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The Impact of Bt Crops on the Developing World

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Genetically modified (GM) plants are grown on more than 67 million hectares in 18 countries worldwide. A major trait used in GM crops is plant resistance to insects; this trait is based on several Bt proteins. The benefits accruing to farmers growing Bt crops are substantial across a number of geographies and economic strata, especially in developing countries. These benefits include increased crop yields, reduced pesticide use, less environmental damage, less fungal contamination, and reduced labor. Constraints to broader use of GM traits in a wider variety of food crops and in a larger range of countries include the lack of regulatory bodies in some countries, access to credit, support institutions such as extension or seed company technical advisors, and public acceptance, especially as it relates to international trade.

Key words: Africa, Bt, Bacillus thuringiensis, China, cotton, developing world, GM, India, insect, pest, maize, Philippines, potato.

Genetically modified (GM) plants are already phenomenally successful; they are being grown on more than 67 million hectares (ha) in 18 countries worldwide, and the amount is increasing by 10% or more annually (Table 1; James, 2003a, 2003b). This remarkable growth has all occurred since 1994, when the first transgenic crop, the Flavr Savr tomato, became available to farmers. Seven such crops are currently being grown (cotton, canola, maize, papaya, potato, soybean, and squash), but most of the world's bioengineered hectarage is in cotton (7 million ha), maize (10 million ha), and soybean (33 million ha; James, 2003a, 2003b). Two agronomic traits—resistance to herbicides and resistance to insect pests—account for virtually all planted hectares.

The commercial, economic, and social benefits resulting from the use of herbicide and insect resistance traits is now widely established in North and South America as well as Australia and Asia (Table 2; James, 2003a, 2003b; Shelton, Zhao, & Roush, 2002). Genetically modified crops are most often associated with high-input industrial economies, but farmers in the developing world are rapidly adopting them. Surprisingly, nearly one third of all GM crop hectares are now grown in developing nations. Genetically modified crops provide much for the developing world, where yield constraints such as insects are often far more crippling than in the industrial world. In those places where high percentages of the population are farmers and crop productivity is low, the ramifications of crop pest, weed, and disease control are profound. To explore the implications of GM crops for the developing world, it is useful to focus on just one trait—resistance to insect pests. We will proceed by first briefly outlining the experience gained using insect-resistant crops in the industrialized world over the last decade and then describing how these technologies are being adopted and adapted for use in developing countries.

Plant Incorporated Protectants—Bt Crops

Crop plants bioengineered to produce insect specific toxins—termed "plant incorporated protectants" (PIPs) by the United States Environmental Protection Agency (EPA)—were first sold to farmers in the late 1990s. They have proven to be one of the safest, most effective means of insect control ever developed (http://www.epa.gov/pesticides/biopesticides/pips/). Currently, all commercial PIP crops are based on genes encoding various forms of insect-specific toxins from the bacterium *Bacillus thuringiensis* (Bt; Federici, 2002). Bt is a natural choice for this role, because it produces a large variety of toxins expressed from single genes that are very specific for certain orders of insect pests (e.g., *Lepidoptera*, larvae of butterflies and moths, or *Coleoptera*, beetle larvae). Bt also has a long history of safe use going back to the 1930s (Shelton et al., 2002). Past or present commercialized Bt crops and their respective Bt genes include cotton (*cry1Ac*, *cry2Ab2*, *cry1Fa2*), maize (*cry1Ab*, *cry1Ac, cry1Fa2, cry3Bb1, cry9C*), and potato (*cry3Aa)* (Federici, 2002; Shelton et al, 2002). Future PIPs include engineered chimeric Bt toxins (e.g., a Cry1Ac/Cry1Fa hybrid protein; Perlak et al., 2001), vegetative insecticidal proteins such as Vip3A (Estruch

Table 1. Countries growing Bt-based PIP crops in 2004.

Country	Crop	Trait	All GM acreage
Australia	Cotton[a]	Cry1Ac, Cry2Ab	0.1 million ha
Argentina	Cotton[a]	Cry1Ac, Cry2Ab	13.9 million ha
	Maize[b]	N/A	
Brazil	GM (but not PIP)		3.0 million ha
Bulgaria	Maize[b]	Cry1Ab	<0.05 million ha
Canada	Maize[b]	Cry1Ab	4.4 million ha
China	Cotton[a]	Cry1Ac	2.8 million ha
	Rice	Multiple	
Columbia	Cotton[a]	Cry1Ac	<0.05 million ha
	Maize	Cry1Ab	12,000 acres
Germany	Maize[b]	Cry1Ab	<0.05 million ha
Honduras	Maize[b]	Cry1Ab	<0.05 million ha
India	Cotton[a]	Cry1Ac	0.5 million ha
Indonesia	Cotton[a]	Cry1Ac	<0.05 million ha
Mexico	Cotton[a]	Cry1Ac	<0.05 million ha
Philippines	Maize[b]	Cry1Ab	<0.05 million ha
Romania	Soybean	No insect traits	> 0.05 million ha
South Africa	Cotton[a]	Cry1Ac	0.4 million ha
	White and yellow maize[b]	Cry1Ab	
Spain	Maize[b]	Cry1Ab	<0.05 million ha
United States	Cotton[a]	Cry1Ac, Cry2Ab	42.8 million ha
	Maize[b]	Cry1Ab, Cry1Fa, Cry3Bb	
Uruguay	Maize[b]	Cry1Ac	>0.05 million

