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Bollgard Cotton: An Assessment of Global Economic, Environmental, and Social Benefits

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INTERPRETIVE SUMMARY

In the late 1980s, Monsanto began development of Bollgard (*Bt*) insect-protected cotton by transformation with a construct containing the *cry*1Ac gene from *Bacillus thuringiensis* var. *kurstaki*. The goal was to provide constitutive in-plant control of key lepidopteran pests in an environmentally friendly manner at a reduced cost. After receiving appropriate regulatory approvals, *Bt* cotton was launched commercially in the United States in 1996, and subsequently in Argentina, Australia, China, Mexico, and South Africa. In 2000, *Bt* cotton was commercially grown on approximately 4 million acres of cotton globally, with >97% grown in the United States. The registration of Bollgard cotton has brought cotton growers an in-plant protection method for use as part of an integrated pest management system.

Numerous published reports have examined the impact of *Bt* cotton on insect pest control, grower cropping methods and lifestyle, and the environment. Yet, few reports have viewed the benefits from a holistic perspective and fewer still have focused on risks associated with *Bt* cotton. In an effort to understand the totality of the benefits associated with *Bt* cotton, this paper focuses on the economic, environmental, and social effects of *Bt* technology as reported in peer-reviewed scientific literature, conference proceedings, government and institutional reports, market research, and company literature.

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The direct benefits documented from using *Bt* cotton to control insect pests include reduced use of broad-spectrum insecticide, lower farming risks and production costs, better yields and profitability, expanded opportunities to grow cotton, and a brighter economic outlook for the cotton industry. The indirect benefits that arise from the use of the crop primarily stem from the reduction in broad-spectrum insecticide use when *Bt* cotton is used for pest control. Reducing the use of broad-spectrum insecticides in cotton produces benefits that include increased effectiveness of beneficial arthropods as pest control agents, improved control of non-target pests, reduced risk for farmland wildlife species, reduced runoff of broad-spectrum insecticides, reduced fuel usage, lower levels of air pollution and related waste production, and improved safety of farm workers and neighbors.

Five years of commercial *Bt* cotton use demonstrate that *Bt* cotton technology has achieved the goal of providing an effective tool for lepidopteran control that is safer to humans and more environmentally benign than broad-spectrum insecticides. Nevertheless, many of the benefits of *Bt* cotton to the environment and to society require further documentation, especially the less tangible benefits, such as increased population densities of wildlife and greater effectiveness of beneficial insects for pest control. Such studies will help to expand our understanding of the range of benefits offered by insect-protected crops that are developed through biotechnology. In addition, an evaluation of any risks associated with biotechnology-derived pest control is necessary to achieve a full perspective on the impact of *Bt* cotton on agroecosystems, growers, the cotton industry, and society.

ABSTRACT

Insect-protected crops like Bollgard (Monsanto Company, St. Louis) *Bacillus thuringiensis* (*Bt*) cotton are bringing cotton growers new alternatives

to broad-spectrum insecticide use in integrated pest management. After five years (1996-2000) of commercial use, a number of benefits of *Bt* cotton technology to growers, the environment, and society at large have been reported; however, the benefits of the technology have not been examined to date from a holistic point of view. Accordingly, the objectives of this paper were to examine the potential economic, environmental, and social benefits of *Bt* cotton compared with broad-spectrum insecticide use, as reported in current literature, and to determine whether the benefits are directly (primary) or indirectly (secondary) related to growing *Bt* cotton. Data reported are from current scientific literature, conference proceedings, government and institutional reports, market research, and company literature. The direct benefits of *Bt* cotton include reduced broad-spectrum insecticide use, improved control of target pests, better yield and profitability, lower production costs, and farming risk, expanded opportunities to grow cotton, and a brighter economic outlook for the cotton industry. The indirect benefits of *Bt* cotton are associated with a reduction in broad-spectrum insecticide use and include increased effectiveness of beneficial arthropods as pest control agents, and better control of non-target pests, reduced risks for farmland wildlife species, less runoff of broad-spectrum insecticides, reduced fuel usage, lower levels of air pollution and related waste production, and improved safety for farm workers and neighbors. While more focused research is needed to fully assess the economic, environmental, and social benefits and risks of *Bt* cotton, the findings after 5 yr of commercial use on >2 $\times$ 10^{6} ha globally indicate that *Bt* cotton provides an effective method for lepidopteran control that is safer to humans and the environment than conventional broad-spectrum insecticides, making *Bt* cotton a valuable new tool in integrated pest management.

Modern biotechnology is dramatically redefining pest management in global cotton production. After a decade of research, transgenic, insect-resistant cotton varieties were developed that enable growers to use an in-plant protection method as part of their integrated pest management programs (Perlak et al., 1990). Data indicate that insect-resistant Bollgard (*Bt*) cotton is helping cotton growers to increase profitability, reduce environmental impact, and enhance their quality of life. *Bt* cotton technology provides benefits not only to the grower, but also to the cotton industry and society at large.

While there are inherent benefits and risks to all agricultural technologies, this report focuses on the global economic, environmental, and social benefits of Bollgard insect-resistant cotton based on current data. Data are from peer-reviewed scientific literature, conference proceedings, government and institutional reports, market research, and company literature. This report also suggests weaknesses in the present knowledge base on the benefits of this new technology.

BACKGROUND

Monsanto developed Bollgard cotton, commonly known as *Bt* cotton, as a novel approach to the control of insect-pest injury in production agriculture (Perlak et al., 1990; Benedict, 1996; Jenkins et al., 1997). The original goal was to provide cotton farmers with more environmentally friendly and efficacious insect control at a reduced cost (Benedict and Altman, 2001).

Resistance to pests, a successful evolutionary survival strategy used by most wild plant species, including cotton, has been dramatically increased through the techniques of modern biotechnology (Adkisson et al., 1999), such that cotton plants developed through biotechnology have been bred to provide specific insecticidal activity against certain cotton pests. To provide cotton with its own in-plant resistance to insect attack from specific lepidopteran species (caterpillars), researchers inserted a gene into the cotton plant's DNA (Perlak et al., 1990). In the plant, the gene produces an insecticidal protein that was modeled on a naturally occurring soil bacterium, *Bacillus thuringiensis* (*Bt*) var. *kurstaki*, with known insecticidal properties (Peferoen, 1997).

