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ECONOMICS & MARKETING

Testing the Efficacy and Economic Potential of Bollgard II under Burkina Faso Cropping Conditions

O. Traore, S. Denys, J. Vitale*, K. Traore, and K. Bazoumana

ABSTRACT

Cotton production in Burkina Faso regularly suffers from significant pest damage. Conventional pest control measures have failed to adequately control the main cotton pest, *Helicoverpa armigera*. Burkina Faso began testing of genetically modified (GM) cotton in 2003 to assess the efficacy of the Bollgard II (BII) genes in controlling Lepidoptera pests. Field trials were conducted at two agricultural research centers in Burkina Faso (Farako-Bâ and Kouaré). The field trials compared conventional cotton varieties to GM cotton varieties in order to estimate the effectiveness of the BII genes in protecting cotton plants and improving cotton yields. The field trial results found that Bollgard II cotton would increase cotton yields by as much as 38% compared to conventional cotton. Significant differences in yield gains were found between the two sites, with higher yield gains reported at Farako-Bâ. An economic simulation model found that BII cotton would increase farm income in the range of $35 to $110 per hectare depending on the seed price.

INTRODUCTION

Cotton is an important cash crop throughout West Africa, particularly in the "cotton four" (C4) countries of Mali, Burkina Faso, Benin, and Chad. In rural areas where cotton is grown, cotton has been the primary catalyst to economic development. Rural infrastructure has been built around cotton, which has been the driving force behind the construction of roads, schools, banks, and hospitals. Rural households are highly dependent upon cotton for supplying their basic needs, as cotton typically accounts for 60 percent of household income (Vognan et al., 2002). National exports in the C4 countries are dominated by cotton, which has earned the nickname of "white gold". Cotton is their most important agricultural export and constitutes a major share of export earnings in Burkina Faso (56%), Mali (25%), Benin (38%), and Chad (36%) (FAOSTAT, 2006).

Cotton has been produced in West Africa since the colonial era and has been one of the major agricultural success stories since independence took hold of the region in the early 1960s (Lele et al., 1989; Roberts, 1996; Bingen, 1998). The prevalence of disease and insect pressure limited agricultural development in the wetter, higher yield potential areas, focusing it instead on the drier, semi-arid locales (Bassett, 2001). Over the past two decades, frontier areas in the sub-humid tropics have opened (MacMillian et al., 1998). Cotton production has expanded into these more humid areas and has enabled a 250% increase in cotton area over the recent past, but has also increased the need for improved crop protection (Figure 1). Yields have increased steadily over the past few decades; today cotton yields in West Africa 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).

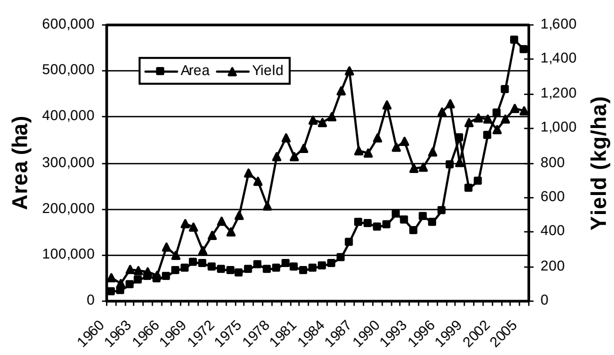

Figure 1 Cotton Yield and Area in the Burkina Faso Cotton Sector.

O. Traore, Institut de l'environnement et de recherches agricoles (INERA), Cotton Program Division, 01 BP 208, Bobo-Dioulasso, Burkina Faso; S. Denys, K. Traore, K. Bazoumana, INERA: Cotton Program Division, 01 BP 208, Bobo-Dioulasso, Burkina Faso; J. Vitale*, Oklahoma State University, 308 Ag Hall, Stillwater , OK 74078-6026
*Corresponding author: jeffrey.vitale@okstate.edu

The West Africa cotton sector has a strong tradition of government ownership and vertical control over the sector. The Burkina Faso cotton sector had traditionally been owned and operated by the Burkina Faso government, in joint cooperation with a privately owned French company, DAGRIS, in which the Burkina Faso government owned 70 percent and DAGRIS the remaining 30 percent. The government owned cotton company, SOFITEX, had complete control over the cotton sector. This was a "one-stop" cotton farming system in which SOFITEX provided all of the production inputs and also purchased the seed cotton from the farmers. Cotton producers benefited from gaining access to the input supply chain which provided them with modern seeds, fertilizers, insecticides, and animal draft power. Conversely, Burkinabé cotton producers were under the monopoly control of SOFITEX and were paid some of the lowest share of world cotton prices (Bates, 1981; Baffes, 2007).

In 2002 the Burkina Faso government divested itself of complete control of the cotton sector. Under the new institutional arrangement the cotton sector is jointly owned by the Burkina Faso government, the private sector, and Burkina Faso cotton producers. Three cotton companies now operate in Burkina Faso, with each operating in a different region. Although each company maintains the "one-stop" cotton farming system, cotton prices are now negotiated among the principal stakeholders giving producers a significant voice in determining cotton price levels. This new arrangement is expected to streamline the cotton sector and make it more competitive in world markets by introducing modern production practices, including crop biotechnology.

