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The Economic Impacts of Introducing Bt Technology in Smallholder Cotton Production Systems of West Africa: A Case Study from Mali

Jeffrey Vitale and Tracey Boyer
Oklahoma State University

Rafael Uaiene and John H. Sanders
Purdue University

Africa has been slow to respond to biotechnology even as its pest management grows increasingly obsolete and insects remain a major adversary of its farming. Opponents of biotechnology cite concerns over the scientific boundaries and potential North-South domination that transgenic crops could bring. This paper reports on the positive aspects of introducing biotechnology in Africa. An economic model was developed to predict the economic impacts to consumers and producers from the introduction of Bt crops in the smallholder cotton farms of Mali. Since farmers rotate cotton and maize in three-year rotations, the analysis considered the introduction of both Bt cotton and Bt maize. Results from an economic model indicate that the potential economic impacts to West African consumers and producers would be significant, potentially reaching $89 million in an average year. For Bt cotton, the benefits would primarily accrue to producers. At a technology premium of $60 per hectare, where seed company revenue is maximized, Malian producer would capture 74% of the benefits and the seed company would capture the other 26%. The model found that the adoption of Bt maize was weaker than Bt cotton. If Malian maize producers were charged the same technology premium as South African producers, the model found that adoption would be less than 10%. The introduction of Bt maize in the region is likely to require complementary changes in maize markets and technology in order to boost profitability.

Key words: Bt cotton, Bt maize, Mali, sector, technology-premium, economic impacts.

Introduction

Insect pests constitute a major problem to African agriculture (Banwo & Adamu, 2003; Oerke, 2002). Pests essentially steal from farmers' fields, reduce their profits, and make it harder for households to put enough food on their table. Globally speaking, when left untreated, insect pests typically destroy about one-third of the cotton yield and about one-fifth of the maize yield (Oerke, 2005). In Africa, pests are an even greater problem since warm temperatures and higher humidity foster heavier pest densities (Abate, van Huis, & Ampofo, 2000). In severe infestations pests can often eat and destroy more than they leave behind for humans, forcing producers to abandon their fields (Traoré, Héma, & Ilboudo, 1998). Corresponding economic losses from pests run into the millions at the national level and billions globally (Oerke, 2005). In Kenya, for instance, the economic losses from insect pests can reach as high as $90 million per year for maize (De Groote, Overholt, Ouma, & Mugo 2003). Associated losses from pests are even more problematic in smallholder production because food security can be jeopardized, particularly since rural households value food at higher prices than markets would indicate (DeJanvry, Fafchamps, & Sadoulet, 1991).

Existing spray-based practices are increasingly ineffective, costly, and hazardous (Vognan, Ouédraogo, & Ouédraogo, 2002). Pests appear to be winning the battle through resistance to conventional chemical spraying methods (Institut de l'Environnement et de Recherches Agricoles [INERA], 1999). Pesticides are showing signs of diminishing returns: farmers are spraying more frequently but are losing more of their crops to pests (Vitale, Glick, Greenplate, Abdennadher, & Traoré, 2006). Recommended sprayings, about six per season, will protect only about 11% of the cotton yield from insect pests; about 23% of the cotton yield will still be lost (Oerke, 2002). The aerosol-based spraying methods currently used by farmers is damaging to their own health as well as the local flora and fauna (Ajayi & Waibel, 2003; Drafor, 2003; Maumbe & Swinton, 2003). Moreover the pest problem is expected to worsen over the long-term. All of the major global climate change models forecast higher temperatures that will promote higher pest populations within the region (Hulme, 2005; Pimentel, 1993).

Bioengineered crops offer African farmers an alternative pest control practice to chemical sprays (Huesing & English, 2004). In particular, Bt cotton and Bt maize have been developed to allow plants to protect themselves from insect pests. Scientists have engineered these varieties to express a gene derived from soil bacterium, *bacillus thuringiensis* (Bt), which is an effective agent in killing bollworms and other insect pests that afflict cotton and maize (Greenplate et al., 2003; Perlak et al., 1990). Individual Bt cry proteins are highly specific to certain caterpillars and do not target other insects (Hofte & Whiteley, 1989; MacIntosh et al., 1990; Sims, 1997), unlike conventional pesticides, many of which kill across a wide spectrum of both targeted and non-targeted (often beneficial) insects. The primary advantages of bioengineered crops are higher yields and reduced pesticide costs. The direct application of Bt from within the plant itself provides enhanced protection that increases yields and eliminates the need for conventional chemical sprayings to control Lepidoptera, the chief enemies of cotton (American bollworm) and maize (spotted stem borer).

Studies such as Qaim and DeJanvry (2005) in Argentina show that although Bt cotton reduced the number of pest sprayings, secondary pests such as sucking and piercing insects remained a problem. Bennett, Ismael, Morse, and Shankar (2004) found similar reductions of spraying for Bollworm control compared to conventional cotton in Mahareshtra State, India. Smale, Zambrano, and Cartel (2006) provide an overview of the economic impact of Bt cotton use in developing countries that includes an assessment of yield, pesticide use, input cost, and profits that show Bt cotton to provide significant benefits.