Since the 1950s, this bacterium has been used widely by organic and conventional farmers as an aerial insecticidal spray. When a target pest ingests it, the *Bt* protein interferes with the insect's digestive system and causes death. The targets of Bollgard cotton are major caterpillar pests, including tobacco budworm (*Heliothis virescens* Fabricius), bollworm (*Helicoverpa zea* Boddie), and pink bollworm (*Pectinophora gossypiella* Saunders) (Luttrell, 1994; Luttrell et al., 1994), which are some of the most damaging insect pests worldwide (Bottrell and Adkisson, 1977).

Activity of the *cry*1Ac protein produced by the *Bt* gene in Bollgard cotton replaces conventional broad-spectrum insecticide sprays traditionally used to control these major caterpillar pests. Crops genetically enhanced to resist cotton insect pests are expected to facilitate a shift away from current reliance on broad-spectrum insecticides. This genetic enhancement provides a more biologically sustainable method of managing insect pests (Adkisson et al., 1999) in an integrated system for pest management. It also enables growers to manage pests currently resistant to certain insecticides and may allow people who have abandoned cotton production due to economically devastating insect infestations to re-establish their cotton industry (Benedict, 1996).

The production of the *Bt* protein by Bollgard cotton reduces, and in some cases eliminates, the need to spray for major caterpillar and other lepidopteran pests such as cotton leafperforator (*Bucculatrix thurberiella* Busck), cabbage looper (*Trichoplusia ni* Hubner), cotton leafworm (*Alabama argillacea* Hubner), European corn borer (*Ostrinia nubilalis* Hubner), and saltmarsh caterpillar (*Estigmene acrea* Drury). *Bt* cotton has value not only as a replacement for conventional broad-spectrum insecticide applications for specific pests, but also as a pest management tool that can provide benefit beyond replacement of conventional insecticide costs (Wier et al., 1998). These additional benefits include reduced risk to growers' health, improved environment for beneficial insects and farmland wildlife, and a more stable economic outlook for the cotton industry.

The first commercial fields of transgenic insect-resistant *Bt* cotton were grown in the United States in 1996 (Hardee and Herzog, 1997). In the first full season of commercial *Bt* cotton introduction, U.S. cotton growers planted 729,000 ha of *Bt* cotton, which represented 14.0% of the total cotton hectarage (National Agricultural Statistics Service/USDA, 1999a, 1999b) (Table 1). The rate of adoption of *Bt* cotton increased to $>1 \times 10^6$ ha in 1997. Monsanto also has commercialized stacked trait varieties with the genes of both Bollgard and Roundup Ready, which are herbicide-tolerant to applications of Roundup (glyphosate) [*N*-(phosphonomethyl)glycine] herbicide (Table 2). Growers planted an additional 405,000 ha of stacked trait varieties. In 1998 and 1999, U.S. growers planted 972,000 and 931,500 ha of single trait Bollgard cotton, and 202,500 and 648,000 ha of Bollgard/Roundup Ready cotton, respectively. As a result, the amount of total U.S. Bollgard cotton hectarage (both Bollgard single-trait and Bollgard/Roundup Ready stacked-trait varieties) was 1.05, 1.17, and 1.58×10^6 ha in 1997, 1998, and 1999, respectively. The trend continued with 2.10 $\times 10^6$ ha planted in 2000, which represented 33% of the U.S. cotton market (Williams, 2001).

Outside the United States, 78 750 ha *Bt* cotton were planted during the 1998–1999 season in Mexico, Argentina, China, Australia, and South Africa; and the number of *Bt* cotton hectares increased to >121 500 ha in the 1999–2000 season (K. Reding, personal communication, 2000). Bollgard cotton was first commercialized in Mexico and Australia during the 1996–1997 season, and commercial availability in China, Argentina, and South Africa began in the 1998–1999 season.

In the United States, >84% of growers who planted *Bt* cotton in 1999 were satisfied with the crop, and >73% of *Bt* cotton users also indicated they were more satisfied with *Bt* cotton than with a conventional cotton and insecticide program (Marketing Horizons, 1999). *Bt* cotton users considered the new technology a "good value" because it offered "cost effective/efficient insect control" (40% of respondents) and "lower insecticide costs/input cost/cheaper insect control" (25% of respondents). In 1999, *Bt* cotton users planted a majority of their field space (69%) in *Bt* cotton (Marketing Horizons, 1999).

METHODS

Literature from peer-reviewed scientific articles, conference proceedings, government and institutional reports, market research, and company literature was examined for data about economic, environmental, and/or social benefits of *Bt* cotton. Data were analyzed as directly (primarily) or indirectly (secondarily) related to growing *Bt* cotton.

Table 1. Use of Bollgard and Bollgard/Roundup Ready cotton in the United States 1996–2000.†

Year	Bollgard and Bollgard/ Roundup Ready	Total U.S. cotton	Proportion of Bollgard and Bollgard/ Roundup Ready
	ha × 10⁶		%
1996	0.73	5.20	14.0
1997	1.05	5.40	19.5
1998	1.17	4.30	27.2
1999	1.58	5.90	26.8
2000	2.10	6.20	33.9

† Sources: Natl. Agric. Stat. Serv./USDA (1999a, 1999b); Williams (2001).

RESULTS

Primary Benefits

Introduction of *Bt* cotton has provided cotton growers with a new alternative for insect pest management. By utilizing the in-plant insect control offered by *Bt* cotton, in conjunction with other insect management practices, cotton growers worldwide have the potential to improve control of certain pest insects with less use of conventional broad-spectrum insecticides. Increased yield, reduced production costs, and ultimately improved profitability for growers and the cotton industry should result.

Reduced Broad-Spectrum Insecticide Use

A significant benefit that *Bt* cotton brings to growers is a reduction in the use of conventional broad-spectrum insecticide sprays and in associated total kilograms of insecticidal active ingredients for control of lepidopteran species. In a poll conducted among U.S. growers in 1997, 79% of respondents considered potential savings in insecticide applications an important factor in their decisions to grow *Bt* cotton (ReJesus et al., 1997). In this poll, the growers' main reason for adopting *Bt* cotton technology was the potential savings in expenses for broad-spectrum insecticide sprays.