[a] Bt cotton is grown in nine countries: Australia, Argentina, China, Colombia, India, Indonesia, Mexico, South Africa, and the United States.

[b] Bt maize is grown in eleven countries: Argentina, Bulgaria, Canada, Columbia, Germany, Honduras, Philippines, South Africa, Spain, Uruguay, and the United States.

Note. Data from James (2003a, 2003b, 2004a, 2004b).

et al., 1996), binary Bt toxins (Baum et al., 2004; Ellis et al., 2002), as well as hybrid Bt toxins targeting multiple insect orders (Naimov, Weemen-Hendriks, Dukiandjiev, & de Maagd, 2001). Additional crops (e.g., apple, broccoli, cabbage, tobacco, tomato, soybean, and rice) have also been engineered to express Bt genes but have not yet been commercialized.

Insect-Protected Cotton

The first broadly successful commercial PIP crop, Bollgard cotton, was marketed in the United States in 1996. By 2000, it was planted on 1.8 million acres (or about 12% of the total US cotton acreage; Perlak et al., 2001). Bollgard cotton was developed to control several lepidopteran pests of cotton through the Bt *cry1Ac* gene. Bollgard cotton has two significant benefits for US farmers and society. The first benefit is economic: Studies conducted in the late 1990s showed that US growers obtained an average yield advantage (the sum of increased yield and decreased insect control costs) of nearly $50/acre (Perlak et al., 2001). The second benefit directly impacts farmers and indirectly impacts consumers. Because of the high value of cotton lint and the extensive damage done by insect pests, cotton fields were heavily sprayed with conventional insecticides. The introduction of Bollgard cotton triggered a dramatic reduction in the use of insecticides. During the first year Bollgard was planted, the US cotton belt had the lowest recorded pesticide application rate since the 1940s (Smith, 1997).

Nine countries now produce or shortly will produce commercial Bt cotton. These are Argentina, Australia, China, Columbia, India, Indonesia, Mexico, South Africa, and the United States (Cabanilla, Abdoulaye, & Sanders, 2003; James, 2003b). This list illustrates that cotton is also an important crop in many developing

Table 2. The commercial, economic, and social benefits of Bt crops.

Impacted areas	Current	Future
Agricultural practices	• Less and/or more efficient use of pesticides • More efficient use of water • Increased productivity	• More diversified agricultural products • Quality traits crops • Pharmaceutical crops
Government and social	• Macroeconomic gains • Higher efficiency of agricultural sector • Improved food and feed quality	• Increased consumer confidence • Greater improvements in food and feed quality
Economic benefits—growers	• Improved control of insects and weeds • Reduced input costs such as labor and chemical application costs • Increased yields • Reduced exposure • Increased incomes	• Trends will continue • Movement away from subsistance farming as farmer incomes improve and more modern agricultural practices are adopted
Economic benefits—consumers	• Reduced food costs • Less pesticide usage • Lower pathogen loads	• Greater range of affordable food choices, including quality traits

nations and is particularly well suited to small-scale farming (Burgeat & Tangermann, 2003). Cotton pests are similar around the world, so Bt cotton can be used effectively in most places. Indeed, the developing world badly needs better cotton insect control for several reasons. First, conventional insecticides are not always the best solution, due to their lack of availability and high cost, insect resistance, the need for applicator training and sprayers that are expensive and not widely available, and so forth. Second, the inherent value of the cotton crop is high. Third, cotton plants are largely outside the consumer food chain. For these reasons, insect-resistant cotton was one of the first transgenic crops used in the developing world. As we will later see, Bt cotton has had an even greater impact in the developing world than in the developed countries.