The technical merits of the Bt crops are hard to argue against since so many farmers throughout the world are using them. The adoption of Bt crops has taken place at unprecedented levels. Since its introduction on US farms in 1996, the adoption of Bt cotton has risen to cover 83% of US cotton acres (James, 2006). Similar levels of Bt cotton adoption have occurred in Australia. Among developing countries, China and India are the leading adopters of Bt cotton. China planted 3.5 million ha of Bt cotton, and India planted 3.8 million ha of Bt cotton in 2006 (James, 2006). Globally, 38% of the world cotton acreage was planted to Bt cotton, and 19% of total area planted to maize was genetically engineered in 2006 (James, 2006).

Ironically, opposition to biotechnology has, at times, been strongest in Africa, a region that could potentially benefit the most from it (Cohen & Paarlberg, 2002). Bt crops are a scale-neutral technology and benefit both the smallholder and commercial producer. Of the 10.3 million farmers growing biotech crops in 2006, close to 90% were small, resource-poor farmers from developing countries who grew Bt cotton (James, 2006). However, the biotechnology debate in Africa has been divisive with concerns over the boundaries of science and issues of political economy loudly voiced by special-interest groups and African governments (Paarlberg, 2001; Spielman, 2007). Most visibly, southern African nations, such as Zambia, refused food aid in the form of GM corn during widespread drought-induced famine in 2002 (Zerbe, 2004). The Zambian government cited fears that GM corn would contaminate local seed stocks since adequate segregation measures have not been established (Zerbe, 2004). The Bt debate should, however, be balanced. It needs a factual assessment of the benefits that Bt technology can generate for African farmers and consumers, even if the technology is privately provided. Only through an open debate can policy makers and its citizenry make informed decisions regarding biotechnology.

This paper documents the potential economic impacts of introducing bioengineered crops, Bt cotton and Bt maize, in the West African region. The expected benefits from Bt cotton and Bt maize are initially assessed from an entomological perspective. The insect pests that cause the most significant damage to cotton and maize production in West Africa are identified. The expected efficacy of control that existing Bt cotton and Bt maize products would have on each pest is then assessed using empirical evidence drawn from field studies in Burkina Faso and from other sources in the region. An economic model is then used to estimate the potential economic impacts from the introduction of Bt cotton and Bt maize in Mali. The Mali study area was chosen since Mali well represents cotton and maize production in West Africa and is a significant producer of both commodities.

The paper is structured as follows: (a) the next section provides background on the importance of maize and cotton to West African agriculture; (b) this is followed by a section on entomology that describes the nature of the insect pest problem within the West Africa region; (c) the economic model and methodology is then presented, and model results of the potential impacts from Bt cotton and Bt maize are provided and dis-

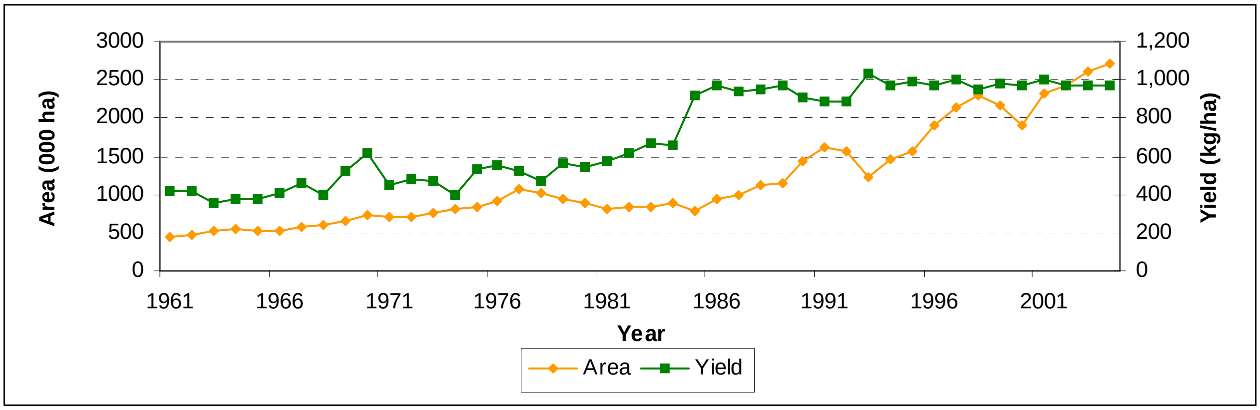

Figure 1. Cotton area and yield patterns for West Africa.
Source: FAOSTAT (2006).

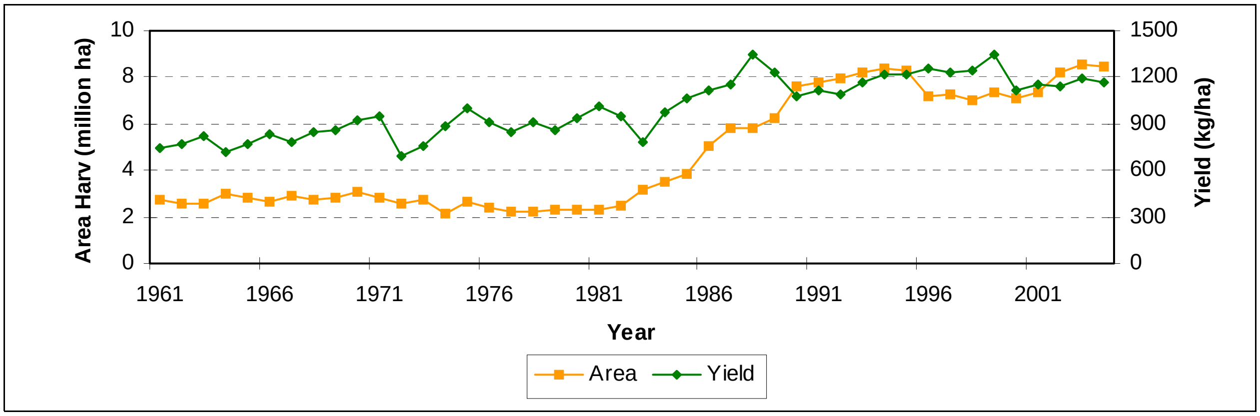

Figure 2. Maize area and yield patterns for West Africa.
Source: FAOSTAT (2006).

cussed; (d) the paper ends with conclusions on recommended policies and future areas of research.