Over the past several years, the C4 countries of West Africa have attracted international attention for their stance against cotton subsidies among developed countries, particularly the United States (Baffes et al., 2004; Liebhardt, 2005). The frequent collapse of world cotton prices since 1999 has created a crisis situation in the West African cotton sector (CMDT, 2001). A recent study by Anderson and Valuenzuela (2006) estimated the economic damage to West African cotton producing countries at $143 million per year, which is consistent with Sumner's (2003) earlier study that estimated the damage at $116 million per year[1]. Many countries, notably Mali, have found their nationally owned ginning company insolvent, kept afloat by international donor aid (World Bank, 2004). Burkina Faso has responded to the shrinking profit margins by producing more cotton (OECD, 2006). Throughout the past several years as world cotton prices have plunged downward, Burkina Faso has introduced 25 percent more cotton acreage (Figure 1).

Equally problematic, yet less publicized, is the damage caused by insect pests which has become a major issue confronting the West Africa cotton sector. On unprotected fields pests can damage up to 90% of the cotton crop (Traoré et al., 1998). The larva of *Helicoverpa armigera,* the American bollworm, a Lepidoptera of the Noctuidae family, is the main cotton pest in Burkina Faso and throughout West Africa (Vaissayre and Cauquil, 2000). Over the past 10 years, *H. armigera* control measures have not been successful (Programme Coton, 1999). The pesticides that have been developed have neither controlled *H. armigera* nor suppressed its population in the cotton growing areas. Pest populations have been able to develop resistance to the chemical agents as the efficacy of pyrethroid insecticides has been waning (Goldberger et al., 2005; Martin et al., 2002). Typically, cotton producers spray about six times per year, but as many as ten sprayings can be required as the number of sprays per crop season varies from place to place and from one year to the next. Insecticides worth about 120 billion CFA francs ($60 million) are used annually in Burkinabé agriculture to control bollworms (Vognan et al., 2002). Without adequate control measures for *H. armigera* and other pests, pest damage has contributed to the stagnation in cotton yields in Burkina Faso, which have not only been stagnant, but on the decline. This underscores the economic importance of controlling cotton bollworms in the region and, in particular, the American bollworm (*H. armigera*).

In order to achieve enhanced control of *H. armigera*, the Monsanto Company developed Bt cotton technology (Perlak et al., 1990; Purcell and Perlak,

1 The economic literature contains several studies that have estimated the economic damage from U.S. subsidies on West African cotton export earnings. Alston and Brunke (2006) summarize the study findings and report on a wide variation in estimates due to differing methods and data sources. Pan et al. (2006) also provide a review of previous impact estimates, while estimating much smaller impacts of U.S. subsidies on world cotton prices than Alston and Brunke.

2004). Bt cotton contains a gene of *Bacillus thuringiensis* which synthesizes the Bt protein in the plant and provides protection against *H. armigera* and other Lepidopteran pests. Bt cotton was introduced over a decade ago on U.S. farms and in 2006 was grown on 80 percent of U.S. cotton acres. Many studies have documented the superior performance of Bt cotton over conventional cotton in the control of Lepidopteran pests (Qaim and DeJanvry, 2005; Bennet et al., 2004; Smale et al., 2006). The yield advantage of Bt cotton over conventional methods has been about 10 percent in the U.S. (Benedict and Altman, 2001; Perlak et al., 2001) and from 5 to 10 percent in China (Pray et al., 2001, 2002). The yield advantage of Bt cotton is expected to be even higher in West Africa where pest populations are denser and existing control methods less effective (Abate et al., 2000).

Despite the accumulated evidence of Bt cotton's capabilities and the continued ineffectiveness of conventional pest management, the West African countries remain hesitant to adopt Bt cotton (Cohen and Paarlberg, 2002). Concerns over scientific boundaries, and a strict adherence to the precautionary principle similar to many European countries, has maintained barriers to Bt cotton in West Africa (Paarlberg, 2001; Spielman, 2007). Burkina Faso has taken the most progressive stance on Bt cotton among the C4 countries, allowing monitored field trials of Bt cotton beginning in 2003. Field trials were conducted at two Burkinabé experiment stations to test the performance of B II cotton in the West African setting (Traoré et al., 2006; Vitale et al., 2006). Two international seed companies, Monsanto and Syngenta, participated in the field trials. The field trials were repeated for three years from 2003 through 2005 on experiment station test plots.

The purpose of this paper is to present the findings of B II cotton field trials conducted in Burkina Faso. Statistical analysis is used to develop a pest control model that estimates B II cotton's efficacy in controlling *H. armigera* and other Lepidopteran pests based on the field trial data. An economic analysis is then presented to predict the economic benefits that B II cotton would generate for Burkina Faso cotton producers if B II cotton were introduced in the region.

