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The Socio-economic Impacts of GM Cotton in Burkina Faso: Does Farm Structure Affect How Benefits are Distributed?

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This article documents the impact of GM cotton in Burkina Faso on input use and productivity. Six years of farm survey data found that GM cotton used two-thirds less insecticide and produced higher yields than conventional cotton while reducing farm labor allocated to spraying. Estimating a Cobb-Douglas cotton production function found that farm size, insecticide sprays, number of bullocks, and type of cotton significantly explained cotton yield. Farm size was not found to be a deterrent to GM cotton adoption: farms of all sizes benefitted significantly from growing GM cotton. On a relative basis, farms of all sizes benefitted equivalently, though larger farms were found to be more productive and generated larger absolute benefits from GM cotton. Interpreting production function technical coefficients suggest that household labor is higher valued and more efficiently utilized on GM cotton farms compared to conventional cotton.

Key words: Bt cotton, Burkina Faso, efficiency, smallholder.

Introduction

The diffusion of genetically modified (GM) cotton has been rapid in many of the major cotton-producing countries. Initially concentrated in developed countries, e.g., United States and Australia, and more recently in the emerging Asian economies of India and China, global adoption of GM cotton reached 68% (25 out of 37 million ha) in 2014 (International Service for the Acquisition of Agri-Biotech Applications [ISAAA], 2014). The most widely adopted type of GM cotton is Bt cotton. Genetic engineering techniques inserted genes into cotton to encode and promote the production, within the plant, of proteins toxic to certain caterpillar pests (e.g., *Helicoverpa armigera*) of cotton to protect plants from bollworms (Perlak et al., 2001). In Bt cotton, these proteins, Cry1Ac and Cry2Ab, are encoded by genes originating from the common soil bacterium *Bacillus thuringiensis* (Bt). These Cry proteins are both highly effective in killing certain lepidopteran larvae (caterpillars) but do not target other insects, unlike conventional pesticides, many of which kill across a wide spectrum of both targeted and non-targeted (sometimes beneficial) insects[1] (Greenplate et al., 2003; Höfte & Whiteley, 1989; MacIntosh et al., 1990; Sims, 1997). Once ingested, the Cry proteins bind to specific molecular receptors on the lining of the caterpillar's gut, where they create holes and quickly cause death (Höfte & Whiteley, 1989).

Bt cotton has greatly advanced pest management by reducing the number of chemical sprays applied to control bollworms. In most regions of the world, bollworm spraying constitutes the largest share of pesticide applications and are typically the most pernicious to human and environmental health[2] (Hossain et al., 2004; Huesing & English, 2004; Qaim & de Janvry, 2005; Qaim & Zilberman, 2003). Significant impacts of Bt cotton have been consistently reported over the past two decades—improved control of pests, enhanced yield performance, reduced production costs, farming risk and increasing profitability, and secondary environment benefits (Carpenter, 2010; Edge, Benedict, Carroll, & Reding, 2001). In most regions, Bt cotton has been shown to reduce insecticide sprayings by about two-thirds (Vitale & Greenplate, 2012). When combined

1. *Formulations of microbial Bt fermentation products, containing Cry proteins, have been used for more than 60 years as natural insecticides in spraying programs in agriculture and forestry pest control (Aronson, Beckman, & Dunn, 1986). While these Bt formulations can be quite effective under certain conditions, the products have never been widely adopted in crops such as cotton for various reasons. Cry proteins have short half-lives when placed under field conditions due to UV light degradation and other environmental factors. Many types of insect larvae may escape control by these products if spray coverage is not optimal, including wash-off when applied.*
2. *Pesticide applications are still required to control against late-season flying insects, e.g., aphids and jacids, which attack plants once bolls emerge by piercing and sucking the cotton boll. Late-season pests are outside the control spectrum of Bt cotton and are controlled by chemical sprays, which typically use less than half the number of sprays applied in the early season.*

with herbicide-tolerant GM varieties, i.e. "stacked" Bt cotton, additional benefits have been obtained by producers. Environmental externalities and other unintended consequences—concerns voiced loudly by anti-GMO lobbyists—have yet to materialize (Carpenter, 2010; Paarlberg, 2012).