Background

Cotton is one of the most important cash crops in West Africa and is a vital catalyst to economic development in the region. Cotton is the most important agricultural export and constitutes a major share of export earnings in Mali (25%), Benin (38%), Burkina Faso (51%), and Chad (36%) (Food and Agriculture Organization of the United Nations, Statistics Division [FAOSTAT], 2006). Cotton has been produced in West Africa since the colonial era, where it was concentrated in the semi-arid regions. The prevalence of disease and insect pressure limited agricultural development in the wetter, higher potential areas. Over the past two decades, frontier areas in the sub-humid tropics have opened (McMillan et al., 1998). Cotton production has expanded into these more humid areas that has enabled a 250% increase in cotton area over the recent past, but has also increased the need for improved crop protection (Figure 1).

Cotton has been one of the major agricultural success stories since independence took hold of the region in the early 1960s (Bingen, 1998). Yields have increased steadily over the past few decades; today they approach those obtained in the developed world (Figure 1). Despite the advances in technology and increased efforts to better manage soils, cotton yields have leveled off due to soil depletion and ineffective pest management (Vognan et al., 2002). Opportunities to raise yields in conventional ways are dwindling. Bt cotton offers an alternative approach to raising cotton yields through improved pest management that leaves more fiber in the field at harvest.

A major co-benefit from the development of the cotton sector has been the simultaneous increase in maize production (Sanders, Ramaswamy, & Shapiro, 1996). As cotton expanded throughout West and Central Africa, so did maize (Figure 2). Maize remains primarily a subsistence-oriented crop, but marketing condi-

Table 1. Principal bollworms in certain countries of West Africa and their susceptibility to Bt cotton.

Country	Early season pests (In order of importance)	Control by Bt cotton[a]	Late season pests (In order of importance)	Control by Bt cotton[a]
Benin	*Helicoverpa armigera*	Complete	*Helicoverpa armigera*	Complete
			Pectinophora gossypiela	Complete
Ivory Cost	*Helicoverpa armigera*	Complete	*Pectinophora gossypiela*	Complete
			Earias spp.	Partial
			Helicoverpa armigera	Complete
Mali & Burkina Faso	*Helicoverpa armigera*	Complete	*Helicoverpa armigera*	Complete
			Diparopsis castanea	Partial
			Earias spp.	Partial
Senegal	*Helicoverpa armigera*	Complete	*Helicoverpa armigera*	Complete
			Earias spp.	Partial
			Diparopsis watersi	Partial
Togo	*Diparopsis watersi*	Partial	*Diparopsis watersi*	Partial
			Helicoverpa armigera	Complete
			Pectinophora gossypiela	Complete
			Earias spp.	Partial

[a] *Complete control is 95% control efficacy or higher and partial control is less than 95% control efficacy.*

Source: Secretariat for the 61st Plenary Meeting of the International Cotton Advisory Committee (2002).

tions are improving. Its role as a staple food remains limited to the wetter areas where it is grown; in the drier areas the traditional cereals (sorghum and millet) remain the most popular staples (Vitale & Sanders, 2005). Maize arrives earlier than traditional cereals; it has helped to shorten the hungry season and reduce price volatility.

Maize and cotton are usually found in the same cropping system since they demand similar levels of rainfall and soil nutrients (Coulibaly, 1995). Cotton requires a crop rotation to maintain an adequate soil nutrient balance and to minimize pest pressure. West African farmers typically use a three year rotation of cotton-maize-maize. Given the popularity of the cotton-maize cropping system among West African producers, this paper considers the introduction of both Bt cotton and Bt maize.

Bt Crops in West Africa

Insects are a major pest to cotton and maize farmers around the globe. About 15% of world cotton production is lost to insects every year (Oerke, 2005). In West Africa the numbers are even higher, with about 23% of cotton production lost to insects (Oerke, 2002). Among insects, the cotton bollworm complex is the most damaging to cotton yields in West Africa (Vaissayre & Cauquil, 2000). In particular, the major bollworm pest throughout West Africa is American bollworm (*Helicoverpa armigera*), which is found throughout the region (Table 1). Other bollworm pests vary from country to country and include the pink bollworm (*Pectinophora gossypiella*), the spotted bollworm, the spiny bollworm (*Earias spp*), and the red bollworm (*Diparospsis spp*).

Damage to cotton plants is characterized by feeding activity on squares (flower buds), flowers, and cotton bolls. Flower and boll damage is the most severe as it results in the shedding of the plant's reproductive parts and reduces potential yield. Pest infestation is particularly damaging to cotton yields when infestation occurs during the critical growth development stages that begin ten weeks after plant emergence.