Table 2. Chemical names of insecticides mentioned.†

Trade name	Active ingredient(s)	Chemical name of active ingredient(s)
Ammo	cypermethrin	Cyano(3-phenoxyphenyl)methyl 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropane-carboxylate
Asana	esfenvalerate	[S-(R*,R*)]-Cyano(3-phenoxyphenyl)methyl 4-chloro-a-(1-methyl-ethyl) benzeneacetate
Baythroid	cyfluthrin	Cyano(4-fluoro-3-phenoxyphenyl) methyl 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropanecarboxylate
Curacron	profenofos	O-(4-bromo-2-chlorophenyl)O-ethyl S-propyl phosphorothiate
Decis	deltamethrin	(1R,3R)-3(2,2-dibromovinyl)-2,2-dimethylcyclopropane-carboxylic acid (S)-alpha-cyano-3-phenoxylbenzl ester
Fury	zeta-cypermethrin	S-cyano (3-phenoxyphenyl)methyl (±) cis/trans 3-(2,2-dichloroethenyl)-2,2dimethylcyclopropane carboxylate
Karate	lambda-cyhalothrin	[1a(S*),3a(Z)]-(±)-cyano-(3-phenoxyphenyl) methyl 1-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate
Lannate	methomyl	{N-[(Methylamino)carbonyl]oxyethanimidothioic acid methyl ester}
Larvin	thiodicarb	{Dimethyl N,N'-thio-bis[(methylimino)carbonyloxy]bis[ethanimidothioate]}
Ovasyn	amitraz	N'-(2,4-dimethylphenyl)-N-[[(2,4-dimethylphenyl) imino]methyl]-N-methylmethanimidamide
Pirate	chlorfenapyr	(4-bromo-2-(chlorophenyl)-1-(ethoxymethyl)-5-(trifluoromethyl)-1H-pyrrole-3-carbonitrile)
Roundup	glyphosate	N-(phosphonomethyl)glycine
Scout	tralomethrin	(1E,3S)3[(1'RS)(1',2',2',2',-tetrabromo-ethyl)]-2,2dimethylcyclopropane-carboxylic acid(S)-alpha-cyano-3-phenoxybenzyl ester
Tracer	spinosyn A	2-[(6-deoxy-2,3,4-tri-O-methyl-a-L-mannopyranosyl)oxy]-13-[[5-(dimethylamino)tetrahydro-6-methyl-2H-pyran-2-yl]oxy]-9-ethyl-2,3,3a,5a,5b,6,9,10,11,12,13,14,16a,16b-tetradecahydro-14-methyl-1H-as-Indaceno[3,2-d]oxacyclododecin-7,15-dione,[2R-[2R*,3aS*,5aR*,5bS*,9S*,13S*(2R*,5S*,6R*),14R*,16aS*,16bR*]](9CI)
	spinosyn D	2-[(6-deoxy-2,3,4-tri-O-methyl-a-L-mannopyranosyl)oxy]-13-[[5-(dimethylamino)tetrahydro-6-methyl-2H-pyran-2-yl]oxy]-9-ethyl-2,3,3a,5a,5b,6,9,10,11,12,13,14,16a,16b-tetradecahydro-4,14-dimethyl-1H-as-Indaceno[3,2-d]oxacyclododecin-7,15-dione,[2S-[2R*,3aS*,5aR*,5bR*,9R*,13R*(2S*,5R*,6S*),14S*,16aR*,16bR*]](9CI)

† Source: Modified from Gianessi and Carpenter (1999).

Numerous studies conducted across the United States and in Australia, China, Mexico, and Spain have demonstrated an overall reduction in broad-spectrum insecticide sprays for lepidopteran pests (Davis et al., 1995; Mitchener, 1996; Bacheler et al., 1997; Bryant et al., 1997; ReJesus et al., 1997; Roof and DuRant, 1997; Stark, 1997; Wier et al., 1998; Addison, 1999; Mullins and Mills, 1999; Novillo et al., 1999; Obando-Rodriquex et al., 1999; Xia et al., 1999; Benedict and Altman, 2001) (Table 3). The total number of spray reductions per hectare for all arthropod pests ranged from 1.0 to 7.7 sprays. Of the research reviewed for this report, an average reduction of 3.5 sprays ha^{-1} was achieved when growers used *Bt* varieties rather than non-*Bt* varieties.

Reductions in the number of sprays of broad-spectrum insecticides translate into reductions in related costs to the grower and kilograms of active ingredient used to control insects in cotton. Using a conservative average for the reduction of insecticide applications, 2.2 ha^{-1}, Benedict and Altman (2001) recently demonstrated that insecticide concentrates were reduced by 2.05 L ha^{-1} through use of *Bt* cotton. When extrapolated out to the estimated 972,000 ha of *Bt* cotton planted in the United States in 1998, cotton growers reduced insecticide concentrate used by >2.0 x 10^6 L. This insecticide reduction amounted to >960,000 kg active ingredient across all U.S. hectares of *Bt* cotton (Benedict and Altman, 2001).

In China, *Bt* cotton decreased total insecticide use by 60 to 80%, compared with conventional cotton in 1998 (Xia et al., 1999). Conventional cotton in China can require 15 to 20 sprays per growing season to control lepidopterans. *Bt* cotton has been shown to reduce those applications of insecticides for lepidopteran pests by 90 to 100%.

In field trials conducted in Spain, *Bt* cotton decreased the number of sprays by 5.0 ha^{-1} vs. conventional cotton (Novillo et al., 1999). As a result, an average of 15.8 L ha^{-1} of insecticidal spray was not applied. According to Novillo et al. (1999), the cost and resources saved as a result of this decrease in insecticide sprays were considerable.

Gianessi and Carpenter (1999) showed a reduction of 927 500 kg in insecticide usage in a comparison between the total amount of insecticide active ingredient used before (1995) and after (1998) introduction of *Bt* cotton (Table 4). Their findings are supported by similar findings in a study conducted by the Fernandez-Cornejo et al. (2000). Gianessi and Carpenter (1999) studied 12 insecticides and their total annual use in Arkansas, Arizona, Louisiana, Mississippi, and Texas. Of the 12 insecticides, nine showed decreases and three showed slight

Table 3. Differences between number of sprays per hectare for *Bt* vs. non-*Bt* cotton varieties.

Location	Difference in number of sprays per hectare†	Source
Australia	7.70	Addison (1999)
Mississippi	5.50	Davis et al. (1995)
Spain	5.00	Novillo et al. (1999)
Arkansas	4.00	Bryant et al. (1997)
South Carolina	4.00	ReJesus et al. (1997)
South Carolina	3.25	Roof and DuRant (1997)
Georgia	2.50	Stark (1997)
North Carolina	2.50	Bacheler et al. (1997)
Southern and southeastern United States	2.40	Mullins and Mills (1999)
Midsouth and southeastern United States	2.20	Benedict and Altman (2001)
Georgia	2.00	Carlson et al. (1998)
Mexico	1.00	Obando-Rodriquex et al. (1999)
Average across studies	3.50	

† A minus sign is implied in all cases because *Bt* cotton required fewer sprays at all locations.