MATERIAL AND METHODS

The field trials were conducted at two experiment stations in Burkina Faso. Two sites were deemed necessary since insect pressure varies throughout the cotton production zone. One set of field trials was conducted in Farako-Bâ, located in western Burkina Faso, where insect pressure is typically greatest. A second set of field trials was conducted in eastern Burkina Faso at Kouaré, where insect pressure is lower. Annual rainfall recorded in the two experimental zones was above 800 mm in each of the experiment years. The soils at both sites are tropical ferruginous with an organic matter content of 0.72% at the soil surface, which increases to 1.16% at a depth of 40 cm. The soil pH ranges between 5.2 and 6.2 at the Farako-Bâ and Kouaré stations.

Vegetal material. The study consisted of comparing the performance of conventional cotton pest management practices to B II cotton. At the time of the experiments the Bt gene had not been introduced into any of cotton varieties grown by Burkina Faso producers. All of the experiments were conducted using American cotton varieties, Coker 312 and DP50. In the 2003 experiments, the B II cotton tested was developed from the Coker 312 cotton variety. In the 2004 and 2005 experiments the B II cotton tested was developed from the DP50 cotton variety, a more up-to-date variety of Bt cotton. Also included in the experiments were the cotton varieties grown by Burkina Faso producers to test whether there was a significant effect in using an American variety as opposed to a local variety. In Farako-Bâ the FK-37 variety was tested and in Kouaré the STAM 59 A variety was tested[2].

Experimental design. A Fisher block design was used in the Bollgard II experiments. Each Fisher block design had two pest treatment levels and each treatment level was replicated four times. The experimental units were composed of rows that measured 15 meters in length, with 80 cm between lines and 40 cm between cotton plants. In 2003 the experimental units contained eight rows, and in 2004 and 2005 the experimental units contained ten rows. The tests were conducted in fields that had been planted under a cotton-maize rotation for the past six years.

The fields were disk plowed on or about June 20th in each year. This deviates somewhat from farmer practices since most Burkina Faso farmers

2 The designations on the FK-37 and STAM-59A varieties refer to the research stations where they were developed, FK-37 at Farako-Ba in Burkina Faso and STAM-59A at Anié Mono in Togo. Neither variety has been commercially released, but both are produced under license by nationally owned ginning companies in the West Africa region.

(70 percent) use animals for plowing. The tractor was deemed necessary for the increased uniformity and precision that it provided in establishing the test plots. The test plots were seeded on or before June 25^{th}, following the plowing operation. The test plots were weeded three times during the growing season. Weeding was performed manually, which is the standard method used by Burkina Faso farmers. The plots were fertilized twice during the growing season, and followed the recommended fertilizer applications for growing cotton prescribed by the national ginning company's extension services. Fifteen days after emergence the cotton plots were fertilized with an application of 150 kg ha^{-1} of NPKSB (14-23-14-6-1). Urea was applied 40 days after emergence using an application of 50 kg (46%N).

The pest control alternatives compared in 2003 were the following: (1) Coker conventional cotton, treated six times to control bollworms, leaf worms, and sucking insects, and (2) Coker B II, treated six times against sucking insects. In the 2004 and 2005 field trials the treatments consisted of: (1) DP50, treated six times against bollworms, leaf worms and sucking insects, and (2) DP50 B II treated six times against the sucking insects.

The sucking insect control measures followed the standard control practices in the region, which consists of six insecticide applications during the growing season. Three different chemical agents were used. Carbosulfan was applied at 30 and 44 days after plant emergence using a rate of 300 g ha^{-1}. Imidaclopride was applied at 58 and 72 days after emergence using a rate of 50 g ha^{-1}. Acetamipride was applied at 86 and 100 days after emergence using a rate of 8 g ha^{-1}.

Beginning 30 days after plant emergence the cotton fields were scouted for primary (Lepidoptera) and secondary (piercing/sucking) pests. In each test plot 30 cotton plants were randomly selected and each plant was completely inspected, including foliage, squares, flowers, and bolls. The bugs were then identified, counted, and recorded in a database. The scouting occurred once per week during the growing season. Cotton yields were determined for each variety by harvesting the two central rows of each experimental unit. This removed any edge effects from the test plots.

Statistical analysis. The Bollgard II data was analyzed using a two-stage process of pest control and pest damage (Fox and Weersink, 1995; Hennessy, 1997). This modeling approach first considers the effect of pest control measures on reducing pest populations, using either conventional pest management or B II cotton. The model then considers the subsequent damage caused by the remaining pest population on crop yields. The first stage of the model contains the pest control function, which determines the extent to which the initial pest population, Z_0, has been reduced to its final population, Z_1, by the level of pest control effort, T. The control function can be written as:

$$Z_1 = Z_0(1 - C(T)) \tag{1}$$

In this form the control function is analogous to a cumulative probability distribution since it takes on values between 0 and 1 (Fox and Weersink, 1995). With no control effort, T=0, the control function is zero and there is no change in pest population. Alternatively, at the maximum control effort, as T grows large, the control function approaches 1 and the pest population is reduced to zero. Between these two extremes the value of C(T) indicates the pest control efficacy at the effort level T.