Chemical insecticides are used extensively in cotton production to control insect pests, with the primary target being bollworms. The number of sprays per crop season varies from place to place and from one year to the next. Typically, cotton producers spray about six times per year, but as many as ten sprayings can be required. Insecticides worth about 120 billion CFA francs ($60 million) are used annually in Burkinabé agriculture to control bollworms (Vognan et al., 2002). This underscores the economic importance of controlling cotton bollworms in the region and, in particular, the American bollworm (*H. armigera*).

Despite farmer efforts, the effectiveness of bollworm control through chemical pesticides has been declining. Pests such as the American bollworm (*H. armigera*) have developed resistance to most of the currently recommended insecticides, including pyrethoids (Goldberger, Merrill, & Hurley, 2005; Martin, Chandre, Vaissayre, & Fournier, 2002). Nevertheless, West African farmers continue to use conventional insecticides in more intensive manners, even as they expand into more marginal agricultural lands. The increasing impotence of conventional insecticide approaches has frustrated cotton farmers, agricultural scientists, and policy makers. Bt cotton arrives at a time when all stakeholders are desperately searching for alternative and more efficient insect-control measures.

The most damaging pest species to West African cotton, the American bollworm, is completely controlled by Bt cotton (Table 1). While Bt cotton only partially controls some of the bollworm species, Bt cotton provides superior performance to conventional insecticide approaches and has been found to either eliminate or significantly reduce the number of chemical sprays used on conventional cotton in various parts of the world (Bennett et al., 2004; Hofs, Fok, & Vaissayre, 2006; Ismael, Bennett, & Morse, 2002; Qaim & de Janvry, 2005; Qaim & Matuschke, 2005; Morse, Bennett, & Ismael, 2004; Pray, Huang, Hu, & Rozelle, 2002; Thirtle, Beyers, Ismael, & Piesse, 2003; Traxler, Godoy-Avila, Falck-Zepeda, & Espinoza-Arellano, 2003). Bt cotton has already been shown to be effective in Africa. South African farmers in the Makhatini Flats have used Bt cotton since 2001. Success has been reported on both commercial and smallholder farms (Gouse, Pray, & Schimmelpfennig, 2004; Hofs et al., 2006; Ismael et al., 2002). Yield increases of roughly 25% have been achieved with Bt cotton, accompanied by reduced spraying costs of 66%. On average, the S. African farmer's income increased by $137/ha.

Piercing and sucking insects also attack cotton plants but are less damaging than bollworms. The most common sucking pests are the jassids (*Empoasca facialis*) and aphids (*Aphis spp*). Since Bt is not toxic to the sucking insects, Bt cotton does not provide control for this group of insects. Cotton producers planting Bt cotton still need to control for sucking pests using sprays.

Burkina Faso has been the most progressive in West Africa. Regulations still prohibit farmers from planting Bt cotton, but monitored field trials are allowed. Monsanto's line of Bt cotton products, Bollgard, has undergone three years of field testing in Burkina Faso (Traoré, Sanfo, Traoré, & Koulibaly, 2006). Test results have been encouraging. On average Bollgard cotton has increased cotton yields by 20% over conventional cotton (Vitale et al., 2006). The corresponding demand for chemical insecticides dropped from six sprayings per year to just two sprayings per year. Further research is expected to achieve more impressive yield increases. Existing Bt cotton varieties have been based on Monsanto's US cotton varieties. Their performances in South and West Africa have been sound, but Bt cultivars adapted to local conditions are expected to produce higher yields.

Table 2. Resistance to different maize borers by different Bt constructs.

	Lepidopteran maize borer			
Bt construct	***C. partellus***	***B. fusca***	***S. calamistis***	***E. sacharina***
Cry1B	Yes	No	No	No
Cry1Ab	Yes	No	Yes	Yes
Cry1Ab-1B	Yes	No	Yes	Yes

Source: DeGrassi (2003).

Bt Maize

The lepidopteran stem borer is the most damaging insect known to attack maize plants. In West Africa, the two most prominent stem borers are the African stalk borer (*Busseola fusca)* and the spotted stem borer (*Chilo partellus)*. Less important, yet still damaging borers, include the pink stem borer (*Sesamia calamistis)* and the sugar cane borer (*Eldana saccharina*). Stem borers first attack the leaves on the maize plant and then bore into the stem and stalk. Once the pests have bored in, they inflict their damage. Stem borers interfere with the movement of water and metabolites through the plant's vascular system, which shunts its growth and development. The early attacks disrupt the plant's reproductive stage. Fertility is significantly decreased and farmers are left with less grain to harvest. Once inside the ear, the borers often damage maize tissue that enables fungi, particularly *Fusarium* species, to colonize. This rots the stalk and ear and promotes harmful mycotoxins to accumulate within the grain. Mycotoxins create phytosanitary concerns within the human food and animal feed chains and the risk of spreading disease in storage. Additional damage can result from lodging (stalk breakage) and maize ear-drop.

Maize corn borers are difficult to control with insecticides anywhere in the world. Only modest amounts of insecticides are used to control for maize stem borers, even in developed countries. In the US, about 18% of the total maize area is sprayed for stem borers (James, 2003). The limited control efficacy of chemical sprays prohibits wider use. Bt maize has been bioengineered to produce cry protein variants known to be effective against lepidopterean maize borers (Table 2). There are three cry proteins that are very effective against *C. Partellus*. Other stem borers are controlled only by a selected cry protein, and are resistant to the others. None of the cry genes have been found to be completely effective against *B. fusca* (De Groote et al., 2003).