Table 4. Total conventional insecticide use against budworm and cotton bollworm in 1998 after the introduction of *Bt* cotton in the United States compared with its use before introduction in 1995.†

Insecticide active ingredient	Brand name	Active ingredient kg $\times$ 10^3
Amitraz	Ovasyn	‡–19.0
Cyfluthrin	Baythroid	–16.0
Cypermethrin	Ammo	–37.0
Deltamethrin	Decis	+5.0
Esfenvalerate	Asana	–9.0
Lambda-cyhalothrin	Karate	–26.0
Methomyl	Lannate	–71.0
Profenofos	Curacron	–460.0
Spinosad	Tracer	+9.0
Thiodicarb	Larvin	–302.0
Tralomethrin	Scout	–2.0
Zeta-cypermethrin	Fury	+0.5
Total reduction		–927.5

† Source: Modified from Gianessi and Carpenter (1999).

‡ A minus (–) sign indicates a decrease in total active ingredient used on cotton after introduction of *Bt* cotton, and a plus sign (+) indicates an increase.

increases in use. Further evidence of this reduction in the use of chemical insecticides can be seen by the impact on the pesticide industry. BASF, a pesticide manufacturer, reported that the industry was losing approximately $200 to $300 million a year since introduction of biotech crops in general (Manitoba Cooperator, 1999). While *Bt* cotton does not account for all the losses in the pesticide industry, it is replacing a significant amount of conventional insecticide that would be used to treat lepidopteran pests.

Improved Control of Target Pests

Bt cotton provides effective control of the three major caterpillar pests in cotton (Jenkins et al., 1997). U.S. growers surveyed in 1999 perceived that they had "much better/somewhat better" control of tobacco budworms (77%), bollworms (66%), and pink bollworms (57%) (Marketing Horizons, 1999) when they compared their experiences with *Bt* cotton to those with conventional cotton pest control systems. In Texas, Moore et al. (1997) estimated that two *Bt* cotton varieties provided 95% control of tobacco budworm, 90% control of bollworm (pre-bloom), and 99% control of pink bollworm.

For many growers, decisions about insecticide application are based on the level of infestation and the potential for crop injury from certain pests. At low levels of infestation and injury, it is not economically feasible to spray insecticides even though yield-reducing insect activity is occurring. With *Bt* cotton, plant protection is active throughout the growing season, irrespective of the level of infestation. As a result, yield that a grower normally would give up to low-level infestations is maintained by use of *Bt* cotton, thereby improving the grower's overall yield (Benedict et al., 1989; Benedict, 1996). In general, economic infestations of target insect pests are slower to develop or do not develop at all in *Bt* cotton crops, compared with cotton varieties without built-in lepidopteran insect resistance (Adkisson et al., 1999).

Bt cotton varieties decrease overall levels of insecticide application for lepidopteran pests. When supplemental insecticide sprays are applied, they have greater efficacy on *Bt* than on non-*Bt* varieties. Mann and Mullins (1999) showed that a 54% higher insecticide efficacy was related to reduced bollworm feeding injury on *Bt* cotton vs. non-*Bt* cotton. In field tests in 1997 and 1998, Mann and Mullins (1999) demonstrated that insecticides like lambda-cyhalothrin (Table 2, Karate 1E, Syngenta, Greensboro, NC), chlorfenapyr (Table 2, Pirate 3F, BASF, Research Triangle Park, NC) and spinosad (Table 2, Tracer 4F, Dow AgroSciences, Indianapolis, IN) exhibited "enhanced efficacy… against bollworm feeding on Bollgard cotton."

Improved Yield

With its new tool for insect management, *Bt* cotton is bringing significantly higher yields in most years for some cotton production regions (Fernandez-Cornejo et al., 2000). In 1998, *Bt* cotton boosted total U.S. lint production by 38.6×10^6 kg (Gianessi and Carpenter, 1999). Overall, the *Bt* cotton varieties tested so far have produced profitable yields and fiber quality comparable (Presley et al., 1999) to that of conventional varieties. Yield potential on most farms ranges from good to well above average, with *Bt* cotton meeting or exceeding growers' expectations. Growers are receiving returns on their investments, even in years when lepidopteran pest populations are light (Smith, 1997).

In the United States, a significant yield increase for *Bt* cotton has been documented in studies across the Cotton Belt. Specifically, Kerby (1996), in a 75-field comparison of three *Bt* cotton varieties and their non-*Bt* near-isogenic parents, showed a lint yield increase of as much as 207.2 kg ha^{-1}, which represented a 20% improvement in yield. In a 109-field comparison in the southern and southeastern United States, Mullins and Mills (1999) demonstrated a yield advantage of 22.4 kg ha^{-1} that resulted from adoption of *Bt* cotton. In Mississippi, *Bt* cotton outyielded the non-*Bt* cotton varieties examined by 103, 51.5, and 94 kg ha^{-1} on average in 1995, 1996, and 1997, respectively (Wier et al., 1998). Benedict and Altman (2001) showed a yield increase of ~14% (174.8 kg ha^{-1}).

The U.S. results are further supported by the experiences in countries such as China, India, and Spain. The average gross yields from *Bt* cotton increased by 15% over conventional strains in China (Buranakanonda, 1999). In India, a study conducted at 30 locations showed a 14 to 38% increase in cotton yield without a single spray of insecticide for arthropod species (Hindu Business

Line, 2000). In Spain, Novillo et al. (1999) reported *Bt* cotton trial plots offered a yield advantage of 12% over conventional varieties sprayed with insecticides.

Another way to look at improved yield from *Bt* cotton is through the change in the amount of yield loss caused by tobacco budworm, bollworm, and pink bollworm infestations. Gianessi and Carpenter (1999) found that the average percentage loss in yield before *Bt* cotton introduction (1985–1995) was 3.7%, whereas the average percentage loss in yield after *Bt* cotton introduction was 2.3% (1996–1998). Even if data from 1995, one of the worst years for bollworm and budworm infestation ($665 million loss in production), are omitted, the average loss in yield (3.2%) without *Bt* cotton was still greater than it was with *Bt* cotton. Although this is a crude measure of change, the reduction in yield losses resulting from tobacco budworm, bollworm, and pink bollworm infestations with the use of *Bt* cotton is a trend that merits attention.

Reduced Production Costs

Bt cotton not only reduces the number of insecticide sprays necessary, it also impacts the total production costs associated with insect control. *Bt* technology makes it possible for a cotton grower to lower his investment in supplies, equipment, and labor (Benedict, 1996; Benedict et al., 1996; ReJesus et al., 1997; Benedict and Altman, 2001). For every spray eliminated, a grower reduces the number of spray trips and related fuel, machinery, and labor costs. This situation translates into potentially lower annual loan requirements to support the farm and less interest to pay to the bank each year (J.H. Benedict, personal communication, 2001). Thirty-nine percent of U.S. *Bt* cotton users surveyed perceived a cost advantage related to labor and equipment (Marketing Horizons, 1999).

