practices adopted. Llewellyn et al. (2007) considered those growers who adopted three or more practices (out of a possible six) as IWM adopters. Such evaluations based
on the number of practices adopted, however, do not address directly whether growers are adopting the most important practices.

*Short-run costs of resistance management*

Costs of adopting resistance management practices may also have been lower for Bt than for HR crops. In 1999, 40% of U.S. cotton growers using Bt cotton planted *more* non-Bt-cotton than the minimum required under regulations, effectively planting larger refuges than required by law (Frisvold and Reeves, 2008). In a detailed survey of Arizona cotton growers (Carrière et al. (2005) also found evidence of over-compliance with embedded and infield refuge size requirements among some growers.\(^1\) Embedded refuges are blocks of non-Bt cotton at least 150 ft wide planted within fields of Bt cotton. EPA regulations require refuge area to be at least 5% of total cotton area. In Arizona, embedded refuge size was 35% in 2002 and 2003 – seven times the minimum requirement. For in-field refuges, growers must plant at least one row of non-Bt cotton for every 6–10 Bt acres (a minimum 10% refuge requirement). Average in-field refuge size was 28% in 2002 and 25% in 2003, more than double the minimum requirement. Frisvold and Reeves (2008) offer two explanations for over-compliance. First, risk aversion can explain partial adoption of technologies (Just and Zilberman, 1983). For risk-averse growers, the refuge size that maximizes expected utility may be greater than the minimum requirement. Second, halo effects and area-wide suppression of pest populations allow some growers to reduce their Bt crop acreage and still maintain effective pest control (Carrière et al., 2003; Alstad and Andow 1996; Frisvold and Reeves, 2008). Frisvold and Reeves (2008) report that in areas with high adoption rates of Bt cotton, opportunity costs of refuges (foregone gains from planting Bt cotton) on remaining non-Bt acreage may be less than Bt technology fees. For some growers, refuge compliance costs are relatively small.

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\(^1\) They found area-weighted compliance rates above 88% in 5 of 6 years for all cotton refuges.
Turning to HR crops, in a study of adoption of 10 RM practices among U.S. corn, cotton, and soybean farmers, Frisvold et al. (2009b) found infrequent adoption of three practices: supplemental tillage, cleaning equipment, and using multiple herbicides with different modes of action. Hurley et al. (2009b) found that cleaning equipment was associated with higher weed management costs among soybean growers, supplemental tillage increased costs among corn growers, and using herbicides with different modes of action increased costs for cotton and soybean growers. Many of the practices used to delay resistance are the same as those to manage weeds after resistance has evolved (Beckie, 2006; Green et al., 2008). Some studies suggest that growers may delay adoption of IWM practices until after resistance is present (Beckie and Gill, 2006; Llewellyn et al., 2004; Frisvold et al., 2009b).

The ease, flexibility, and management timesaving aspects of HR crops make them attractive to part-time farmers, or farmers for which agricultural income is a small share of total household income. This, however, can present a problem for resistance management. Part-time farmers have a relatively small economic stake in preserving the efficacy of HR crops. For example 26% of U.S. grain and oilseed farms and 12% of cotton farmers had less than $25,000 in gross sales. These farms would have substantially less net income from agriculture. It is an open empirical question of (a) whether these small-scale operations are a source of resistant weeds and (b) if so, whether they would adopt more management-intensive IWM practices needed to control resistance. Frisvold et al. (2009b) found no strong evidence of scale effects in adoption of weed resistance management practices. However, their survey data did not include smaller farm-size classes.

**Plant breeders to the rescue?**

There is still scope to delay resistance to Bt and HR crops via plant breeding. Pyramiding and stacking traits in individual crop varieties can accomplish this. Here, I follow the convention of
using the term “pyramiding” for combining multiple genes that confer the same trait to a crop (Ferre; Tabashnik et al., 2009). Including multiple Bt toxins in one crop is an example of pyramiding. Stacking refers to using different genes to confer multiple traits. For example, stacked varieties might have both insect pest and herbicide resistance or might be resistant to herbicides with different modes of action.