Concerns over potential risks of Bt maize within the food and feed chains have led to opposition of Bt maize introduction throughout Africa (Pelletier, 2006). Bt maize is grown only by small scale farmers in South Africa, and in West Africa regulations even prohibit field trials. Yield gains from Bt maize in South Africa and elsewhere have been less apparent than in Bt cotton. On average, between 1996 and 2002, US maize producers increased yields by 5.2% using Bt maize (James, 2003). In S. Africa, yield gains of 10% were found during a three-year study period from 1999-2001 (James, 2003). In W. Africa, Bt maize is expected to produce larger yield gains since pest damage is much higher than in the US or S. Africa and W. African maize producers typically do not use any pest control. Given that pest damage from stem borers averages about 17% of maize yields in W. Africa, Bt maize is expected to provide yield gains of 15%.

Economic Impact Model: Methodology

Impacts of Bt cotton and Bt maize are measured using the economic surplus method (Alston, Norton, & Pardey, 1995/1998). This is an approach used in other studies to assess the economic impacts of introducing Bt crops (Moschini, Lapan, & Sobolevsky, 1999; Traxler & Falck-Zepeda, 1999; Falck-Zepeda, Traxler, & Nelson, 2000; Elbehri & MacDonald, 2004; Huang, Hu, van Meijl, & van Tongeren, 2004; Jefferson-Moore & Traxler, 2005; Frisvold, Reeves, & Tronstad, 2006; Langyintuo & Lowenberg-DeBoer, 2006). Economic surplus is generated through new technology introduction: farmers increase market supply and produce at lower costs. The economic-surplus method places a monetary value on the increased supply and reduced production costs. A supply-demand framework is used to detail how markets respond to downward price pressure. Consumers obtain a surplus from purchasing their bundle of goods at a lower price. Producers obtain a surplus from selling greater quantities in the market and by reducing production costs. The consumer-surplus measure represents “freed resources” that can be transferred to other parts of the economy. The producer surplus (PS) is the sum of the additional rents that accrue to farmers’ internal resources, as given by the model’s shadow prices.

Empirical estimates of the economic impacts are obtained using an agricultural sector model. This is an equilibrium model that details how markets would respond to the introduction of Bt crops. It determines the new equilibrium following the introduction of Bt technology. Equilibrium is governed by well-established economic theory: it achieves the best outcomes for society under perfect competition (Samuelson, 1952). Consumers and producers are made as well-off as possible; consumers maximize utility at minimum cost and producers maximize profits. The model determines the long-run outcomes following technology introduction; it does not detail the dynamics of how equilibrium was established. Typically, early adopters will achieve large benefits that will dissipate as more producers adopt.

A distinguishing feature of the approach is the use of farm-level models. This allows farmers’ decision making and socio-economic constraints to be included in analysis that is aggregate in nature. Farm-level effects are ignored in more standard approaches and remain hidden. In regions where income literally changes with the weather risk, this is an important issue. Risk is modeled using lexicographic preferences consistent with observed farmer behavior. Farmers will choose among their production alternatives beginning with their most important criteria, such as ensuring subsistence needs are met, rather than weighing the tradeoffs between multiple possible outcomes. Farmers secure income and staple food requirements before pursuing profit maximizing objectives. This captures the subsistence-oriented nature of production as household value of food and fiber are determined endogenously (DeJanvry, 1991). Household resource endowments on land, labor, and capital are modeled using constraint inequalities. Cotton places a strong demand on soil nutrients; nutrient balances are typically negative on cotton fields. Farmers rotate cotton with maize in three-year rotations. This rotational constraint is included in the model.

Model Empirical Structure

Markets are modeled using supply and demand equations. Markets are included for the major standing crops and legumes: sorghum, millet, maize, cotton, rice, peanuts, and cowpeas. There are twelve regional markets in the model, one for each of the major urban areas throughout Mali. Trade-flows between regional markets are included within the model; they are governed by the transportation costs required to ship commodities from one market to another.

Table 3. Bt cotton yield increase and cost reduction data used in model scenarios.

Variety	Pest sprayings (number/ year)	Spraying cost ($/ha)	Cotton yield: (kg/ha)	Bt cotton yield increase
Conventional	6	60	1,200	-
Bollgard® II	2	20	1,440	+ 20 %

The model's empirical structure of the cotton and maize markets is worth noting. Nearly all of the cotton produced in the region (98%) is sold in the world market. Mali is a "small country" and does not have market power; the introduction of Bt cotton is not expected to change world cotton prices. *Cotton* demand is perfectly price *elastic*: cotton prices paid to farmers remain constant under the Bt cotton scenario. Maize markets are much the opposite of cotton; there are limited export opportunities. Nearly all of the maize produced is traded in domestic markets within Malian borders; maize imports are infrequent. *Maize* demand is largely price *inelastic*: prices can fall quickly with the introduction of Bt maize. Maize demand includes a storage component. Farmers let prices fall only so far before grain is held back in silos. Maize impacts are likely to accrue more to consumers and producers' impacts and will be governed more by cost reductions.

Adoption profiles are determined endogenously within the model. Adoption of Bt cotton and Bt maize are determined by farm profits. Bt cotton and Bt maize are introduced into the model under the biotech scenarios. For adoption to occur, Bt cotton and Bt maize must pass over a "profit hurdle" established by the embedded farm models: they must be more profitable than the conventional cotton and maize technology. The extent of adoption, hence, is dictated by how "high" this hurdle is. Adoption is influenced by farmers' decision making preferences, resource constraints, yield increases, costs, and prices. The model presumes farmers have complete information.