The substantial number of smallholder farms engaged in cotton production throughout the world has brought attention to the benefits of GM cotton in less developed countries (Ali & Abdulai, 2010; Shankar & Thirtle, 2005; Vitale, Boyer, Uaiene, & Sanders, 2007; Vitale & Greenplate, 2012). Large cotton farms in the United States and Australia benefit from labor savings and higher yields, but impacts are likely to accrue differently to smallholder farms, which have lower labor costs and yields, and are more resource and financially constrained than large, commercial farms. Such constraints make it more difficult to apply new technology that sometimes incurs higher production costs and greater risk exposure, including establishing the proper protocols required of GM seed technology (e.g., refugia). Concerns have also been raised that smallholder farmers are particularly vulnerable to monopolistic pricing structures that can be present in Bt seed markets (Basu & Qaim, 2007; Fukuda-Parr, 2007; Lalitha, 2004; Qaim & de Janvry, 2005).

India received international attention when cotton farmers in some regions reported economic losses, and severe hardship on household welfare, when growing Bt cotton (Qayum & Sakkhari, 2005; Sahai & Rahman, 2003). National media purportedly linked several cases of farmer suicides to Bt cotton. Most other studies, however, have tempered those early concerns, and have refuted the media's suicide claims. Qaim, Subramanian, Naik, and Zilberman (2006) concluded that the negative impacts from Bt cotton were explained primarily by weaker agroecological conditions and drought that persisted in the semi-arid Andhra Pradesh region, the source of most of the early concerns. Farmers in India's primary cotton regions, with more favorable production conditions, benefitted significantly from growing Bt cotton. Follow-up surveys conducted in subsequent years confirm that Indian producers have continued to benefit from growing Bt cotton throughout most regions (Crost, Shankar, Bennett, & Morse, 2007; Kathage & Qaim, 2012; Krishna & Qaim, 2012; Sadashivappa & Qaim, 2009; Subramanian & Qaim, 2009, 2010).

The poor initial experiences of smallholder farmers in certain regions of India, e.g., Andhra Pradesh, are more likely an exception rather than a general tendency. The largest share of GM cotton grown in the world is on smallholder farms. India, along with China, account for the two largest areas of Bt cotton in the world (ISAAA, 2015). Numerous studies report smallholders (typically defined as < 5ha) benefitting from higher yields and reduced pesticide costs in India and China, as well as elsewhere, e.g., South Africa, Pakistan, and Burkina Faso (Carpenter, 2010; Huang, Hu, Rozelle, Qiao, & Pray, 2002; Krishna & Qaim, 2007; Morse, Bennett, & Ismael, 2005; Qaim & de Janvry, 2005; Subramanian & Qaim, 2009; Wossink & Denaux, 2006). Although opposition groups have been successful in garnering attention to the plight of smallholder producers growing GM crops, farm size often has an inverse effect on productivity. This relationship became well known to the development literature in the early 1960s when Sen (1962) observed a decline in wheat yields on Indian wheat farms as farm size increased. The paradoxical relationship found by Sen (1962) spawned a legion of follow-up studies and most studies confirm the inverse relationship between farm size and productivity, including with GM crops. Ali and Abdulai (2010) found that Bt cotton adoption in Pakistan increased cotton yield significantly more for small farms compared to the medium and large farms included in their sample. All farm types had reduced pesticide use and obtained higher household income and reduced poverty when growing Bt cotton. In South Africa, Shankar and Thirtle (2005) shows that Bt cotton enabled smallholder farmers to regain lost productivity resulting from the loss efficacy of chemical insecticides due to the development of pest resistance to pyrethroids. The increased productivity helped smallholder farmers to alleviate credit and labor constraints associated with pesticide use.