Bt Cotton in China

The Chinese government began investing heavily in agricultural biotechnology research in the mid-1980s. China's huge population and historic problems with food supply were driving forces for this change. The need for the technology was especially evident for cotton. Growers had used a long list of pesticides on cotton over the years, only to have each fail, due to poor stewardship, when the insects became resistant to them (Pray, Huang, Hu, & Rozelle, 2002). Indeed, China used more insecticides on cotton than most other cotton-growing countries (Pray et al., 2002), and the use was increasing at an alarming rate at the time PIP cotton was introduced (Huang, Hu, Pray, Qiao, & Rozelle, 2003). In addition to a robust program of plant breeding for pest resistance, the Chinese government commissioned the Chinese Academy of Agricultural Sciences (CAAS) to develop at least two Bt-based cotton varieties for release to growers (Shelton et al., 2002). One of the resulting varieties makes use of a bioengineered *cry1Ab/cry1Ac* hybrid gene. The other expresses a hybrid combination of a Bt gene and a gene encoding a cowpea trypsin inhibitor (*CpTI*). Monsanto Company also collaborated with the CAAS and the Hebei Seed Company to introduce Bollgard cotton into China. As of 2000, about 60% of all Bt cotton hectares in China were planted with the Bollgard-derived varieties (Pray et al., 2002; Huang et al., 2003). In 2003, 2.8 million ha of Bt cotton were planted in China (James, 2004a).

Bt cotton varieties in China dramatically reduced the use of conventional pesticides, by an average of 60–70%, positively affecting farmer profits. Like other developing countries, cotton plots in China are small, averaging 0.5–2 ha for the country's 3.5 million cotton farmers (Thomas, Burke, Gale, Lipton, & Weale, 2003). Chinese growers using Bt cotton varieties averaged profit increases of about US$500 per hectare versus growers using conventional non-Bt varieties. This cost savings was due to the reduction in pesticide use and the reduced associated labor costs (Huang et al., 2003). Reductions in insecticide usage has additional benefits in developing countries like China, where pesticides are sometimes manufactured and used with minimal training and few protective measures (Huang et al., 2003; Pearce, 2002).

China's experience with the introduction of GM crop varieties illustrates the need for developing counties to continuously develop and refine country-specific legal, educational, and regulatory stewardship guidelines for GM crops. The CAAS varieties were originally sold through China's national seed network but more recently have been moved into the private sector (Thomas et al., 2003). By 2002, the Chinese government had approved 22 Bt cotton varieties (Thomas et al., 2003). By 2003, those varieties accounted for 58% of all the 4.8 million ha planted to cotton (James, 2003b). Profit margins for institutions that developed the Bt technology remain low, because Bt seed in China costs little more than conventional seed. This is because many farmers save their own seed or purchase seed from other farmers that do (Huang et al., 2003). This may seem a positive result for Chinese farmers at first glance, but over the longer term it will likely result in more restricted access to new varieties (Tatge, 2000). Generally speaking, removing the mechanisms for technology producers to benefit from the development of the technology also removes the incentive to develop and sell the new varieties; this practice will likely continue to erode value and availability (Tatge, 2000). Another problem is that seed produced outside of the institutional quality control of breeding programs may frequently result in poorer-performing varieties that could be problematic from an insect-resistance management perspective.

Bt Cotton in India

India is a major cotton-producing country. It ranks first in total land area devoted to cotton, with some 4 million cotton farmers growing 25% (9 million ha) of the world's total. Cotton plots average a little more than 2 ha each (James, 2003b). Yet India ranks third behind the United States and China in total cotton lint production, with about 2.7 million tons produced annually ("Monsanto-backed survey," 2004). Major production constraints are insects, disease, water, and fertilizer (James, 2003a, 2003b). Indian farmers often lose up to half of their entire cotton crop to the cotton bollworm (Tatge, 2000) and spend nearly $350 million dollars a year on conventional pesticides (Jayaraman, 2004).

The demand for a technical solution to the bollworm problem was quite intense in India. Bollgard cotton was the first commercial Bt hybrid cotton seed sold in India for insect control. Indian Bt varieties were developed by a licensing agreement between Monsanto India Ltd. and the Maharashtra Hybrids Seeds Co. (Mahyco), who bred the resistance gene into locally adapted Indian germplasm (James, 2004a). These hybrids were released to farmers and planted on approximately 24,000 ha in 2002 (Jayaraman, 2004). The use of Bt cotton continues to increase in India, with hectarage expanding to nearly 90,000 ha in the 2003 plantings, and is estimated to have climbed to nearly 1,300,000 acres (520,000 ha) for 2004 plantings ("Monsanto's bio-engineered cotton seed," 2004). New varieties are also being developed for regions of India that experience colder temperatures or shorter growing seasons (Tatge, 2000).