The total fixed and variable costs of spraying insecticide are between $4.94 and $9.88 ha^{-1} for labor, fuel, and machinery (e.g., repairs, depreciation, interest, and sprayer purchase) (L.L. Falconer, unpublished data, 2000). Using the estimated 972,000 ha of *Bt* cotton planted in the United States in 1998 as a basis, the use of *Bt* technology has saved $4.8 to $9.6 million in total and variable costs to the grower.

In terms of fuel costs, a grower uses ~0.3738 L ha^{-1} of diesel fuel to spray insecticide (Mississippi State Univ., 1999). Assuming fuel costs of ~$0.24 L^{-1}, a grower can save an estimated $0.0897 ha^{-1} for every spray of insecticide that is obviated by the *Bt* cotton. Assuming this ratio, for the 972,000 ha of *Bt* cotton planted in 1998, fuel consumption was reduced by ~799,000 L, which saved ~$190,000 in fuel costs via a reduction of 2.2 sprays ha^{-1} (Benedict and Altman, 2001).

The above figures account for only the fuel spent in the field, but most farmers also must move equipment to the fields, expending fuel in that process as well. The distance factor is important because the farther away the field is from machinery storage and work areas, the greater the savings in the machinery, labor, and fuel costs associated with fewer insecticide applications. ReJesus et al. (1997) found in surveys that *Bt* cotton reduced the costs associated with moving equipment to distant fields. Interviewed growers stated they used *Bt* cotton in fields that were logistically difficult to spray either due to configuration or the distance to move equipment. Additionally, growers may travel 10 to 150 km to get two or more vehicles to and from a field (J.H. Benedict, personal communication, 2000).

With every eliminated trip to spray for control of insect pests, the grower and/or farm employees reduce the time spent purchasing, transporting, mixing, and spraying insecticides for caterpillar control (Benedict, 1996; Benedict et al., 1996), and, therefore, save on the associated costs. In some cases, labor costs related to insecticide applications for a growing season can add up to $120 ha^{-1} (Falconer, 1999; Mississippi State Univ., 1999). Thus, labor savings can be a significant part of the advantage of *Bt* cotton. Because a typical spray of insecticide requires 0.0272 h ha^{-1} (Falconer, 1999; Mississippi State Univ., 1999), a reduction of 2.2 sprays ha^{-1} on 972,000 ha (Benedict and Altman, 2001) means a reduction of >58,000 h of labor time. This particular reduction translates into the savings of >$870,000 in labor costs (based on $15 h^{-1} labor cost). In many cases, this new technology enables a grower to farm additional hectares without additional labor, when compared to farming non-*Bt* cotton.

Improved Profitability

When growers are able to improve yields and reduce production costs with *Bt* cotton, profit per hectare is higher. In six trials conducted in

Arkansas, Bryant et al. (1997) compared income, insecticide savings, plant growth regulator costs, harvest costs, technology fees, and seed costs between *Bt* and non-*Bt* cotton. The increase in net income that results from use of *Bt* cotton averaged \$196.36 ha^{-1}, with net income ranging from a gain of \$436.69 ha^{-1} to a loss of \$38.78 ha^{-1}. Of the six observations in Bryant et al. (1997), five showed an increase in net income, primarily based on an increase in lint yield with the *Bt* varieties and enhanced by savings on production costs. In a test conducted on 109 sites across southern and southeastern cotton-growing states in 1998, the average *Bt* cotton advantage was \$98.80 ha^{-1}, which was the result of both insect control savings (\$39.52 ha^{-1}) and higher yield returns (average of \$59.28 ha^{-1}) (Mullins and Mills, 1999).

Gianessi and Carpenter (1999), in their review of eight studies, found a high increase (\$259.15 ha^{-1}), a low decrease (\$201.75 ha^{-1}), and an average net return (\$94.32 ha^{-1}) for *Bt* cotton compared to non-*Bt* (Table 5). They also found that in 1998 applications of insecticides were made to 2×10^6 fewer hectares, and production was improved by 38.6×10^6 kg lint (Gianessi and Carpenter, 1999). As a result, growers of *Bt* cotton increased profits by more than \$92 million (Gianessi and Carpenter, 1999), based on Mullins and Mills's (1999) calculations for 1998.

Reduced Farming Risk

Bt cotton not only improves potential profitability for a grower, but also reduces the risks associated with potential crop loss caused by major caterpillar pests. The likelihood of catastrophic insect damage and economic loss is reduced by *Bt* cotton's ability to control crop pests that are currently difficult or impossible to manage (Adkisson et al., 1999). The *Bt* gene provides a level of insurance, so to speak, against a major infestation or against any infestation exacerbated by poorly timed applications, insecticides that are washed off by a storm, or the unanticipated development of resistance to insecticides by a particular pest (Wier et al., 1998). Timing of insecticide application is not an issue with *Bt* cotton, thus reducing some of the uncertainty associated with managing insect pests with conventional synthetic insecticidal sprays (Mitchener, 1996). There are no missed swaths and no missed fields as can occur with conventional insecticide spray applications. Along with continuous self-acting insect control, other aspects of cotton growers' operations benefit from increased attention and lack of interruptions. For example, center pivot irrigation systems do not need to be stopped as they would be during insecticide application.

Table 5. Summary of studies that compare net returns for *Bt* cotton varieties compared with conventional varieties.†

Source	Crop year	Region	Change in net return (\$ ha^{-1})
Allen et al. (1999)	1998	AR	–27.61
Bryant et al. (1997)	1996	AR	196.39
Bryant et al. (1997)	1997	AR	–155.34
Carlson et al. (1998)	1996	NC, SC	131.43
Carlson et al. (1998)	1996	GA, AL	201.38
Gibson et al. (1997)	1995	MS	234.23
Gibson et al. (1997)	1996	MS	40.05
Mullins and Mills (1999)	1998	AL, AR, GA, LA, MS, NC, SC, TN, VA	98.45
ReJesus et al. (1997)	1996	SC	259.15
ReJesus et al. (1997)	1997	SC	–201.75
Stark (1997)	1996	GA	179.82
Wier et al. (1998)	1995	MS	203.78
Wier et al. (1998)	1996	MS	61.03
Wier et al. (1998)	1997	MS	132.71
Wier et al. (1998)	1995-97	AL, GA, FL	134.69
Wier et al. (1998)	1995-97	MS, AR, LA	87.76
Wier et al. (1998)	1996-97	East TX	27.22
		High	259.15
		Low	–201.75
		Average	94.32

† Source: Modified from Gianessi and Carpenter (1999).