Burkina Faso has emerged as one of the leading adopters of agricultural biotechnology in sub-Saharan Africa (Vitale & Greenplate, 2012). Genetically modified (GM) cotton, Monsanto's Bollgard© II, was legalized by the government of Burkina Faso in 2007 and was commercially introduced in 2009 (Vitale & Greenplate, 2012). Adoption rates compare well with other countries where GM cotton has been successfully introduced, e.g., the United States, Australia, China, and India. Adoption has trended upward since 2009 except for 2012, when a limited supply of Bt cotton seed temporarily slowed Bt cotton use (Figure 1). By 2014, the adoption of Bt cotton (Bollgard II) had already approached 80%, the level considered by many in the production literature as the long-term upper limit of new technology adoption.[3] Bt cotton has significantly and

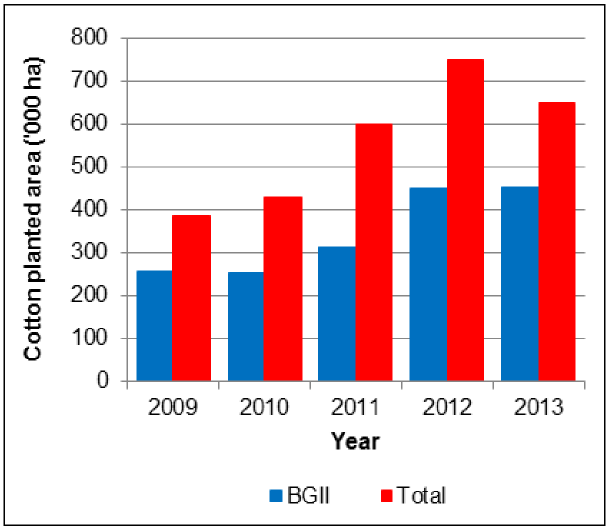

Figure 1. Adoption profile of Bt cotton in Burkina Faso.

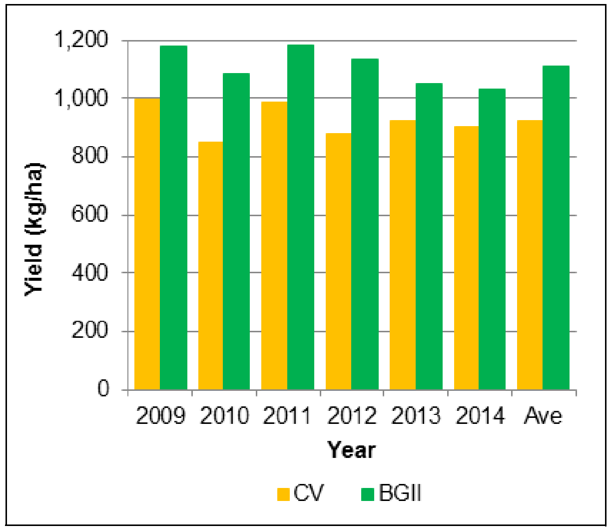

Figure 2. Comparison of Bt versus conventional cotton yields in Burkina Faso.

consistently outperformed conventional cotton in each of the six years of commercial production (Figure 2).

The overwhelming presence of smallholder producers in Burkina Faso provides an opportunity to investigate how Bt cotton benefits smallholder farmers. Burkinabé cotton farm size ranges from 1 to 8 ha, with most producers growing 3 ha or less of cotton (Figure 3). Previous studies from the first three years of commercial use of Bt cotton found that it generated positive impacts on Burkinabé smallholders (Vitale & Greenplate, 2012). Vitale and Greenplate classified farms into four types using the number of bullock pairs owned by the farm to differentiate between manual, small (1 pair), large (2 or more pairs), and mechanized farms. For all three years studied, farm size had no substantial effect on benefits, as producers of all farm sizes benefitted on a relative (percent) basis from growing Bt cotton, including manual producers.