In the second stage the damage caused by the pests left uncontrolled is given by:

$$Y = Y_0(1 - D(Z)) \tag{2}$$

where D(Z) is the damage function, Y is the observed cotton yield, and Y_0 is the yield corresponding to zero pest condition. The damage function also has properties consistent with a cumulative probability distribution. With zero pest population, Z=0, the damage function is zero, D(0)=0. Under extreme pest pressure Z grows large and D(Z) approaches 1. In this case of extreme pest pressure, cotton yields approach zero in the damage function.

Various functional forms have been found to fit the pest control and pest damage functions, C(T) and D(Z). In this study, functional forms for the pest control model were not necessary since the pest control levels were held fixed throughout the B II cotton field trial experiments. For instance conventional cotton was sprayed four times to control Lepidopteran pests irrespective of the pest population, and B II cotton had a consistent level of pest control from the Bt genes. Equation 1 was estimated using an OLS procedure with dummy variables representing the pest control levels. This was considered an acceptable approach since it provided a good statistical fit to the observed data (R^2=0.856) and the model was readily solved using standard software (SAS 1998). The results of the pest control model were then placed into the second stage pest damage model.

The pest damage model was estimated using an exponential damage function, which included both primary and secondary pests. The exponential function was used since it has been found to be consistent with observed pest damage in other studies and in this study was found to provide a satisfactory statistical fit to the observed data (Lichtenberg, E. and Zilberman, 1986; Babcock et al., 1992; Blackwell and Pagoulatos, 1992). The damage function is given by the following:

$$Y = Y_0 e^{(\beta_P Z_{1,P} + \beta_S Z_{1,S})} \quad (3)$$

where $Z_{1,P}$, $Z_{1,S}$ are the primary and secondary pest densities and β_P, β_S are parameters to be estimated.

Economic Analysis

The pest control and pest damage model provides the foundation for conducting the economic analysis. An integrated economic-entomological model is developed that translates the pest control efficacy into economic terms through a partial farm budgeting procedure. This procedure compares the economic profit between B II and conventional cotton based on unit returns, typically one hectare of production. The partial budget approach was taken since the introduction of B II cotton affects only a couple of items in the cotton enterprise budget. Most production practices, such as land preparation, fertilization, and weeding remain unchanged. Using the partial budgeting approach, the change in profit between B II and conventional cotton is given by:

$$\Delta\Pi = \Pi_{Bt} - \Pi_C = P_c\Delta Y + \Delta C + \Delta L \quad (4)$$

Where Π_{Bt} is the unit profit (per ha) of B II cotton, Π_C is the unit profit (per ha) of conventional cotton, P_c is the cotton price, ΔY is the yield difference between B II and conventional cotton, ΔC is the change in insecticide costs between B II and conventional cotton, and ΔL is the change in labor costs between B II and conventional cotton. Equation 4 states that the potential economic gains from B II cotton are given by its increased revenue (yield advantage), $P_c\Delta Y$, the reduction in insecticide costs, ΔC, and the reduction in labor costs, ΔL. All other production costs were identical for B II and conventional cotton and were dropped out of the partial budget model.

The model determines ΔY by considering a distribution of population densities for the primary and secondary pests, which is written as:

$$\Phi = f(Z_{0,P}, Z_{0,S}) \quad (4)$$

where Φ is the probability density function, $Z_{0,i}$ is the untreated pest population level, and i is the subscript denoting primary or secondary pest. Each level of the pest population is reduced through pest management control according to OLS estimates derived from Equation 1. The pest control model includes only two treatment levels, the standard number of sprays used on conventional cotton, and the effect of the B II gene in the transgenic cotton. To account for the variability in pest control efficacy, the model includes a random component to the control of pests, ε_i. The pest control model is given by:

$$Z_{1,i} = \delta_j Z_{0,i} + \varepsilon_i \quad (5)$$

where $Z_{0,i}$ is the initial pest density, $Z_{1,i}$ is the final pest density, and δ_j is the pest control coefficient for pest control alternative j. The random component ε_i has mean zero and a variance estimated from the OLS model of Equation 1.

The pest damage model, Equation 3, is then used to determine the change in yield given the pest densities obtained from Equation 5. This enables the change in yield between B II and conventional cotton to be written as:

$$\Delta Y = Y_0 e^{(\beta_P (Z^C_{1,P} - Z^{Bt}_{1,P}) + \beta_S (Z^C_{1,S} - Z^{Bt}_{1,S}))} \quad (6)$$

and the partial budget equation to be written as:

$$\Delta\Pi = PY_0 e^{(\beta_P (Z^C_{1,P} - Z^{Bt}_{1,P}) + \beta_S (Z^C_{1,S} - Z^{Bt}_{1,S}))} + \Delta C + \Delta L \quad (7)$$

The partial budget, Equation 7, is simulated by drawing random numbers from the two probability distributions, Φ and ε. The simulations were considered a convenient way to assess the interaction between Φ and ε since an analytical solution to the partial budget in Equation 7 is not readily obtained. Instead of using a joint probability density function for Φ, the primary pest population was drawn from a univariate distribution. The secondary pest population was then obtained from the following equation:

$$Z_{0,S} = \alpha_1 + \alpha_2 Z_{0,P} \quad (8)$$

where α_1 and α_1 are parameters to be estimated. Equation 8 was estimated using data from the field trials on primary and secondary pest populations. By drawing the initial pest densities in this manner the change in pest densities can be obtained using the pest control model in Equation 5, which requires drawing from the random component term, ε_i. With the final pest distributions determined, the yield advantage can be calculated along with the net change in income from Equation 7. The simulations result in a distribution of incomes across the pest distribution, which provides for a more realistic accounting of B II cotton's economic potential since it is assessed under a more realistic distribution of pest density than found in the experiment.