Preliminary figures on hybrid performance are just now becoming available. They suggest that the new Bt cotton varieties are performing very well. For example, in a nationwide survey conducted by AC Nielsen ORG-MARG, Bt cotton hybrids produced lint yields approximately 22% better than conventional varieties and produced nearly 1,898 kg/ha versus 1,473 kg/ha for the conventional varieties. This means an increase in net profits for the Bt cotton growers of 78% over that of conventional growers ("Monsanto-backed survey," 2004). The success and widespread use of the initial Bt cotton varieties has encouraged other institutions to participate as well. For example, the Indian National Agriculture Research System is developing Bt cotton varieties that will make use of the *cry1Ac* gene as well as a *cry1Ec* gene and are expected on the market in the next three years (James, 2004a; Jayaraman, 2004). Finally, India is also conducting field trials for several other crops, including mustard, rice, potatoes, and cauliflower ("Monsanto-backed survey," 2004).

Bt Cotton in South Africa

Cotton is grown widely in Africa and is planted on some 2.5 million ha, usually on plots of less than 10 ha each (Thirtle, Ismael, Piesse, & Beyer, 2003). Currently, South Africa is the only country in Africa in which GM crops of any kind are grown commercially. Bt cotton and Bt maize are being grown (Thirtle et al., 2003). Cotton accounts for about 1% of the total South African crop production, generating about $50 million annually (Thirtle et al., 2003). In many ways, South Africa contains an amalgamation of both first and third world farming practices. The demographics of cotton production in South Africa provide a model for comparing the benefits of the Bt cotton technologies among farmers using different growing practices. Cotton growers in South Africa are comprised of two groups. The first consists of some 1,530 commercial farmers, who raise 50,000–100,000 ha of cotton annually, or an average of somewhere around 50–65 ha per farmer. The other group, comprised mainly of Zulu people, consists of some 3,000 smallholders who raise some 3,000 ha of cotton annually, or an average of about one hectare per farmer.

Many smallholders in South Africa adopted Bt cotton rapidly. The adoption rate and pattern may provide lessons for the adoption of PIP technologies in other developing countries. Early surveys conducted in the Makhathini Flats area of South Africa show that early adopters of Bt cotton were older farmers with larger farms; traits associated with a farmer's experience and ability to access credit (Bennett, Buthelezi, Ismael, & Morse, 2003; Thirtle et al., 2003). In the early surveys, nonadopting farmers indicted that they too would purchase Bt cotton if they had access to credit to purchase the seed. Even with this limitation, the adoption rate of the technology is phenomenal. Within four years of its introduction, the adoption rate rose from 2.5% to nearly 90%. As with commercial introduction experiences in the United States, factors such as (a) efficacy, (b) lower chemical-related costs, in particular the labor component, and (c) increased yields were the driving forces for adoption of the technology in South Africa. Perhaps the most important factor for adoption was the reduction in labor (Bennett et al., 2003). An average farmer spends one day collecting water and one day spraying for every hectare of cotton grown per season. Spraying is done with hand sprayers, and a cotton farmer typically walks an average of 63 km per season. No protective clothing is worn due to the extreme heat. Efficacy was also important, particularly in years in which heavy rains fell. In those years, traditional spray insecticides perform very poorly. Economically, the use of PIP cotton by smallholders generated an average $40/ha in income in addition to savings in labor. If that profit margin were extended to the rest of Africa, the potential income generated for farmers would be about US$100–600 million (Cabanilla et al., 2003; Thirtle et al., 2003).

Finally, one area that is critical for long-term success of the product is grower education on the use and practical consequences of Insect Resistance Management (IRM). The sustainable use of PIP technologies is dependent on the managed use of the technology in a manner that minimizes selection for resistant insects. Extensive efforts have been made to educate growers in this arena, but continued efforts to improve these programs are needed (Bennett et al., 2003). South Africa is likely not unique in this regard.

Bt Cotton in West and Central Africa

West and Central Africa (WCA) are two of the world's poorest regions. In Nigeria, the largest economy in the WCA, 70% of the population lives in poverty, subsisting on less than a dollar a day (United States Agency for International Development, 2004). Cotton is the major cash crop grown in many WCA countries and can supply as much as 19% of the GDP, thus affecting millions of lives (Elbehri & MacDonald, in press). Cotton is also a major WCA export commodity, supplying 15% of the world's total cotton supply. Cotton production in WCA increased fourfold from the early 1960s until 2000, and then started falling due to rising production costs and declining subsidies and yields. Insecticides are one of the major input costs for cotton production in WCA. The emergence of insecticide-resistant insect populations, as well as a desire to reduce the use of pesticides, has led to a push by some WCA countries to assess the potential value of Bt cotton.