The purpose of this article is to investigate how smallholder farmers have benefitted from Bt cotton in Burkina Faso using a more extensive dataset from six years of Bt cotton outcomes (2009-2014) than previous three-year studies. An econometric model of cotton production, incorporating pest damage, is used to test whether variables related to farm size and farm structure explain Bt cotton benefits. Findings of the study contribute to the development literature by supporting/refuting

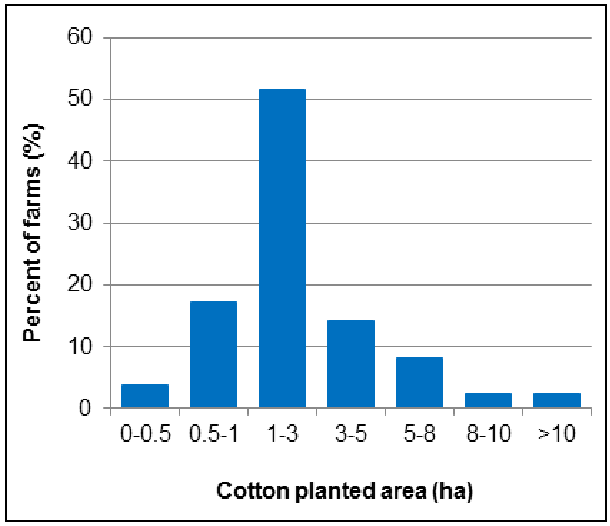

Figure 3. Distribution of farm size in Burkina Faso from surveyed data (2008-2014).

concerns voiced by some skeptics that GM crops are inherently biased against smallholder farms. The following two sections describe cotton production in Burkina Faso and the foundations of the econometric model. Results from producer surveys and the econometric model are then presented, discussed, and placed in context with similar studies. The article ends with a section including policy implications, suggestions for future research, and concluding remarks.

3. *Rogers theory explains adoption as approaching a long-run asymptote at 80% adoption along an S-shaped logistic curve. Refugia concerns with GM would reduce the asymptote below the 80% threshold.*

Background: Farm Structure and Benefits of Bt Cotton

The effect of farm size and farm structure on rural household welfare has been widely studied in the development literature, across a range of countries and crops. Studies have often been conducted to refute/support agrarian policy that has tended to favor large, commercial farms over smallholders under a working hypothesis that larger farms are more efficient than smaller ones (Adesina & Djato, 1996; Alvarez & Arias, 2003). While the proposition that larger farms are more efficient is likely accepted at face value by the policy-making community and general public, according to the results of many empirical studies in the development literature, however, there is only mixed evidence that increasing farm size leads to greater farm efficiency. In a seminal paper, Sen (1962) found an inverse relationship between farm size and productivity that sparked many follow-up studies, many of which confirmed Sen's results. Among wheat producers in Asia, farm size has had both a positive and negative effect on farm efficiency (Bagi, 1982; Khan & Maki, 1979; Lau & Yotopoulos, 1971, 1973; Sen, 1962). Other studies have found no relationship between farm size and efficiency, including rice farmers in Cote d'Voire (Adesina & Djato, 1996; Garcia, Sonka, & Yoo, 1982). Studies of farm production systems have often found a positive relationship between farm size and efficiency.

Alternative explanations and working theories have been posited in the development literature to support the empirical findings. Barrett (1996) summarized prior studies in the development literature and argued that smaller farms have a lower opportunity cost of labor than larger, commercial farms. This results in smaller farms allocating labor with a lower marginal value product (MVP) of labor than larger farms and, hence, a more intensive use of labor on smaller farms. A second common explanation for the inverse relationship between farm size and productivity is market failure, typically occurring in labor and land markets (Bardhan, 1973; Carter & Kalfayan, 1989; Eswaran & Kotwal, 1986; Feder, 1985; Sen, 1981; Taslim, 1989). In labor markets, attracting and maintaining hired labor as required on commercial farms (i.e., principal agent problems) results in higher labor costs and larger MVP of labor compared to smaller farms that supply their own labor from the household proper (Frisvold, 1994). Assunçao and Ghatak (2003) suggested that failures in credit markets can also explain the inverse farm size/productivity relationship. Decreasing returns to scale technology and land quality have also been used to explain how small farms can be more productive than larger ones (Barrett, 1996; Benjamin, 1995; Carter, 1984; Sen, 1975).