Model Data

Bt cotton yield data is taken from recent field trials conducted by INERA, the national agricultural institute of Burkina Faso (Table 3). The field trials found that cotton yields increased by an average of 20% using Bollgard® II, Monsanto's Bt cotton variety. Field trials on Bt maize have not yet started in W. Africa. In its place, Bt maize data was obtained from S. Africa. Bt maize was presumed to increase yields by an average of 15% (James, 2002). Other model data is documented in the Appendix.

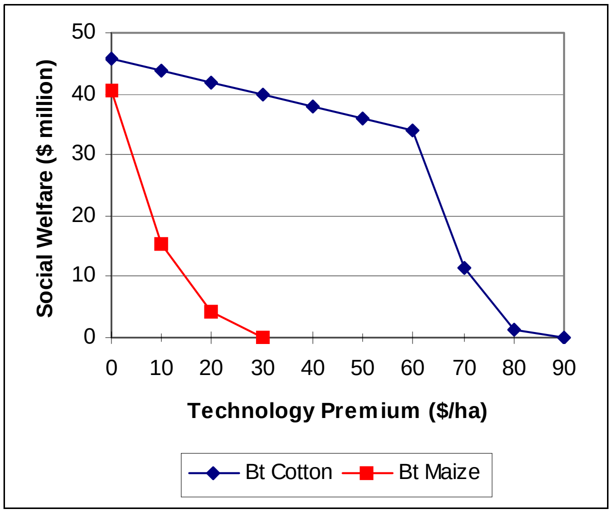

Figure 3. Economic impacts from the introduction of Bt cotton and Bt maize in Mali.
Source: Authors' economic model.

Results

The introduction of Bt cotton is expected to increase cotton yields by 20%. Under this scenario, the aggregate impacts on social welfare in Mali would reach $45.7 million per year in the absence of a technology premium (Figure 3). Since nearly all of the cotton produced is exported to world markets, the change in social welfare accrues primarily to producers. As the technology fee charged to farmers *increases*, the aggregate impacts *decrease*. The Bt technology fee marginally affects aggregate impacts up to the $60/ha level. Throughout this range, farmers' adoption of Bt cotton remains constant. This is evident from the curve in Figure 3 since the change in social welfare declines in a linear manner. The linear decline up to $60/ha is due to the technology premium which extracts surplus from the producers and transfers it directly to the technology provider (seed company).

Bt cotton adoption begins to weaken beyond the $60/ha level at which point social welfare declines more rapidly, indicating that the number of Bt cotton adopters has decreased. The economic model indicates that the decline in Bt cotton adoption would be fairly abrupt between technology premiums of $60 and $80 per hectare. Farmers in the marginal production areas would be the first to find Bt cotton unprofitable due to the increased technology premium. For technology premiums greater than $90/ha, there would be no adoption of Bt cotton.

Table 4. Economic impacts ($ million) of introducing Bt cotton and Bt maize in Mali across an alternative range of technology premiums.

	Technology premium ($/ha)									
Group	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
					Bt cotton					
Producers	45.7	43.8	41.8	39.9	38.0	36.0	34.1	11.4	1.2	0
Seed co.	0	1.9	3.9	5.8	7.8	9.7	11.7	3.6	0.9	0
Total	45.7	45.7	45.7	45.7	45.8	45.7	45.8	15.0	2.1	0
					Bt maize					
Consumers	32.7	12.3	3.5	0	0	0	0	0	0	0
Producers	7.6	2.9	0.8	0	0	0	0	0	0	0
Seed co.	0	3.5	1.2	0	0	0	0	0	0	0
Total	40.3	18.7	5.5	0	0	0	0	0	0	0

Source: Author's economic model.

The seed company providing the Bt cotton technology would gain at most $11.7 million in revenue from the technology premium. The maximum revenue would occur at a technology premium of $60/ha. Beyond this point, Bt cotton adoption would fall off too quickly for the seed company to capture any additional revenue. The model results indicate that the seed company would not have any incentive to use monopoly power and restrict the types of farmers to whom it would sell. At the technology premium where revenue is maximized, all of the cotton farmers would find it profitable to adopt Bt cotton. Moreover, the majority of the benefits from Bt cotton would remain with the Malian cotton producers. At the $60/ha technology premium, the seed company would capture only 26% of the economic impacts from Bt cotton, with the producers capturing 74% (Table 4).

A $60/ha technology premium would be significantly higher than the technology fee charged by Monsanto to smallholder farmers in developing countries. In 2006, Monsanto charged a technology premium of $38/ha for its Bt cotton (Bollgard) in S. Africa, $22/ha *less* than the technology premium that could be charged in Mali according to the model (Brookes & Barfoot, 2005). However, the $60/ha technology fee is less than Monsanto's technology fee in the US, which averaged about US$83/ha in 2006 (Brookes & Barfoot, 2005).

The introduction of Bt maize is expected to increase maize yields by 15% over conventional maize. Under this scenario, the aggregate impacts on social welfare would reach $40.3 million per year in the absence of a technology premium (Figure 3). Bt maize was found to be much more sensitive to the technology premium than Bt cotton. Even with a $10/ha technology premium, social welfare would decline by 63% from $40.3 to $15.2 million (Table 4). At a technology premium of $20/ha, social welfare would decrease to $4.3 million, and there would be no adoption with a $30/ha technology fee.