In the United States, registered Bt crops use different combinations of 11 Bt toxins (Tabashnik et al., 2009). To be successful, pyramiding requires low initial resistance to each toxin individually in a pest population. While the effectiveness against *H. zea* of the first, commercially used, single Bt toxin Cry A1c was limited, a second toxin, Cry2Ab, achieves a high level of control. Resistance may still develop quickly if single-toxin and two-toxin Bt varieties are grown at the same time and areas. In the United States, substantial cotton acreage with the single Cry1Ac toxin (Bollgard) has been planted in the same areas as cotton varieties with both the Cry1AC and Cry2Ab toxins (Bollgard II). This practice was continued until 2010. In Australia, however, single toxin Bt cotton was completely replaced by two toxin varieties in 2004-5 (Downes et al., 2009). Some *H. zea* populations in the southeastern United States already show field-evolved resistance to Cry1AC or to Cry2Ab (Ali and Luttrell, 2007; Ali et al., 2007; Tabashnik, et al., 2009). Interestingly, in Australia *H. armigera* (a similar pest to *H. zea*) has not had field level resistance to either Cry1Ac or to Cry2Ab. Tabashnik et al. (2009) argue that this conforms to theoretical predictions because Australia had larger refuge requirements for Bt cotton than the U.S. did, while in Australia single and double Bt cotton varieties were not planted contemporaneously. Resistance of *H. zea* to Bt toxins has not yet led to significant field level control failures because conventional insecticide sprays still effectively control the pest.

Weed resistance may be delayed by developing crop varieties resistant to multiple herbicides (Green et al., 2008). Resistance can be delayed by rotating between herbicides with different modes of action (reducing selection pressure on any one compound) and by using herbicide mixtures (Beckie, 2006). If a particular weed is resistant to one type of herbicide, it may still be sus-
ceptible (and killed) by another herbicide that relies on a different mode of action. Companies are developing new crop varieties that combine resistance to glyphosate resistance with resistance to herbicides with different modes of action (Green et al., 2008) One example will be varieties that stack glyphosate resistance with resistance to different of ALS-inhibiting herbicides. These new, stacked varieties will be combined with homogeneous blends – herbicide mixtures with different modes of action. Because these will generally be mixtures of currently registered herbicides, they may receive regulatory approval relatively quickly.

Combining herbicide mixtures with multiple resistant crop varieties can reduce overreliance on any single mode of action. This strategy also avoids the high cost and lengthy delays in developing novel herbicides with different modes of action. It raises certain questions however. First, how many different modes of action need to be combined in one HR crop variety to delay resistance substantially? How is the potential for delay affected by the fact that some weeds are resistant to the herbicides that are to be combined. For example, some weeds are already resistant to glyphosate, others are resistant to ALS inhibitors, and some are resistant to both (e.g. Legleiter and Bradley, 2008).

**Top down vs. bottom up resistance management**

Development of stacked or pyramided crop varieties will be a critical part of resistance management. However, by itself, this represents a rather top-down approach. Successful resistance management will likely require more than growers passively selecting market products (seed varieties and chemicals). It remains to be seen whether cross resistance develops between different Bt toxins or whether rotation between a rather limited set of herbicides will be sufficient to delay resistance.

A bottom-up approach to resistance management relies on multiple strategies to control insects and weeds that includes non-chemical control and is usually information-intensive. Extension can play a critical role in bottom-up IPM and IWM strategies. First, it can provide basic in-
formation about the nature of intertemporal trade-offs and common pool resource problems of susceptible pests.

The history of cooperative extension in Arizona is a good example of effective extension intervention to further area-wide IPM (Frisvold, 2009). In Arizona and Southern California an extensive area-wide IPM program was already in place before the introduction of Bt cotton. This program included increasing reliance on insect scouting, narrow spectrum insecticides, non-chemical control (such as mandatory plow-down requirements to prevent overwintering of pests), and sterile moths. It also included extension programs in pest complexes and active resistance monitoring. Introduced into this mature IPM system, Bt cotton has performed extremely well. The main target pest in the region is pink bollworm, which has shown no sign of resistance evolving.