Bt cotton is a technology that impacts farms in various ways by providing the potential for higher yields, enhanced fiber quality, reduced labor costs, improved health, and convenience, i.e. less anxiety over managing pest problems. While the control mechanism and corresponding efficacy of Bt cotton is scale-neutral, the actual impacts realized by producers will depend on the type of farming system employed by producers. Bt cotton has benefitted both large farms in developed countries as well as smallholder farmers in developing countries, with some regions of India (e.g., Andhra Pradesh) being an important exception (see above). Even in empirical studies where producers have—on average—benefitted, larger farms were sometimes found to have greater impacts. Hence, empirical evidence suggests that although Bt cotton is a scale-neutral technology, due to the nature of its impacts on production systems and costs, overall economic outcomes can be scale dependent. In the methods section given below, an econometric model is constructed to test whether farm size and related farm structure variables have a significant effect on Bt cotton performance in Burkina Faso. Included in the econometric model is a damage-control function that explicitly considers the way in which pest damage determines cotton yield.

Cotton Production in Burkina Faso

In the grassy savannas of West Africa that span from Western Mali to Chad, cotton is the economic catalyst in rural communities. The cotton sector accounts for the majority of farm income, rural employment, and its "white gold" export earnings dominate foreign exchange coffers in countries such as Burkina Faso, Mali, and Chad (Vognan, Ouédraogo, & Ouédraogo, 2002). Cotton has been a particularly important source of economic growth in rural areas where economies are built around the crop (Bingen, 1998). In Burkina Faso, more than 2.2 million Burkinabé citizens derive a majority of their income (60%) from producing, ginning, or transporting cotton (Catholic Relief, Development and Social Service Organisation [CARITAS], 2004; Elbehri & MacDonald, 2004; Vognan et al., 2002). Public services such as schools, roads, public heath, and a variety of agricultural extension services have traditionally been provided by cotton revenues. The cumulative effects of these investments have been responsible for alleviating rural poverty in many of the areas where cotton has been successfully introduced (Bassett, 2001).

Pest Problems in Burkina Faso and West Africa

In Burkina Faso, as elsewhere in Sub-Saharan Africa, pests are a large problem since favorable climactic conditions allow multiple pest generations per year, fostering heavier pest densities (Abate, van Huis, & Ampofo, 2000). The larva of *Helicoverpa armigera* (cotton bollworm) is the main cotton pest in Burkina Faso and throughout West Africa (Vaissayre & Cauquil, 2000). On unprotected fields, Burkina Faso researchers claim that insect pests can damage up to 90% of the cotton crop (Traoré, Héma, & Ilboudo, 1998). Conventional pest control measures have been losing their effectiveness since pest populations have developed resistance to pyrethroid insecticides, the primary agents used in Burkina Faso and throughout most of West Africa to control *H. armigera* (Goldberger, Merrill, & Hurley, 2005; Martin, Chandre, & Vaissayre, 2002; Martin et al., 2005; Programme Coton, 1999). In Burkina Faso, cotton yield losses often surpass 30% on fields treated with recommended insecticide applications (Goze, Nibouche, & Deguine, 2003; Traoré, Sanfo, Traoré, & Koulibaly, 2006; Vaissayre & Cauquil, 2000). As chemical agents have grown increasingly ineffective, cotton farmers have intensified the use of insecticides, especially where cotton production has expanded into more marginal agricultural lands along the frontier where pest populations are often greatest (McMillian, Sanders, Koenig, Akwabi-Ameyaw, & Painter, 1998). In addition to becoming increasingly ineffective and costly, conventional pest control has also become more hazardous to human and animal health due to increased use of more broadly toxic endosulfans[4] (Ajayi & Waibel, 2003; Drafor, 2003; Glin et al., 2006; Maumbe & Swinton, 2003; Vognan et al., 2002).