Model Data. The economic model was run under conditions reflecting the 2006 cotton production year. Burkina Faso cotton producers were paid 160 FCFA/kg for seed cotton by the national ginning cotton company, SOFITEX. The value of Y_0 was 1,600 kg/ha, which represents the maximum cotton yield that farmers would be able to obtain under zero pest conditions. Current pesticide use in Burkina Faso consists of six chemical sprays, totaling 33,200 FCFA per year. In the field trials B II cotton used only two sprays to control secondary pests, totaling 13,500 FCFA per year. It is expected that the two sprays for secondary pests would be used by B II cotton farmers in Burkina Faso. Therefore B II cotton producers would save about 20,000 FCFA per year. With fewer sprays, labor costs would also be reduced[3]. Spraying two times a year instead of six would reduce cotton farmer's labor costs by an estimated 750 FCFA per hectare (Vognan, 2002).

RESULTS

The pest control model provided a good fit to the observed data (R^2=0.856) using the two treatment effects of standard pest control and B II cotton (Table 1). The model results found that both of the treatment effects, conventional and, B II cotton were highly significant ($P<0.0001$), and the year and site effects to be non-significant ($P>0.05$). The non-significant terms were dropped from the pest control model and the data for experiment year and test site were pooled (Table 1).

The field trials found that Bollgard II performed significantly better than conventional cotton in controlling lepidoptera. The pest control model found that B II cotton had the greatest control efficacy over lepidoptera, 91.8%, which was significantly higher ($P<0.05$) than the standard control efficacy of 57.7% for conventional cotton[4] (Table 1). In practical terms, the results imply that B II cotton controlled more than nine out of ten of the Lepidoptera as compared to conventional cotton, which controlled slightly more than one-half of the Lepidoptera. B II cotton would, therefore, control 34.1% more of the lepidoptera than conventional cotton treated with the standard pest control regiment of six sprays. The estimated pest damage model was found to provide a good fit to the observed data for the across site model (R^2=0.673), with Farako-Bâ having a better fit (R^2=0.763) than Fada (R^2=0.713). The pest damage model was estimated both across and within the test sites since the site effect was found to be highly significant ($P<0.0001$) when included as a variable (Table 2). The pest damage models found significant effects ($P<0.05$) for the yield damage caused by both the lepidoptera and the secondary pests (Table 2). The year effect was not found to be significant ($P=0.70$) and was dropped from the pest damage model.

Table 1 Estimates of the pest control model for the control of lepidoptera pests by standard pest management and B II cotton across experiment year and test site (R^2=0.856)

Effect	Parameter Estimate†	Standard Error	P-Value
Standard pest control	0.577	0.0677	<0.0001
Bt cotton	0.918	0.0677	<0.0001
Site	0.001	0.0574	0.9840
Year	-0.026	0.0384	0.5020

† Parameter estimates correspond to the pest control model based on Equation 1:
$$\frac{Z_1}{Z_0} = 1 - \delta_{STD} - \delta_{Bt} + \delta_{Year} + \delta_{Site}.$$
The estimated parameters from the pest control model, δ_{STD} and δ_{Bt}, represent the pest control efficacy, given as the proportion of the initial pest population controlled (i.e. killed) by each treatment (Bt cotton or conventional cotton). This property holds since the intercept was constrained to one and negative dummy variables were used for the treatment effects.

The within site pest damage models found that lepidoptera damage was greater at Farako-Bâ than Fada. Fada was found to have a lower parameter estimate (-0.00002495) than Farako-Bâ (-0.00009523) as listed in Table 1. The greater extent of pest damage at Farako-Bâ is illustrated in Figure 2, which shows a much steeper slope for Farako-Bâ than Fada. At

3 The insecticide costs are given by ΔC and represent the costs of the chemical sprays. In Burkina Faso, insecticides are applied using a battery powered sprayer that is held on the back of the cotton farmer. The application costs are thus given by the change in labor, ΔL, which represents the time spent by the cotton farmer in applying the sprays. This isn't a very large cost since the opportunity cost of time is small, about $1 per day, and spraying takes one hour. Time is spent traveling to the field, which is on average about 3 kilometers away from the household.