‡ A minus (–) sign indicates a decrease in growers' net return after introduction of *Bt* cotton, and a plus sign (+) indicates an increase.

The main factor that influences risk is the level of target-insect infestation. As the infestations of lepidopteran pests increase, the economic benefit of using *Bt* cotton instead of conventional broad-spectrum insecticides also increases (Benedict and Altman, 2001). In years when there are light insect infestations, *Bt* crops are like an insurance policy (Norgaard, 1976; Turpin, 1977; Benedict et al., 1989) that may not be needed. In any case, because it is difficult to predict level of infestation with much accuracy from field to field, region to region, and year to year (James, 1998, 1997), *Bt* cotton generally reduces the normally high risk related to unpredictable infestation levels.

To prevent crop failure, cotton growers make numerous decisions about insect control prior to and throughout the growing season. The *Bt* cotton system effectively eliminates at least some of the decisions growers must make concerning lepidopteran pest control. Decisions related to scouting, timing of insecticide applications, and precision in application are all minimized relative to lepidopteran control by *Bt* cotton. *Bt* technology provides peace of mind to the grower (Benedict and Altman, 2001) by reducing the risk of crop loss from tobacco budworm, bollworm, and pink bollworm and the risk of insecticide-related accidents and law suits (Benedict, 1996; Mullins and Mills, 1999).

Improved Opportunity to Grow Cotton

The locations where growers plant cotton also factor into their risk assessments. Land that has been difficult to farm with conventional varieties and spray regimens, as well as areas adjacent to environmentally sensitive areas, urban and suburban areas, or rural neighbors, are now more manageable, and *Bt* cotton has opened up new areas in which to grow cotton.

According to ReJesus et al. (1997), choosing where to plant *Bt* cotton is a major decision for farmers, such that 50% of the respondents to their survey indicated that the characteristics of their fields determined the varieties planted. Distance to the fields, type of soil, and whether the land was irrigated were important factors. The distance factor was significant because the farther away a field is from machinery storage and work areas, the greater savings in the fuel, labor, and machinery costs associated with fewer insecticide applications. Growers interviewed stated they used *Bt* cotton in fields that were logistically difficult to spray due to either configuration of the field or the effort and expense required to move equipment. *Bt* cotton allows growers to plant in irrigated lands, which get muddy and limit the opportunities to apply insecticides with ground-based equipment, especially when conditions are wet and insect activity is high. Soil type was another consideration. Because it is more difficult to ground-spray clay soils than sandy soils during muddy, wet conditions, fewer insecticide applications on clay soils are appealing.

In environmentally sensitive areas, *Bt* cotton is particularly attractive when the control of tobacco budworms, bollworms, and pink bollworms is necessary but conventional insecticide sprays are restricted or would best be avoided (Benedict, 1996). These areas include fields along waterways or near lakes, where the use of conventional broad-spectrum insecticides must be reduced or eliminated, and restricted areas around homes and businesses where foliar insecticides cannot be applied.

Improved Economic Outlook for the Cotton Industry

Bt cotton means an opportunity to grow cotton in new areas or restart the industry in areas that had to abandon cotton due to insect pressures. Globally, there are geographic areas where cotton is no longer grown due to high insect control costs and yields so low that cotton production is unprofitable (Benedict, 1996). In the United States, producers in areas of Southern California, Texas, and Arizona have abandoned growing cotton because of the losses due to pink bollworm. With *Bt* cotton's control of pink bollworm, these producers now have the opportunity to produce cotton profitably again.

In the 1980s, the Hebei Province of China was the third largest cotton farming area, yielding $>1 \times 10^6$ t cotton annually; however, when bollworms began attacking in the 1990s, many growers had to abandon the crop (Buranakanonda, 1999; Pongvutitham, 1999). The high costs of chemicals, the health risks posed by excessive chemical exposure, and the threat to local water supplies were too much for the growers to accept, plus the fact that bollworms were developing resistance to the chemicals available for treatment. With the advent of *Bt* cotton, cotton is being grown in the Hebei Province for the first time in a decade and growers are more optimistic about restoring the Chinese cotton industry (Buranakanonda, 1999).

Similar stories can be told about India, where the *Bt* technology is being considered for areas that have been forced to abandon cotton because of excessive insect infestation levels. In India, as a result of pest infestations of cotton crops and pesticides that have become ineffective, >700 growers have committed suicide since October 1997 (Lambrecht, 1998). Nearly 50% of all broad-spectrum insecticides used in India are purchased by cotton farmers alone at the significant costs of 16 billion rupees ($368 million) annually, as well as the immeasurable impact on the environment and human health (Hindu Business Line, 1999). *Bt* cotton varieties are expected to enhance the overall welfare of Indian farmers as it fosters the Indian economy and its environmental preservation efforts.

In Australia, chemical resistance among caterpillar pests has been advancing and threatening the longevity of the Australian cotton industry. Peacock (1996) considered “the advent of transgenic plants in combination with new chemical strategies to be the savior of the cotton industry in Australia.”

Falck-Zepeda et al. (1999) showed in their analysis of the net benefits from *Bt* cotton that the rapid adoption of *Bt* cotton from 1996 to 1998 in the United States provided all stakeholders (growers, Monsanto Co., Delta and Pine Land Co., and others) with a combined additional wealth of $134 million in 1996 and $213 million in 1998. They found that the growers who adopted transgenic technology earliest benefited most. They estimated that growers gained between 43% and 59% of the economic benefits, while Monsanto and Delta and Pine Land gained between 26% and 47%. As adoption of *Bt* cotton grew, consumers worldwide benefited through a slight reduction in prices of chemical insecticides (Falck-Zepeda et al., 1999).

In a similar study, Frisvold et al. (2000) found an annual net benefit to U.S. cotton producers that ranged from $20 to $26 million in a low- to $146 to $175 million in a high-pest-impact scenario. In determining their figures, they considered four main effects: yield, cost, market price, and a commodity program payment. Frisvold et al. (2000) noted that Gianessi and Carpenter’s (1999) calculation of a $92.7 million gain was close to their own 1998 estimate of gains for adopters of *Bt* cotton. The total global benefit of U.S.-produced *Bt* cotton for 1 yr is estimated to range from $189 to >$500 million, based on extrapolation models (Shaunak, 1994; Eddleman et al., 1995).