Commercializing Bt Cotton in Burkina Faso

Discontent and frustration with conventional pest-control methods prompted Burkina Faso's initial interest in Bt cotton. Stakeholders in the Burkina Faso cotton sector began to explore new pest-control options to increase productivity, improve the competitiveness of Burkina Faso cotton growers in international markets, and reduce the environmental and health consequences of chemical sprays. Following several years of field trials and the establishment of biosafety protocols and other business and legal frameworks, in June of 2008, the National Biosafety Agency authorized the commercial planting of Bollgard II (BGII) in Burkina Faso. This was a significant accomplishment for Burkina Faso, marking the first commercial use of Bt cotton in the country, and only the third commercial release of a bioengineered crop in Africa. In the 2008 cotton-growing season, Sofitex, together with its contract seed producers, planted 15,000 ha of two local varieties containing BGII. The modest area of 15,000 ha was due to the limited supply of BGII seed available at that time and represented a seed multiplication year for the anticipated broad commercial deployment that occurred in 2009.

Methods and Materials

The Bt cotton literature has tested yield and economic performance of Bt cotton using a variety of statistical and econometric techniques, including ANOVA, discrete choice, propensity scoring, and production function analysis (Hossain et al., 2004; Huesing & English, 2004; Qaim & de Janvry, 2005; Qaim & Zilberman, 2003). In the previous Burkina Faso studies, ANOVA models were constructed using data from 2009 through 2011 (Vitale & Greenplate, 2012). The ANOVA model in Vitale and Greenplate—used to test Bt versus conventional cotton yield performance—was constructed using the following equation.

$$Cotton\ Yield_i = \alpha + \beta_1\, year_t + \beta_2\, zone_i + \gamma \mathbf{X}_i\ , \qquad (1)$$

where *year* denotes the production year, *zone* indicates one of the three cotton-producing regions in Burkina Faso (Sofitex, Socoma, or Faso Cotton), and $\mathbf{X}_i$ is a vector of input variables used in cotton production including labor hours, operating size, insecticide use, fertilizer, and seeding rate (density).

Cotton Production Function

The ANOVA model was sufficient in the previous studies to conduct means separation and hypothesis testing, but it is cumbersome and at times limited in its ability to address more detailed questions such as how farm size and other explanatory variables impact productivity. In particular, the effects of farm scale on crop productivity requires more elaborate mathematical functional forms to accurately portray the extent to which production

4. *In Benin, numerous cases have been reported in recent years, including 105 poisoning cases in the 2007/08 cotton-growing season (Badarou & Coppieters, 2009). Kodjo (2007) reported that endosulfan poisoning cases typically reach 500 per annum.*

conforms to decreasing, constant, or increasing returns to scale. Hence, a cotton production function was constructed in this study to investigate whether the type of cotton (Bt or conventional), farm size, and production input variables explain yield. In a production function, cotton yield is specified as a function of a vector of inputs. The production function is often specified with a Cobb-Douglas functional form due to its relative simplicity and usefulness of its output, i.e. Cobb-Douglas regression coefficients correspond directly to input elasticities. These elasticities provide useful information on technology scale effects and productivity measures (Crost et al., 2007; Shankar & Thirtle, 2005; Theriault & Serra, 2014).

When applied in settings where crop damage has a significant effect on yield outcomes, Lichtenberg and Zilberman (1986) argued that a conventional production function is inconsistent when estimating insecticide use, making implications on the optimal use of insecticide inefficient and perhaps erroneous. They suggested that a damage-control component be included in the production function whenever crop damage is anticipated to have a significant explanatory power. The damage-control component is a function specifying those inputs that protect the plant from pest damage but do not have a direct effect on increasing yield as discussed in Lichtenberg and Zilberman (1986). The cotton production function with damage-control component is defined as follows:

$$Y = f(\mathbf{x})G(z), \tag{2}$$

where Y is cotton yield and $\mathbf{x}$ is a vector of ordinary (non-damage related) inputs, z is damage-control input, $f(\mathbf{x})$ is Cobb-Douglas (CD) production function, and $G(z)$ is the pest damage-control function. The damage function $G(z)$ is defined on the closed interval from zero to one, [0,1]. When the damage-control input z increases, the damage function $G(z)$ approaches 1, which does not affect cotton yield, i.e., there is no crop damage included in the production function. Conversely, when the damage control z decreases, as $G(z)$ approaches 0, cotton yield is reduced, i.e., the effect of pest damage is present in the production function. Hence, estimated values of z are interpreted as control efficacy and management techniques and inputs that result in larger z values are more effective in mitigating yield loss.