4 The estimated parameters from the pest control model represent the pest control efficacy, given as the proportion of the initial pest population controlled (i.e. killed) by each treatment (Bt cotton or conventional cotton).

a modest lepidotera pest population of 5,000 units ha^{-1}, for instance, the within site models predict a yield damage of 49.9% in Farako-Bâ and 26.3% in Fada. Hence the extent of lepidoptera damage at Fada was nearly twice as large as at Farako-Bâ. The differences in the pest damage estimates between Fada and Farako-Bâ is primarily due to the higher levels of pest density that were observed in Fada, which had several observations with pest densities greater than 5,000 units ha^{-1}, and one that reached 15,000 units ha^{-1}. According to the Fada observations, the effect of Lepidoptera pest damage diminished at the higher pest density levels, suggesting that most of the damage occurs over the initial 5,000 units ha^{-1} (Figure 2). Yield damage tapers off since at higher populations the Lepidoptera have to compete for feeding on the bolls. As a result, the Fada pest damage model was influenced by the higher pest density levels and its model reflected this by having a more modest slope and a lower parameter estimate than found in the Farako-Bâ model.

The across site model was also found to provide a good fit to the observed pest damage (R^2=0.676) and its estimates of pest damage were much closer to the Fada model than the Farako-Bâ model (Figure 2). The similarity of the across site damage model to the Fada damage model indicates that the higher pest density observations have a substantial effect on predicting yield damage. This weakens the predictive power of the Farako-Bâ model since it was estimated at much lower pest density levels than the

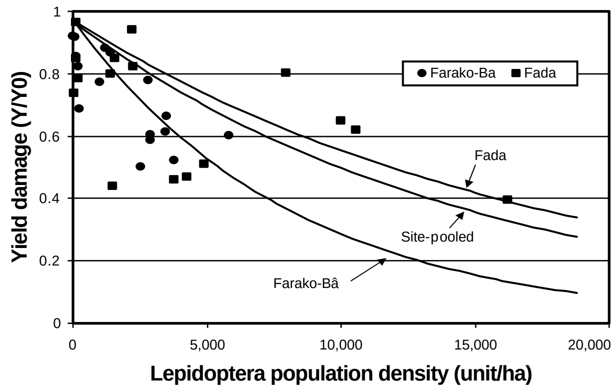

Figure 2 Lepidoptera Pest Damage Models for Site-specific and Site-pooled Models

Fada model. The across site pest damage model was thus considered to be the most appropriate of the models considered since the Fada model appears to understate pest damage while Farako-Bâ appears to overstate it. For this reason the across site model was used in conducting the economic analysis.

Results of the pest damage model found that the primary and secondary pests caused essentially the same extent of damage on cotton yields in both the within site and across site models (Table 2). On a unit basis secondary pests were found to cause more damage than the primary pests (Figure 3). Secondary pest damage on cotton yield was estimated at -0.00015714 kg $unit^{-1}$ ha^{-1} in the across site model, whereas lepidoptera damage on cotton yield was estimated at -0.00003194 kg $unit^{-1}$ ha^{-1} (Table 2). When the observed pest density levels are factored

Table 2 Pest damage model estimates for Lepidoptera and secondary pests across experiment year, and across and within test site

Variable	Parameter Estimate	Standard Error	P-Value	R^2
	Across Sites			
Model	-	-	-	**0.673**
Lepidoptera	**-0.00003194**	**0.00000733**	**<0.0001**	-
Secondary pest	**-0.00015714**	**0.00002134**	**<0.0001**	-
	Farako-Bâ			
Model	-	-	-	**0.763**
Lepidoptera	**-0.00009523**	**0.00001471**	**<0.001**	-
Secondary pest	**-0.00012420**	**0.00004223**	**0.0046**	-
	Fada			
Model	-	-	-	**0.713**
Lepidoptera	**-0.00002495**	**0.00000869**	**0.0056**	-
Secondary pest	**-0.00014131**	**0.00003035**	**<0.0001**	-

† Parameter estimates correspond to the pest damage model based on Equation 3: $Y = Y_0 e^{(\beta_P Z_{1,P} + \beta_S Z_{1,S})}$

in, however, the predicted pest damage from the primary and secondary pests are not significantly different. The field trial results found that on average lepidoptera pest densities were 396% greater than the secondary pest densities. The across site model predicts that under average pest density conditions there would be no significant difference (P>0.05) between the damage caused by lepidoptera or the secondary pests. Lepidoptera maintain their importance in the region since their populations are typically much higher than the secondary pests. There are growing concerns over secondary pests in the region however, since the control methods for secondary pests are growing as ineffective as those for lepidoptera.