Since nearly all of the maize produced is consumed in domestic markets, the change in social welfare accrues to both Malian consumers and producers. Existing markets for maize are subsistence oriented with a low price elasticity of demand. The weak maize markets have difficulty absorbing surplus grains without a significant fall in prices. As a result of this, 81% of the social welfare accrues to Malian consumers, who gain $32.7 million per year from the introduction of Bt maize. Producers would gain much less: $7.6 million per year.

The seed company providing the Bt maize technology would gain at most $3.5 million in revenue from the technology premium. The maximum revenue would occur at a technology premium for Bt maize of $10/ha. Beyond the $10/ha technology premium, Bt maize adoption would fall off too quickly for the seed company to capture any additional revenue. For instance, at $20/ha the total revenue would fall from $3.5 to $1.2 million per year. As with Bt cotton, the model results indicate that the seed company would not have any incentive to use monopoly power and restrict the types of farmers to whom it would sell. The majority of the benefits from Bt maize would remain within Mali. The seed company would capture just 19% of the total economic impacts from Bt maize, with consumers capturing 66% and producers capturing 15% (Table 4).

A $10/ha technology premium for Bt maize would be much lower than the technology fee charged by Monsanto to farmers in either developed or developing countries. In 2006, US farmers paid, on average, a technology fee of $36/ha, and in S. Africa farmers paid $30/ha (Brookes & Barfoot, 2005). With such a weak demand for Bt maize, as measured by the technology premium, it is questionable whether a technology provider would have adequate incentives to conduct business in the W. Africa region. It is likely that seed companies would wait until maize markets improved and became more commercialized, which would not only provide higher maize prices but would also promote improved maize technology.

The model results indicate that Bt cotton would provide larger aggregate impacts than Bt maize, about $10.3 million more per year. The larger benefits generated by Bt cotton and its ability to maintain adoption at higher technology premiums are explained by a couple of factors. One is the greater profitability of cotton compared to maize. Cotton and maize have nearly the same yield in Mali, yet cotton is sold at a price ($1.05 kg^{-1}) is nearly double that of the price of maize ($0.60 kg^{-1}). The other is that Bt maize farmers do not spray maize fields, unlike cotton farmers, so farmers could not reduce costs in this manner. Bt cotton saves producers on average $38/ha on pest sprays (Vognan et al., 2002) in addition to the yield advantage it provides. The higher benefits and greater cost reductions provided by Bt cotton relative to Bt maize is consistent with results from studies in other parts of the world (Brookes & Barfoot, 2005).

Conclusions

South African and Burkina Faso field trials have already demonstrated the technical merits of Bt crops in the African setting. The potential economic gains of Bt engineered crops have been shown to be substantial in this paper and others (Gouse et al., 2004; Hofs et al., 2006; Ismael et al., 2002). Yet experience has shown reluctance, often strongly voiced, to bioengineered crops in Africa, with the exception of S. Africa. This has been politicized into regulatory hurdles that often far surpass those established within the political landscapes of developed countries.

Getting Bt engineered crops into the hands of African farmers will require progressively minded policy makers. History has, moreover, shown a propensity towards politically based decisions that favor urban elites over the interests of farmers and low income peoples (Demery & Squire, 1996). Until prevailing attitudes are changed, African agricultural sectors will find it difficult to maintain any sort of competitive stance with the bioengineered-equipped farmers in other countries.

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Appendix: Simulation Model Structure

The introduction of Bt crops is analyzed using an agricultural sector model (McCarl & Spreen, 1980). The agricultural sector model (ASM) maximizes social welfare (SW) of consumers and producers at the national level using the method of economic surplus (Boulding, 1945). The economic surplus approach defines SW as the sum of consumer surplus (CS) and producer surplus (PS). The objective of the ASM is given by

$$Max\ SW = \sum_R \left(CS + PS\right) \tag{1}$$

which states that the sum of CS and PS is maximized across the region (R) producing regions. In this model each R is considered to include only a single market.

The ASM calculates SW in each region using the area beneath the consumer demand curve and the area above the producer supply curve (Tanyeri-Abur et al., 1993). In this form SW is written as

$$Max\ SW = \sum_i \sum_R \int_0^{Q^*} \left(P^{-1}(Q_{D,i}^R) - S(Q_{S,i}^R)\right) dQ \tag{2}$$

which states that SW is maximized in each region by integrating the difference between the inverse demand curve, $P^{-1}(Q_{D,i}^R)$, and the producer supply curve, $S(Q_{S,i}^R)$. The area of integration is from zero to the quantity traded in the market, Q^*. Since ASM includes multiple crops, SW is summed over each of the i^{th} crops in the region.

Market equilibrium is established in each of region using the principle of SW maximization (Samuelson, 1952). Conditions are included in ASM to assure that markets clear, or equivalently that market supply meets or exceeds demand. Inter-regional trade is included in the empirical model (Takayama & Judge, 1964), but is not included in the description of the theoretical model. The market clearing conditions are given by

$$Q_{S,i}^R \geq Q_{D,i}^R \tag{3}$$

which states that market supply, $Q_{S,i}^R$, must be genetically engineered to market demand, $Q_{D,i}^R$. The shadow value, λ_i^R, on Equation 3 has an important interpretation: λ_i^R represents the market price of the last good that was consumed and produced in the region R.