Secondary Benefits

In addition to the direct control of insects and economic benefits that allow growers to produce a cotton crop more profitably, *Bt* cotton also provides numerous secondary benefits. Grower adoption of *Bt* cotton has proven to be extremely beneficial to the environment through reductions in broad-spectrum insecticide applications and use of farm machinery (Falck-Zepeda et al., 1999). The environmental benefits stem directly from a reduction in insecticide applications, which positively affects surrounding ecosystems and associated insect, wildlife, and human populations.

Increased Effectiveness of Beneficial Insects as Pest Control Agents

With the use of in-plant *Bt* technology, non-target, beneficial insects are not harmed as they are with many broad-spectrum insecticidal sprays (Benedict and Altman, 2001). The *Bt* protein specifically affects three major pests (bollworm, pink bollworm, and tobacco budworm) and has not been shown to have an adverse effect on non-lepidopteran, beneficial insects in the same fields.

It is reasonable to expect that a reduction in conventional synthetic insecticides will result in a decrease in the environmental hazards associated with these conventional compounds, such as suppression or elimination of beneficial insects and off-target drift. Roof and DuRant (1997) demonstrated that beneficial arthropod numbers were slightly greater in *Bt* cotton fields than in conventional cotton fields in South Carolina. In a side-by-side comparison of unsprayed *Bt* and conventional cotton, Armstrong et al. (2000) found similar numbers of piercing-sucking predators, such as the minute pirate bug (*Orius* spp.), big-eyed bug (*Geocoris* spp.), cotton fleahopper (*Pseudatomoscelis seriatus* Reuter) and spiders (Araneae), and they concluded that *Bt* cotton may act as a refuge for predaceous insects and spiders. In the Chinese province of Hebei, growers reported a 25% increase in natural enemies of pests in *Bt* cotton fields (Nakanishi, 1999) and specifically observed higher numbers of natural predators such as wasps (Vespoidea and Sphecoidea), aphid-consuming flies (*Syrphus* spp.), and ladybugs (*Hippodamia* spp.) than in non-*Bt* fields (Buranakanonda, 1999).

A few other studies have compared beneficial insect densities and activity in *Bt* cotton with those in sprayed, conventional cotton (Benedict et al., 1996; Lambert et al., 1997). These types of studies are faced with the problem that test plots typically are sprayed for other types of insect pests, such as the boll weevil (*Anthonomous grandis grandis* Boheman) that coexist with the target lepidopteran pests of *Bt* cotton. Thus, all beneficial insects are not at their maximum densities even when *Bt* cotton is grown.

A study by Schuler et al. (1999) does provide some insight into the effect of *Bt* crops, in this case *Bt* oilseed rape (Brassica napus L.), on parasitoid species. In their study, *Bt*-resistant caterpillar pests were used to evaluate the direct effects of *Bt* toxins on parasitoid biology: an innovative way to evaluate ecological risk. Schuler et al. (1999) tested the effects of *Bt* toxins on parasitoid wasps (Hymenoptera spp.) that feed on the diamondback moth (Plutella xylostella) that had fed on *Bt* oilseed rape. They found there was a lack of effect on the wasps' host-seeking ability and hence their survival as the moths' parasite. The authors viewed this as an indication of the environmental advantage of *Bt* plants over broad-spectrum insecticides. They also viewed the ability of the wasps to locate and parasitize *Bt*-resistant pests on transgenic crops as a means of constraining the spread of *Bt* resistance genes in the pest.

Improved Control of Non-Target Pests

In addition to reducing the overall number of insecticide sprays for arthropod species, sprays for other pests of cotton not controlled directly by *Bt*, such as thrips (*Thrips* spp. and *Frankliniella* spp.), aphids (Aphididae), and beet armyworms (*Spodoptera exigua* Hubner), also have been reduced by one to two sprays (Benedict and Altman, 2001). This result has been attributed to the improvement in beneficial predator and parasite insect populations that are influenced by reductions in broad-spectrum insecticide sprays for bollworm, pink bollworm, and tobacco budworm. The active preservation of beneficial insect populations, which are often better preserved in a *Bt* cotton system, provides an opportunity to naturally manage the remaining economic arthropod pests not controlled by *Bt*. In *Bt* cotton fields, beneficial insect species are enhancing the control of beet armyworms and fall armyworms (*Spodoptera frugiperda* J.E. Smith), which can be significant pests in the Gulf Coast area of Alabama and throughout most of the Coastal Plains of the southeastern United States (Smith, 1997). In Alabama in 1996, beet armyworms were less likely to occur at economic levels in *Bt* cotton because of the reduced level of broad-spectrum insecticide use, the higher numbers of beneficial insects that imparted natural protection, and >30% suppression of the target insects by *Bt* cotton itself. Mann and Mullins' (1999) results from 1997 showed 24% improvement in the control of beet armyworms owing to *Bt* cotton.

Reduced Risk for Farmland Wildlife Species

Broad-spectrum insecticidal sprays are toxic to many animal species, either through direct or indirect exposure. Effects of direct exposure to insecticides vary greatly among groups of vertebrates and among terrestrial and aquatic vertebrates (USEPA, 1998a, 1998b). The most obvious means of negative effect is through direct contact with commonly used broad-spectrum cotton insecticides. Although documented mainly with birds, many species of wildlife are negatively impacted through the use of insecticides via indirect degradation of habitat (Campbell et al., 1997; Ewald and Aebischer, 1999). Many birds, especially nesting birds, and small mammals depend on insects as a food source. Removal of all insects through the use of broad-spectrum insecticides eliminates a major food source for wildlife. Although not documented directly in *Bt* cotton, systems that allow more numerous and diverse insect communities should provide a net benefit to farmland wildlife species (Sotherton et al., 1993; Palmer, 1995). A number of U.S. growers (e.g., Pigg, 1999; D. Goldmon, personal communication, 2001) have noticed an increase in bird populations (e.g., songbirds, gamebirds) surrounding their fields after they adopted *Bt* cotton and other *Bt* crops.

Reduced Runoff of Insecticides

A reduction in the amount of broad-spectrum insecticide applied to cotton fields means less insecticide active ingredient should be available to potentially runoff into the local watershed. While insecticides currently on the market have met maximum toxicity requirements from the USEPA, many insecticides have lethal effects on non-target organisms. Many insecticides are toxic to aquatic animals, so a decrease in the total load of broad-spectrum insecticides would reduce the likelihood of negative effects on non-target animals found in streams, rivers, and ponds. For every spray that is prevented through *Bt* cotton's in-plant technology, ~0.45 kg ha^{-1} insecticidal active ingredient are prevented from entering the surrounding ecosystem (Benedict and Altman, 2001). Assuming an average reduction of 2.2 sprays ha^{-1} (Benedict and Altman, 2001) on the 972,000 ha cotton produced in 1998 in the United States, 962 280 kg insecticide active ingredient did not enter the environment and local watersheds, which reduced the potential exposure to non-target animals.