A Bt Cotton Working Group was established in Arizona that instituted intensive farmer education programs emphasizing the common pool resource problem of Bt resistance. The Working Group included participants from grower groups, seed distributors, and cooperative extension. It facilitated detailed geo-coded monitoring of refuge requirement compliance, developed remedial action plans, and has even recommended more stringent location requirements for refuges to EPA. The call for stricter regulation from a grower group seems curious at first. However, through extension and education efforts, growers appreciated the value of taking steps to delay resistance. Second, because the recommendations came from “the bottom up,” growers already expected the change in regulations and had time to adjust voluntarily before the regulations became binding. Third, the Working Group’s science-based recommendations also included calls for regulatory flexibility in other areas that benefited growers (such as variances for seed production and approval to implement more types of refuges). EPA has been willing to increase the flexibility of regulations if it is scientifically defensible and does not undercut their IRM goals. The ability to apply different refuge options substantially reduced the short-run costs of refuges (Frisvold and Reeves, 2008).
The U.S. Southwest is an example where a Bt crop (cotton) has been embedded in integrated pest management system with strong, outward extension linkages to farmers and backward linkages to research institutions. The area has seen no decline in the susceptibility of pink bollworm to Bt cotton and total insecticide use has declined. In some years, reductions in sprays for pink bollworm have outweighed increased sprays to non-target pests. In others, sprays for both pink bollworm and non-target pests have declined (Frisvold, 2009).

Collective action by producers has been a key to the success of Bt cotton in the Southwest. Producer groups have financed data collection and resistance management education programs. They have made data available for both research and regulatory decisions. Extension education has not been unidirectional from the university to growers. Growers have educated scientists and regulators about Bt cotton performance in the field. Grower organizations have also been instrumental in funding and self-enforcement of area-wide IPM practices (such as plow-down requirements and short-season cotton production). The role of growers in providing needed data, funding, and self-regulation serves as a lesson to scientists and regulators. With advances in geographic information systems (GIS) and grower assistance, it is now possible to collect detailed, spatial data on grower adoption of biotechnology, chemical use, yields, and compliance with refuge requirements, as well as data on populations of pests and beneficial insects (e.g. Carriere et al., 2005; Cattaneo et al., 2006). However, if grower-supplied data is only used to ratchet up regulation, it will be less forthcoming (Frisvold, 2000). For growers, a lesson is that providing scientific data to regulators can be a means of supporting appeals for more flexible and less costly regulations.

Arizona’s experience, however, highlights the value of grower collective action in resistance management. There, cotton has gone from an insecticide-intensive crop to a low-insecticide crop in 15 years. Bt cotton has become the centerpiece of an area-wide program in the U.S. Southwest (and northwest Mexico) to eradicate pink bollworm from the region. Pink bollworm populations
have been reduced to such a degree that a program with a target of 100% Bt cotton planting along with release of sterile moths is hoped to achieve regional eradication.

**Lessons for developing countries**

Experience from the U.S. Southwest demonstrates that Bt crops can (a) be highly compatible with IPM, (b) lead to substantial reductions in insecticides sprays for target pests, (c) lead to reductions in sprays for all pests, (d) reduce yield losses and variability, and (e) be deployed extensively over large areas for several years without the evolution of resistance. However, significant investments in IPM institutional capacity were made well before the arrival of Bt cotton. Regulatory agencies also had significant scientific capacity to formulate resistance management policies. Furthermore, grower groups were actively engaged in cooperative resistance management and area-wide pest control both prior to and after Bt cotton introduction. There was also a constant two-way flow of data and scientific information between growers, university specialists, and the EPA. Bt and HR crops have been deployed in many developing countries with far less institutional capacity or active grower engagement in “bottom-up” cooperative resistance management.

The performance of transgenic crops will depend on the institutional and environmental setting where they are deployed as much as properties of the technologies themselves (e.g., see Fitt, 2008; Pemsl, 2007; Pemsl et al., 2008). Resistance management is information-intensive and requires cooperative behavior. A “loading dock” approach of simply making new varieties available and letting growers passively select between a narrow range of products will not succeed at maintaining the effectiveness of Bt or HR crops. Growers with prior IPM training have been better able to achieve benefits from transgenic crops (e.g., Yang, et al., 2005). Problems with secondary pests of Bt crops have been more pronounced in settings where growers had less understanding of pest population dynamics (Wang et al., 2006; Lemaux, 2008; Fitt, 2008). Grower awareness and understanding of the process of resistance also is associated with greater compliance with resistance management policies (Goldberger et al., 2005; Kruger et al., 2009). Grower
awareness of the importance of resistance management has been low among small holders in South Africa (Bennett, et al., 2003; Kruger et al., 2009). In the Vaalharts region of South Africa, rates of compliance with refuge requirements have been low. This has contributed to rapid evolution of resistance of maize stalk borer to Bt corn (Kruger et al., 2009).