ASM determines supply using linear programming models of representative farm households in each region (McCarl, 1982; Sharples & Schaller, 1968; Vitale, 2001). Mixed complementary programming (MCP) is used to embed the farm models into the regional portions of the ASM (Rutherford, 1995). MCP is a programming approach that can be considered to simultaneously solve for both the primal and dual variables of a math programming formulation (Paris, 1979). Similar to traditional math programming, relationships among variables are expressed using strict equalities and inequalities. Each inequality has an associated shadow value and is subject to the complementary slackness condition. Typically in economics, MCP is used to solve the Kuhn-Tucker optimality conditions, which is a set of inequalities among primal and dual variables.

In this application, MCP enables prices from each regional market, λ_i^R, to be fed directly to the farm programming models. Without this feature, the farm programming models would be unable to determine production practices since prices would be unknown. The first-order conditions of the farm programming model are given by

$$\lambda_i^R \geq \sum_j C_{i,j} + \sum_l \mu_l A_{i,j,l} \tag{4}$$

$$AX \leq B \tag{5}$$

Table 5. ASM data used in developing the regional production areas and markets.

Regional Market	Production area (ha)	Average cotton yield (kg/ha)	Average maize yield (kg/ha)	Average farm size (ha)	Maize price
Bamako	309,880	1,132	1,423	16.8	76
Tombouctou	15,769	-	-	3.6	102
Bougouni	305,315	1,176	1,394	11.7	78
Kadiolo	70,164	1,032	1,284	10.5	75
Sikasso	108,806	1,165	1,427	18.9	71
Koutiala	356,018	1,103	1,263	21.5	74
San	241,354	-	-	13.2	82
Segou	606,593	-	-	17.1	81
Mopti	462,688	-	-	14.4	89
Kita	292,187	-	-	13.2	86
Kayes	165,218	-	-	15.3	81
Gao	141,379	-	-	3.9	105
Total/ave	3,075,371	1,122	1,358	13.3	83.3

Source: Malian Statistical Services.

where $C_{i,j}$ is the out-of-pocket cost of producing the i^{th} crop with the j^{th} technology alternative; $A_{i,j,l}$ is the technical coefficient for the l^{th} resource; μ_l is the shadow value for the l^{th} resource; **X** is the vector of the crop acreages planted, and; **B** is the vector of resource availability. ASM assembles the the Kuhn-Tucker optimality conditions from Equation 2 through Equation 5 and develops a MCP formulation from them.

ASM has three primary decision variables: (1) acres produced on each representative farm household, (2) market prices for each crop, and (3) the quantity traded (purchased/sold) in each market. Once the decision variables are determined ASM calculates SW using Equation 2 above. The economic impacts of introducing Bt cotton and Bt maize are calculated using the change in SW. ASM is run initially under baseline conditions to establish SW under conventional crop technology. Bt cotton and Bt maize are then introduced into ASM, which is solved to predict SW under biotechnology. The change in SW is determined as the difference between SW with and without the introduction of biotechnology.

ASM Model Data

ASM is a fairly large model and that requires data from various sources (Vitale, 2001). Data on the regional aspects of the model were obtained from various statistical service departments in Mali (Vitale, 2001). This provided information on population, production areas, crop yields, and market prices (Table 5). Geographic Information Systems (GIS) techniques were used to perform ded farm models to the regional markets. The total cultivated area surrounding each of the primary markets included in the model was estimated using the Cropland Use Intensity (CUI) data layer (Vitale & Bessler, 2006). The average farm size within each region was then calculated using household demographic data. Cotton is sold by farmers to government-owned ginning facilities at a price of $0.40 per lb for seed cotton.

Table 6. Labor demand coefficients for the crop production enterprises included in the (man-hours/ha).

Activity	Crop	Unit demand
Manure application	All	16
Ridging	All	40
Tied ridging	All	75
Seeding	All	8
Weeding	All	35
Inorganic fertilizer application	All	8
Mounding	All	44
Harvest	Cotton	450
Harvest	Cowpea	375
Harvest	Groundnut	450
Harvest	Maize	210
Harvest	Sorghum	150
Harvest	Millet	150

Sources: Coulibaly (1995), Dalton (1996), Vitale (2001).

The farm-household programming models were parameterized using field data that was collected from farmer surveys (Coulibaly, 1995; Dalton, 1996; Vitale, 2001). Primarily, the field surveys were used to estimate the technical coefficients and the labor demands from crop enterprises (Table 6). The technical coefficients listed in Table 6 are for animal traction production systems, which are used on more 85% of the farms in Mali. In the cotton production zone, inputs are provided by the national cotton company, CMDT. Outside of the cotton zone, inputs are purchased from private channels. The out-of-pocket expenses incurred by producers are listed in Table 7.

Table 7. Input prices used in the farm models.

Item	Price
Cereal compound	215 fcfa/kg
Urea	200 fcfa/kg
Improved sorghum seed	300 fcfa/kg
Improved millet seed	300 fcfa/kg
Improved groundnut seed	300 fcfa/kg
Improved cowpea seed	300 fcfa/kg
Sorghum fungicide	350 fcfa/kg
Millet fungicide	350 fcfa/kg
Cowpea insecticide	3,750 fcfa/packet
Groundnut fungicide	195 fcfa/kg

Source: CMDT (2006).