Bt cotton is just now being field tested in one WCA country, Burkina Faso, so data showing the impact of Bt cotton on WCA farmers are not yet available (Ouedraogo, 2003). However, Elbehri and MacDonald (in press) have examined the potential benefits of introducing Bt cotton into the WCA and have concluded that the technology would have many of the same benefits observed in other regions of the world. Of real importance to the countries of WCA are the estimates of labor savings and increased income. Labor inputs in cotton are substantial and often detract from labor needs in food crops such as cowpea, an important protein-containing food in the region. The use of Bt cotton could allow the labor pool to focus more on food-crop production or other capital-generating enterprises. Extra earnings, in turn, would allow farmers to increase food imports to an area that experiences frequent caloric shortfalls. Overall, even a modest adoption of Bt technology could increase the welfare of the region by US$40–100 million annually.

One issue that is often not addressed in discussions of biotechnology-based crop solutions is consequences of nonadoption. For the WCA, estimates suggest that nonadoption in the WCA region could lead to lower earnings, lower exports and a lower share of the global cotton market (Cabanilla et al., 2003).

A lesson learned from the successful adoption of Bt cotton by smallholders in South Africa is probably of relevance to smallholders in WCA as well as to smallholders worldwide. When adoption rates of Bt cotton were compared in two different regions of South Africa—one in which there was a commercial seed company and its attendant support services (e.g., extension specialists and credit suppliers) and one without—the rate of the technology adoption was significantly higher in the region where there were support services (Thirtle et al., 2003). Adoption of this technology, and perhaps adoption of technology in general, is significantly enhanced by services provided to the growers.

Bt Cotton in Mexico

As in the United States, the Bollgard variety of Bt cotton was first commercialized in Mexico in 1996 (Traxler, Godoy-Avila, Falck-Zepeda, & Espinoza-Arellano, 2002). The Bollgard varieties were the same as those used in the United States, Argentina, China, and South Africa. Adoption of Bt cotton varies widely in Mexico, where it currently constitutes about a third of all cotton acres. Adoption appears to depend on the species-specific lepidopteran pest pressure as well as the presence of the boll weevil beetle, which is not controlled by current Bt varieties. Successful cotton farming in Mexico is heavily dependent on a supply of water for irrigation; significant fluctuations in Bt cotton plantings occur due to water availability. Bt cotton is grown on some 200,000 ha with an average plot size of 14 ha. Similar to the Bt experience in other countries, the use of Bt cotton has resulted in a dramatic 80% reduction in pesticide sprays and a spray schedule reduction from six to two when compared to the preintroduction situation. Because Mexico has programs of integrated pest control and boll weevil eradication, not all of the spray reductions can be attributed solely to Bt cotton (Traxler et al., 2002).

The highest rate of adoption of Bt cotton in Mexico is in the Coahuila region, where 96% of the acreage is planted in Bt cotton. The Coahuila region borders the US state of Texas. Cotton producers in Coahuila have access to financing and credit provided by farmer associations as well as industry technical representatives, which together probably account for the high adoption rate. In a theme common in other countries, there are two groups of cotton producers in the Coahuila region, differentiated mostly by the size of their cotton fields. One group, the *Ejidatarios,* farm an average of 2–10 ha, and the other group, the small landholders, farm 30–100 ha (Traxler et al., 2002). Economically, the introduction of Bt cotton into Coahuila has been positive for the growers. The region accrues an estimated US$2.7 million annually in economic benefits due to Bt cotton with nearly 85% of the benefit going to the grower via an average reduction in pest control costs of US$100 and a US$295/ha net revenue increase.

Bt Cotton in Latin America

Like cotton producers in other countries, Argentinean cotton producers suffer substantial loses due to lepidopteran insect pests, yet they have been slow to adopt new Bt cotton varieties that could substantially reduce their losses and increase profits. The adoption rate is about 5% of the national cotton growing area (Qaim, Cap, & de Janvry, 2003; Qaim & de Janvry, 2004). The reasons for the low adoption rate may reflect the socioeconomic conditions of the target country. Bt cotton is also being adopted in other Latin American countries. It was introduced into Colombia in 2001; the area expanded to about 4,800 ha in 2003 (James, 2004a).

Bt Cotton Summary

The future for Bt cotton looks very good. Bt cotton has demonstrated that the benefits of modern biotechnology are useful and desirable by people in low-resource and emerging economies. The best example is South Africa, where low-resource farmers, many of them women, take home an extra US$85 per season and no longer have to walk nearly 100 km carrying hundreds of gallons of water (Bennett et al., 2003; "Developing countries," 2002).