Conclusions

While IR Bt crops and HR crops can provide significant economic and environmental benefits, these benefits are threatened by the evolution of insect and weed resistance. Failure to develop successful resistance management strategies will not only deprive current adopters of the benefits of crop biotechnology, it will also have a powerful negative demonstration effect on regions contemplating biotechnology approval. Field level resistance has developed in three cases for Bt crops. This has not led to economically important field level pest control failures, either because the Bt crop variety was withdrawn from the market, because chemical control of the resistant pest remains effective, or because alternative Bt toxins remain effective. For HR crops, resistance problems are a reality in the southeastern United States. Adoption of HR crops in the United States has been rapid, in part, because HR crops made weed control less management-intensive. I argue however that effective resistance management is fundamentally knowledge and management-intensive.

Public and private plant breeding can play a critical role in delaying resistance by developing pyramided and stacked traits that reduce overreliance on single chemical compounds. For Bt crops this is achieved by pyramiding multiple Bt toxins. For HR crops this involves adding resistance to multiple herbicides with different modes of action. However, this second generation of crop varieties still relies on a relatively narrow set of traits. Moreover, some insects and weeds have already developed resistance to individual traits that are being combined. It remains to be seen whether simply adding this small number of new traits will significantly forestall resistance evolution.
This paper has argued that IR and HR crops will be more sustainably deployed if they are embedded in integrated pest management (IPM) and integrated weed management (IWM) with strong, outward extension linkages to farmers and backward linkages to research institutions.

While extension plays an obvious role in disseminating information, it can also serve two other important functions. First, it can facilitate farmer collective action for area-wide resistance management. Second, it can provide government agencies with information needed to increase the flexibility and cost-effectiveness of resistance management regulations. A lesson for developing countries is that resistance will be less likely to evolve if IR and HR crops are deployed in combination with active IPM and IWM programs.
References


### Table 1. Adoption of genetically modified (GM) crop varieties (as a share of world hectares and as a share of hectares in approving countries)

<table>
<thead>
<tr>
<th></th>
<th>Cotton</th>
<th>Maize</th>
<th>Canola</th>
<th>Soybeans</th>
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<tr>
<td>Total World Hectares Planted to GM Varieties (%)</td>
<td>49%</td>
<td>23%</td>
<td>27%</td>
<td>66%</td>
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<td>Hectares Planted to GM Varieties in Countries Where GM Varieties of Crop Have Been Approved (%)</td>
<td>78%</td>
<td>60%</td>
<td>72%</td>
<td>90%</td>
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<td>Hectares in Countries where GM Varieties of Crop Have Been Approved (% of total)</td>
<td>63%</td>
<td>39%</td>
<td>37%</td>
<td>74%</td>
</tr>
<tr>
<td>Hectares in Countries where GM Varieties of Crop Have Not Been Approved (% of total)</td>
<td>37%</td>
<td>61%</td>
<td>63%</td>
<td>26%</td>
</tr>
</tbody>
</table>

Source: Author’s calculation from James (2009) and FAOSTATS (UN, FAO)
Table 2. Price Indices for Agricultural Inputs in the United States (prices paid by producers)

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<tr>
<th></th>
<th>Herbicides</th>
<th>Insecticides</th>
<th>Fertilizer</th>
<th>Fuels</th>
<th>Labor</th>
<th>Tractors</th>
<th>Production Items</th>
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<tr>
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Percent Change

<table>
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<tr>
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<th>2007-09</th>
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<tr>
<td>Herbicides</td>
<td>4%</td>
<td>16%</td>
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<tr>
<td>Insecticides</td>
<td>14%</td>
<td>9%</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>79%</td>
<td>27%</td>
</tr>
<tr>
<td>Fuels</td>
<td>149%</td>
<td>-14%</td>
</tr>
<tr>
<td>Labor</td>
<td>44%</td>
<td>6%</td>
</tr>
<tr>
<td>Tractors</td>
<td>33%</td>
<td>11%</td>
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<tr>
<td>Production Items</td>
<td>34%</td>
<td>14%</td>
</tr>
</tbody>
</table>
Figure 1. Number of weed species with glyphosate resistant populations (blue) and number of states with glyphosate-resistant weed populations (red).

Source: Heap, 2009
Figure 2. Cost of all herbicides and of glyphosate relative to cost of all production items in US agriculture

Source: US Department of Agriculture, National Agricultural Statistical Service