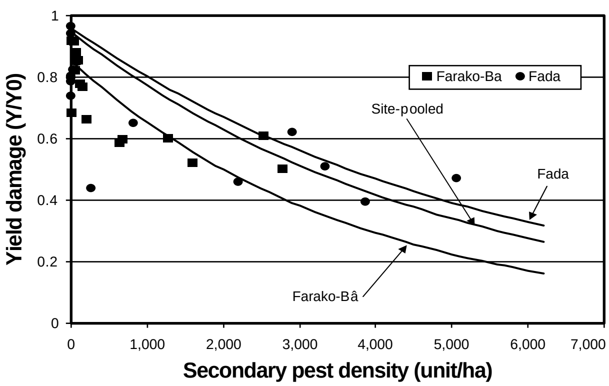

Figure 3 Secondary Pest Damage Models for Site-specific and Site-pooled Models

Yield and Economic Advantage. An important finding from the field trials is that Bollgard II achieved a significant yield advantage (P=0.05) over conventional cotton at both test sites (Figure 4). The magnitude of the Bollgard II yield advantage over conventional cotton was found, however, to be highly dependent on the test site location (Figure 4). In Farako-Bâ, the expected (average) yield advantage was 36% and in Fada the yield advantage was substantially lower, 12%. The across site yield advantage for Bollgard II was 16%, much closer to the Fada yield advantage. The higher yield advantages that were found in Farako-Bâ result from its steeper damage curve which places a higher premium on pest control (Figure 2). When pest populations are brought down through control effort, the steep damage curve means that cotton yields increase more quickly than with shallower curves such as Fada. So given an equal lepidoptera control effect by Bollgard II, the Farako-Bâ model predicts a significantly larger yield increase, and subsequent yield advantage, than Fada. The shapes of the yield advantage curves were also found to be different. The Farako-Bâ curve was spread over a much wider range, indicating that yield advantages could range between 0 and 75% (Figure 4). The Fada yield advantage curve was found to be narrower than Farako-Bâ, with yield advantages ranging between 0 and 29%.

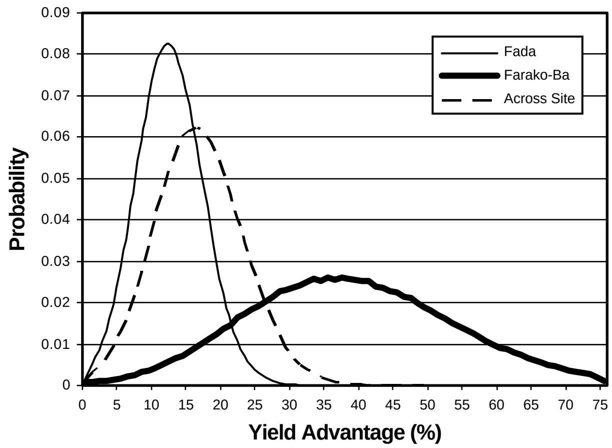

Figure 4 Bollgard II Yield Advantage over Conventional Cotton Simulated from the Pest Damage Pest Control Model

The partial budget equation was simulated (Equation 7) using the results of the across site yield damage equation and was run across an alternative range of technology fees from \$0 to \$75 per hectare (Figure5). Without any technology fee, Bollgard II would generate \$110 per hectare of new farm income under average pest density conditions. Under high pest infestation conditions the economic returns would approach \$185 per hectare, and would approach returns as low as \$50 per hectare in low pest infestations (Figure 5). Under average pest density conditions, 59% of the new cotton income would be generated by higher yields (\$65), reduced insecticide costs, and would account for 36% of the new income (\$40), and the remaining 5% would be from reduced labor costs (\$5). With a \$25 per hectare technology fee, Bollgard II would generate \$85 per hectare of new farm income under average pest density conditions. The economic returns would approach \$160 per hectare under high pest infestation conditions, and in low pest infestations returns would approach \$50 per hectare (Figure 5).

The economic gains are sizeable given that under current farming conditions, with conventional cotton, Burkina Faso cotton producers earn only \$75 per hectare. On average pest infestations Bollgard II would more than double cotton profit. The new economic returns are generated by \$40 in reduced pesticide costs and an additional \$45 to \$70 per hectare in new income from Bollgard II's yield advantage.