Reduced Fuel Usage, Air Pollution, and Related Waste

By using less broad-spectrum insecticides, growers reduced fuel usage and the number of trips across the field to spray for insect pests, positively impacting air pollution and related waste. Kern and Johnson (1993) estimated that for every liter of diesel fuel saved, 1.67 kg CO_2 is not released into the atmosphere. One trip across a field to apply insecticides uses ~0.373 L ha^{-1} diesel fuel (Mississippi State Univ., 1999; L.L. Falconer, unpublished data, 2000) and emits ~16.79 kg CO_2. For each reduction in liters of fuel spent to spray insecticides, the corresponding amount of CO_2 is reduced. Based on the average reduction of 2.2 sprays ha^{-1} (Benedict and Altman, 2001) on the 972,000 ha planted in *Bt* cotton in 1998, the release of ~359,000 kg CO_2 was avoided, which positively impacted air quality in the surrounding ecosystem. It is expected that comparable reductions occur for CO, N_2O, and hydrocarbon emissions.

Spray applications of insecticides produces air pollution not only as emissions but also as spray drift. The USEPA (1999) defines pesticide spray drift as the physical movement of a pesticide through the air at the time of application or soon thereafter to any site other than that intended for application. Droplets of insecticides can be so small that they stay suspended in air and are carried by air currents until they contact a surface or drop to the ground. Weather conditions, topography, the crop or area being sprayed, application equipment and method, and decisions by the applicator can influence spray drift. While airborne, insecticide spray drift is an air pollutant that can affect human health or the environment, depending on the level of toxicity and amount of the insecticide. In the Hebei Province of China, growers have noticed an improvement in the usually serious air pollution in cotton-growing areas caused by the heavy spraying of chemicals (Biotechnology Global Update, 1999).

With a reduction in the total amount of insecticide needed to treat cotton fields, there is a subsequent reduction in the amount of waste associated with the use of the insecticide containers. If $>2.0 \times 10^6$ L insecticide concentrate are not sprayed (Benedict and Altman, 2001), then the corresponding number of containers are not used and disposed of in the waste system.

Improved Safety to Farm Workers and Neighbors

In addition to being runoff and waste hazards, many broad-spectrum insecticides used today provide potential environmental health risks to farm workers, pesticide mixers, loaders, and applicators (Hatfield and Karlen, 1994), as well as health hazards to non-target insects, mammals, birds, and other animals (Benedict and Altman, 2001). Any replacement of insecticide sprays with the in-plant protection offered by *Bt* cotton can have significant benefits to the people handling the chemicals and those exposed to the chemicals via spray drift (e.g., neighbors). Two insecticidal active ingredients that can be largely replaced by *Bt* cotton – methomyl (Table 2, Lannate, DuPont, Wilmington, DE) and thiodicarb (Table 2, Larvin, Aventis Crop Science, Research Triangle Park, NC) – have been shown to present risks to human health, either through skin exposure, inhalation or ingestion, or as a potential carcinogen (USEPA, 1998a, 1998b).

Numerous studies cite the desire by farm workers to reduce their exposures to the more toxic agrichemicals, in particular broad-spectrum insecticides (ReJesus et al., 1997;

Simmons et al., 1998). By allowing a reduction in the number of conventional insecticide sprays, *Bt* cotton technology reduces the amount of exposure and risk involved in purchasing, transporting, mixing, and spraying insecticides for caterpillar control for growers, their families, and employees (Benedict and Altman 2001). Reducing the use of conventional broad-spectrum insecticides in cotton through the use of the in-plant biological pesticide *Bt* could have a major impact on worker safety (Simmons et al., 1998). Neighbors of cotton fields also benefit from reduced exposure owing to decreased instances of spray drift of insecticides.

In Australia, growers report that they are able to grow *Bt* cotton near more heavily populated areas (e.g., schools, neighborhoods) due to the reduction in insecticide use in *Bt* cotton (Addison, 1999). Because *Bt* cotton changes the basis of the restrictions concerning where cotton can be planted, growers who otherwise meet restriction guidelines have the opportunity to optimize their operations and use land best suited for cotton growing, all of which adds to the economic benefits associated with *Bt* cotton.

CONCLUSIONS

This compilation of current literature demonstrates that, compared with conventional broad-spectrum insecticide use, there are many economic, environmental, and societal benefits associated with adoption of *Bt* cotton for insect pest management. These benefits have resulted in quicker and more widespread adoption by growers than any recently introduced conventional cotton insecticide, especially for a biopesticide. Specifically, the benefits of using Bollgard *Bt* cotton in integrated pest management systems worldwide are as follows:

- Provides control of lepidopteran species, such as tobacco budworm, which in some cases have become resistant to some broad-spectrum insecticides.
- Provides control of cryptic lepidopteran species that burrow into cotton tissues, such as pink bollworm and cotton leaf perforator, which are difficult to control with conventional broad-spectrum insecticides.
- Reduces use of broad-spectrum insecticides that complement integrated pest management programs and natural biological control of insect and mite pests.
- Reduces insecticide exposure for farm workers and the agricultural community.
- Improves cotton yields and farm profits when compared with use of conventional broad-spectrum insecticides in traditional pest management programs, depending upon the pest species.
- Increases sustainability of cotton production systems by reducing broad-spectrum insecticide use, pest resurgence, and secondary pest outbreaks, and by increasing the effectiveness of biological control of pests.

This paper focused primarily on the benefits of *Bt* cotton technology because they had not been examined from a holistic viewpoint. At this time, little downside risk from *Bt* cotton use has been documented, other than the cost of the technology fee, which can be greater than the cost of conventional broad-spectrum insecticide costs in years when pest infestation is relatively low. Currently, the most serious concern is the potential development of resistant populations, which poses a risk to the continued efficacy of *Bt* technology; however, this same concern about resistance in target pests applies to broad-spectrum insecticides as well.

While all farming methods result in trade-offs in benefits and risks, all cotton farming systems (including sustainable and organic farming methods) should be compared not only to conventional cotton production systems, but also to systems developed with and relying on the latest technologies, such as *Bt* cotton. At the broadest level, both the benefits and risks of all pest management techniques need to be researched objectively and communicated to growers and to society at large. When presented objectively by the scientific community, these comparative data can help society make informed decisions about all insect management technologies.

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