In addition to the first-generation Bt cotton varieties reviewed above, a number of private and public research institutions are developing new and enhanced PIP cotton products. Monsanto Company is already selling its second-generation Bt cotton product, Bollgard II, which uses a combination of the *cry1Ac* and *cry2Ab* genes—a combination that makes Bollgard II cotton very effective against nearly all lepidopteran pests. Dow AgroSciences is planning to release PIP cotton varieties containing the *cry1A*c and *cry1F* gene combination, which it hopes will also have broad lepidopteran activity. Finally, Syngenta is planning on release of a PIP cotton variety using a Bt *vip* gene (James, 2003b).

Worldwide, the use of Bt cotton has had a significant impact on people and their environment. The use of Bt cotton varieties in the United States has resulted in a decrease of nearly 862 metric tons of insecticides per year while increasing cotton yields by 83,916 metric tons (Penn, 2003). The economic and social impact of Bt cotton on growers in the developing world has been strikingly positive. Most cotton in the developing world is grown on small plots that directly support families. In fact, 99% of the 5 million people involved in growing Bt cotton worldwide reside in developing countries (James, 2003b). The experiences of these Bt cotton farmers has been for the most part very positive, resulting in significant improvements in their lives as measured by effects on their economic and social status, environment, and health (Mackey, 2003). Ultimately, GM technologies may prove to be a useful tool in contributing to the alleviation of poverty and a better quality of life (Pray et al., 2002).

Bt Maize

In the past, in the United States, stalk-boring lepidopteran caterpillars, most notably the European corn borer (ECB), extensively damaged large hectarages of maize causing damage in excess of $1 billion annually. The use of conventional insecticides was not as extensive in maize as in cotton, because stalk borers develop inside maize stalks and are nearly impossible to reach with insecticides. Farmers and consumers simply had to accept the damage and spoilage resulting from insect infestations (Shelton et al., 2002). Effective control required either systemic insecticides or careful scouting to time sprays for maximum effect. When Bt maize became available, it was recognized as a timely solution to control of stalk-boring lepidopteran maize pests, which could not be easily controlled any other way.

Three different Bt maize products for control of stalk borers were commercialized in the 1990s in the North American market. These were Mon810, marketed as YieldGard (Monsanto), Event 176, marketed as Knockout (Syngenta), and Bt11, which was licensed to Syngenta by Monsanto and which has been used in both field (YieldGard Corn Borer) and sweet (Attribute) corn varieties. These products were based on the *cry1Ab* gene (Shelton et al., 2002). Recently, a new maize event for control of lepidopteran pests, based on the *cry1Fa2* gene, was released by Dow AgroSciences and Pioneer Hi-Bred (Herculex I). Other new maize lepidopteran control products now in development include Bt gene combinations from Monsanto, Bt *vip* technologies from Syngenta, and binary Bt-based approaches from Dow Agrosciences. In addition to the lepidopteran control products mentioned above, there is now a commercial product developed by Monsanto for control of a soil-dwelling beetle (western corn rootworm) based on an engineered *cry3Bb1* gene (YieldGard Rootworm).

Spain is the only country in the EU to raise any significant quantity of GM crops. About 22,000 ha (or 5% of the total Spanish maize growing area) have been planted to Bt maize varieties since 1998 (Council for Biotechnology Information [CBI], 2004b; Farinos et al., 2004). The Spanish maize crop is used as animal feed. Overall, Spanish Bt maize growers averaged an additional US$207/ha, reduced or eliminated insecticide sprays in some areas, and saw significant reductions in toxic mycotoxin levels when compared to farmers using conventional maize (CBI, 2004b; James, 2003a). Similar benefits would probably accrue for the whole of Europe if Bt maize were more widely adopted. This might be especially true for control of the western corn rootworm (WCR).

The WCR is native to North America and was introduced into Yugoslavia sometime early in the 1990s. Since that time, it has spread rapidly throughout the Balkans and into France, Hungary, and Italy (Hundley, 2001; Soria, 2003). It is expected to spread next into Austria and the Ukraine. Estimated crop losses in Europe due to WCR damage are as high as US$400 million/year and could put large numbers of farmers out of business (Hundley, 2001). Monsanto's newly developed YieldGard Rootworm Bt maize would seem a timely tool for combating this new pest.

Like Bt cotton, Bt maize has two important benefits to farmers and consumers in North American markets. The first is that growers now have an effective means of controlling stalk-boring insects. Indeed, the use of this technology finally revealed the true extent of the economic damage caused by stalk-borer feeding. Studies conducted since the introduction of Bt maize varieties reveal that stalk-boring insects, such as ECB, cause an estimated 4.5% reduction in maize yields in the United States and up to 10% outside the United States (James, 2002, 2003b). Prior to the introduction of Bt maize, only limited efforts were made to control stalk-borer damage.