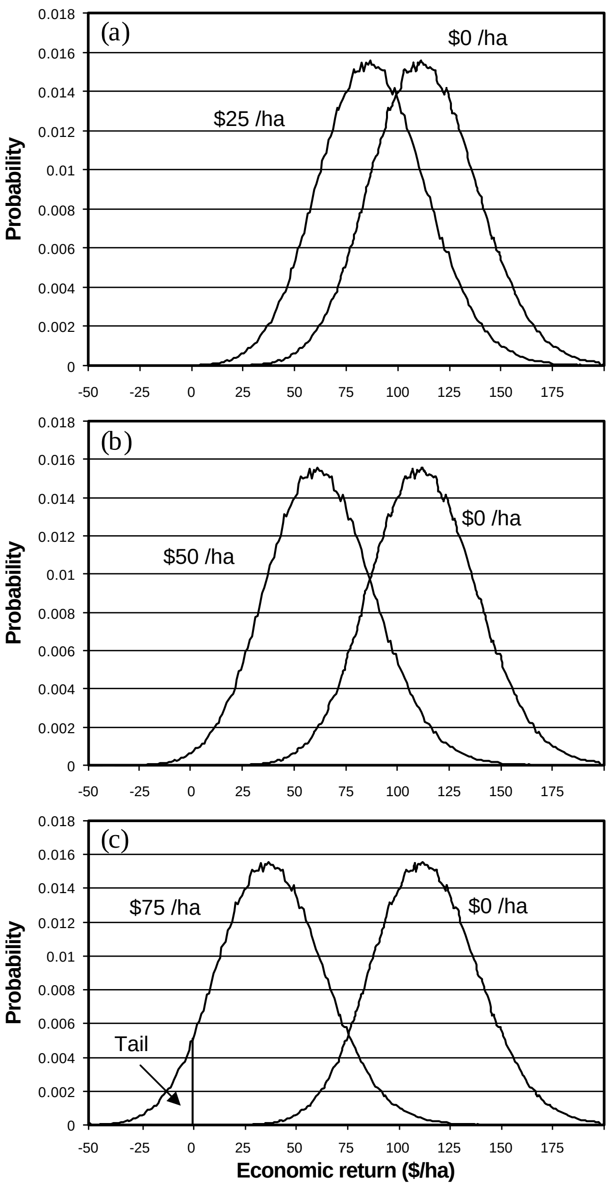

Figure 5 Economic Gains of Bollgard II Relative to Conventional Cotton
(a) Technology fees of $0 and $25 per hectare
(b) Technology fees of $0 and $50 per hectare
(c) Technology fees of $0 and $75 per hectare

With a $50 per hectare technology fee, Bollgard II would generate $60 per hectare of new farm income under average pest density conditions (Figure 5). This technology fee corresponds closely to the technology fee paid by smallholder farmers in South Africa's Makhatini Flats, so a $50 per hectare technology fee is a reasonable first estimate for Burkina Faso's technology fee. The upper end of economic returns under $50 per hectare would approach $135 per hectare under high pest infestation conditions (Figure 5). In low pest infestations the economic returns approach zero. Once returns become negative producers begin to take on risk. Experience with smallholder farmers indicates their unwillingness to adopt new technology if it increases risk. The $50 per hectare technology premium results in only a 0.4 percent chance of a negative return from adopting Bollgard II so it's unlikely to have any practical effect on adoption.

With a $75 per hectare technology fee, Bollgard II would generate $35 per hectare of new farm income under average pest density conditions (Figure 5). This technology fee corresponds closely to the technology fee paid by US cotton farmers, so a $75 per hectare technology fee is a good choice for an upper limit since it's unlikely that Burkina Faso farmers would be charged a higher technology fee than US farmers. The upper end of economic returns under $50 per hectare would approach $110 per hectare under high pest infestation conditions, but the lower end of economic returns become negative and approach -$25 (Figure 5). The lower end of the distribution, i.e. the probability that returns are negative, was calculated to be 7.6%. While this is likely to be considered a small level of risk, particularly when the upper end results in returns of $110 per hectare, further considerations for risk would be required with the $75 per hectare technology fee.

DISCUSSION

The results of this study were obtained in replicated small plot trials at two Burkina Faso experiment stations. As such, the test results are subject to small sample errors and biases. Future research is needed in the testing of B II cotton to on-farm experiments to assess the efficacy of the Bt genes on larger plots and under a wider range of conditions. This would include testing B II cotton under heavier pest density conditions than was found during the three years of trials.

The results of the pest damage control model are consistent with findings elsewhere. Qaim (2003) reported that Bt cotton's yield advantage can reach 80% during years of high pest pressure. Site and location effect the benefits of B II cotton, such as the distinct differences between Farkao-Bâ and Fada, reported by Houdebine (2003). The economic benefits of Bollgard II, were found to be significant, and would be even greater if other benefits were factored into the analysis. Bollgard II cotton promotes a cleaner environment through reduced pesticide use and improved human health. Those benefits were not included in our research.

The most critical issue facing West Africa is that world cotton prices are not expected to return to past levels, when world prices ranged between $0.70 and $0.80 per lb (ICAC, 2003). While the West African cotton sector flourished under those pricing conditions, it will need to find ways to reduce production costs and find a competitive stance in an era of decreasing cotton prices. The C4 countries have levied their share of criticism towards US cotton subsidies, but removing subsidies won't be enough to bring prices back to where they were. Sumner (2003) estimated that removing subsidies would raise cotton prices an estimated 12%, while Pan et al. (2006) estimated much lower impacts. Cotton prices in 2007 and 2008 have risen dramatically due to outside market influences, e.g., ethanol and commodity speculation, so the impact of U.S. subsidies is currently minimal (Welch et al., 2008). The longer term expectation is for eventual supply response with improved technology to eventually increase world supply to keep cotton prices between $0.50 and $0.60 per lb (ICAC, 2003).

The B II cotton field trials conducted in Burkina Faso suggest that the West African cotton sector has significant capacity to increase its efficiency and prevent further financial crises. Even if B II cotton was priced at US levels, about $75 per ha, this study found that B II cotton would generate $53 per ha of increased farm income. This would be equivalent to a $0.07 increase in the world cotton price, about the same magnitude of US cotton subsidies (Sumner, 2003). B II cotton appears to be a timely opportunity for the C4 countries to regain some of their competitiveness on world markets. Without access to B II cotton West African cotton producers fall one more step behind cotton producers in the developed world.

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