The second benefit directly affects consumers. Coarse grains, including maize, are highly susceptible to contamination by fungi. Two common grain-infesting fungi are *Aspergillus* and *Fusarium* (Barrett, 2000). These fungi produce a series of poisons known as mycotoxins, which are linked to organ diseases and cancers in humans and animals. The most important mycotoxins are aflatoxin and fumonisin. Insects frequently contaminate maize grain with *Aspergillus* and *Fusarium* fungal spores as a result of feeding. In addition to vectoring the disease-causing fungi, they also weaken the plant's defenses, increasing the rate of fungal infection. Early studies showed that GM maize varieties expressing insect-controlling proteins in their kernels produced less fumonisin toxins than did conventional varieties (Munkvold, Hellmich, & Rice, 1999). Fumonisin levels were also higher in Bt maize varieties that lacked seed expression, supporting the link between reduction in insect feeding and lower fumonisin levels (Munkvold et al., 1999). Later studies show that fumonisin levels were up to 90 times lower in Bt maize varieties (Hammond et al., 2004; Nester, Thomashow, Metz, & Gordon, 2000). Similar results supporting the utility of Bt maize to reduce mycotoxin contamination has been documented for aflatoxin levels in maize as well (Williams, Windham, Buckley, & Daves, 2002).

As emerging economies continue to grow, the demand for maize grain is estimated to reach 850 million metric tons by 2020 and is expected to exceed that of wheat and rice (James, 2003a). Current worldwide maize production is about 600 million metric tons, leaving a deficit of about 250 million metric tons. Nearly 83% of this will be needed in the developing world. Bt maize, based on the *cry1Ab* gene, could potentially yield an additional 35 million metric tons per year representing about 15% of the needed 266 million metric tons (James, 2003a). Other as yet undeveloped traits, as well as increased use of the current technology in developing countries, could raise the yield potential further.

Bt Maize in Argentina

Bt maize was first marketed in Argentina in 1998 and by 1999 accounted for about 6% of their total maize acreage (United States General Accounting Office [GAO], 2000). Amazingly, by 2000, the adoption rate had increased to about 50% of the national corn crop (Trigo, 2004) and continues to grow at a rate of about 3% per annum (Agrifood Awareness Australia, 2004). Prices for seeds are similar in the United States and Argentina (GAO, 2000). James reports that Bt maize yields average about 10% higher than conventional maize (James, 2003a).

Bt Maize in Brazil

In the 2003 growing season, Brazil planted nearly 3 million ha of GM crops, mostly soybeans, accounting for 4% of the world total (James, 2003a, 2003b). Though not yet approved for commercial use, initial field trial data on the performance of Bt maize in Brazil suggest that the average yield is 24% higher than conventional maize (James, 2003a, 2003b).

Bt Maize in China

Bt maize has not yet been approved for commercial field use in China. Unlike new world maize farmers, Chinese farmers are challenged with many different stem-boring insect pests, so there is a serious need for the technology (He et al., 2003). However, despite the variety of pests, Bt maize tested in field trials has performed very well. Chinese farmers attained yields with Bt maize that are 9–23% higher than with conventional varieties (James, 2003a).

Bt Maize in Honduras

Bt maize was introduced into Honduras in 2001. The area planted increased from an initial 405 ha to nearly 2,025 ha in 2003. Efficacy data and effects on Honduran farmers are not yet available.

Bt Maize in Mexico

Mexico, the center of origin of maize, does not currently grow GM maize (Traxler et al., 2002). However, lepidopteran and coleopteran insects infest Mexican maize; both insect orders could be controlled by the introduction of Bt maize.

Bt Maize in the Philippines

The Philippines grew 20,000 ha of Bt maize for the first time in 2003, becoming the second country in Asia to plant a commercial GM crop (CBI, 2004a; James, 2003b). Yields for Filipino farmers growing Bt maize hybrids averaged 41% to 60% higher than for non-Bt farmers. The average increase in net income was 34%.

Bt Maize in South Africa

Both white and yellow Bt maize are being grown in South Africa. Yellow maize is raised by commercial farmers for animal feed, cornstarch, and corn syrup. Small landholders raise white maize as human food (Thirtle et al., 2003, p. 718). About 1,215 ha of Bt maize were planted in 1998 and 20,000 ha in 1999. Estimates place the current hectarage of Bt maize at 250,000 ha ("GM maize," 2004). The new varieties are performing well, with reported yields averaging about 10% higher than conventional maize (James, 2003a).

Of special interest is the growth in acceptance of Bt white maize, an important food crop in South Africa. Bt maize varieties accounted for 3% of the 2003 harvest and are estimated to account for about 8% and 16% of the 2004 and 2005 harvests, respectively ("Monsanto maize," 2004). By 2010, it is estimated that 50% of both white and yellow maize crops will be Bt maize.

Bt Maize Summary

To date, the worldwide use of Bt maize has significantly benefited people and the environment. Use of Bt-based maize varieties has resulted in an estimated 7,000 metric tons/year decrease in pesticide while enabling a nearly 1.6 million metric ton increase in production (Penn, 2003).

As discussed earlier, an important health benefit accruing to consumers as a result of Bt maize varieties is a reduction in the levels of toxic mycotoxins in maize-based food (Hammond et al., 2004; James, 2003a; Munkvold et al., 1999). In western countries, the maximal daily intake of mycotoxins is rarely exceeded. However, in developing nations where rural people consume large quantities of maize (much of it contaminated with mold), the maximal mycotoxin level is frequently exceeded; the use of Bt maize could help significantly reduce those levels (Hammond et al., 2004; Marasas, 2001).

Though lagging behind cotton, the trend of increased use of Bt maize in the developing world will increase, as exemplified by the recent introduction of Bt maize into Uruguay into 2003 (James, 2004a).

Other Significant Bt Crops in Development

Although not yet commercialized, three other Bt-based crop plants are currently in development: Bt potato, Bt rice, and Bt pulses. Much of the world's population consumes potatoes and rice. Bt potatoes were first developed and sold in the United States in 1994 under the NewLeaf trademark for control of the Colorado potato beetle (Perlak et al., 1993). The use of NewLeaf potatoes led to a significant reduction in pesticide use and cost savings for growers (United States Environmental Protection Agency, 2000). Long considered a niche market and in response to market questions, sales were discontinued in 2001 ("Monsanto exits," 2001).

Bt potato has been under development at the International Potato Center (CIP) in Lima, Peru since the 1990s in an effort to control the potato tuber moth. Potato tuber moths are serious pests in North Africa and Central and South America. Field tests, conducted at multiple locations in each of three years, suggest that the engineered potatoes offer high levels of protection against the moths (Ghislain, Lagnaoui, & Walker, 2003). Deployment of the Bt potato varieties will be dependent on regulatory approvals in the countries in which they are grown as well as the European export market.

Bt rice has been under development at several institutions for several years (Deeba et al., 2004; High, Cohen, Shu, & Altosaar, 2004). Globally, rice stem-borers cause yield losses of 10 million tons (or as much as 5% of all potential grain harvests) and account for 50% of all insecticides used in rice fields. Like maize borers, the rice borers are particularly difficult to control, because they are hard to reach with conventional insecticides. Leading Chinese scientists believe that Bt-rice varieties, developed by several different commercial and academic institutions, are ready for commercial release when the Chinese government approves them ("Scientists push," 2004).

Transgenic rice lines developed using the *cry1Ab* gene have been field tested and found to give complete protection against stem borers (High et al., 2003; Ye et al., 2001, 2003). A modified *cry1Ac* gene also appears to impart resistance (Khanna & Raina, 2002). Lines developed using chimeric *cry1Ab* and *cry1Ac* constructs also performed well (Tu et al., 2000), as did lines using stacked *cry1Ac* and *cry2A* genes (Datta et al., 2002).

Finally, much of the developing world relies on pulses such as beans and peas for a considerable portion of their daily protein requirement. In Asia, particularly India, work is underway to develop Bt chickpeas and groundnuts that resist insect pests (Romeis, Sharma, Sharma, Sampa, & Sarma, in press). For the longer term in WCA Africa, work stimulated by the Network for the Genetic Improvement of Cowpea for Africa (NGICA), in conjunction with the African Agriculture Technology Foundation (AATF) and other partners, has been initiated to develop Bt cowpeas for resistance to pod-boring caterpillars. Initial estimates suggest that Bt cowpea would have a substantial and profound positive effect on the economy and livelihood of WCA peoples.

Summary

In summary, the benefits accruing to farmers growing PIP crops are substantial across a number of geographies and economic strata (Table 2). These benefits include increased crop yields, reduced costs for pesticides, less fungal contamination, and reduced labor. The magnitude of each benefit varies by geography and crop. Reduced labor inputs may be more important to low-resource farmers in South Africa than to farmers in the United States. Reduced pesticide use is important to all farmers but may have more significant social benefits for farmers in a rural emerging economy. Constraints to broader use of PIP traits in a wider variety of food crops and in a larger range of countries remain. These include the lack of regulatory bodies in some countries, access to credit, support institutions such as extension or seed company technical advisors, and public acceptance, especially as it relates to international trade.

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