There are several functional forms that researchers have used to model $G(z)$—Weibull, exponential, and logistic. In practice, the production literature most often uses the Logistic function since it does not require specifying that the marginal production of $G(z)$ is greater than zero, i.e. there is no requirement that $G(z) > 0$ (Crost et al., 2007; Shankar & Thirtle, 2005). Following the previous research, and further supported by the Logistic function fitting the data better than the other forms, this article uses the Logistic functional form. Following other modeling approaches, this Logistic function includes dummy variables to distinguish and enable hypothesis testing between Bt and conventional cotton dummy variables (Huang et al., 2002; Qaim, 2003; Qaim & Zilberman, 2003; Shankar & Thirtle, 2005). The Logistic damage-control function is defined as

$$G(\mathbf{Z}) = 1 / [1 + \exp(\alpha - \beta\mathbf{Z})], \tag{3}$$

where $\mathbf{Z}$ is a vector of damage control variables, including the number of insecticide sprays and a dummy variable for the type of cotton grown.

The general production function, with the CD and logistic damage control components, is specified as

$$Y_{it} = e^{\alpha_1 v_i e_{it}} \prod_{k=1}^{K} X_{it} BT_{it} (1 + \exp(\alpha_2 - Z_{it} - BT_{it}))^{-1} \tag{4}$$

where Y_{it} is the cotton yield per hectare of farm i in year t; $\mathbf{X}_{it}$ is a vector of control variable including year and zone and normal inputs including active household labor, number of bullocks, fertilizer, field size; and $\mathbf{Z}_{it}$ is a vector of damage-control inputs, including number of sprays; BT_{it} is a dummy variable that takes one if Bt and zero if conventional that functions increasing yield as a normal input and reducing the insect damage loss as a damage control input; v_i is a farm-specific random error including unobservable efficiencies or unobserved technological difference in farm i with a normal distribution ~(0, σ_v^2); and e_{it} is the random error of the model with a normal distribution ~(0, σ_e^2).

Taking logs on both sides of Equation 4, the following equation is obtained:

$$Y_{it} = \gamma_0 + \Sigma\beta X_{it} + \alpha BT_{it} + (v_i + e_{it}) \\ - (1 + \exp(\gamma_1 - \delta_1 Z_{it} - \delta_2 BT_{it}). \tag{5}$$

To estimate Equation 5 with ordinary least squares, the estimation equation is given by

$$Y_{it} = \gamma_0 + \Sigma\beta X_{it} + \alpha BT_{it} + u_{it} \\ - (1 + \exp(\gamma_1 - \delta_1 Z_{it} - \delta_2 BT_{it}). \tag{6}$$

Equation 6 can contain two estimation problems if estimated with the OLS method. One problem is self-selection bias and the other is endogeneity.

Estimating Issues for Production Function with Damage-control Function

Self-selection Bias Issue. In the random effects error estimation, the error term is ($v_i + e_{it}$), as given by Equation 4. The error term is reduced to u_{it} in Equation 5 due to omitting the variable v_i. When variables are omitted, there is the potential for self-selection bias. The variable v_i is not observable because the Bt cotton farmers—who likely have advanced skills, superior information on Bt cotton performances, and greater productivity—cannot be directly observed from the data. If a farm's unique characteristics and individual information, e.g., age, education, sex, is included in the data, the potential for self-selection bias is reduced. Otherwise, unobserved information such as farm efficiency or superior knowledge of Bt cotton will be correlated with the residuals in the OLS estimates in Equation 5.

The practical implication of this correlation is potentially serious since the accuracy of hypothesis tests on estimated parameters are poor, making it potentially difficult to identify significance. To remove this effect, unobserved farms' individual heterogeneity should be separated from error terms and the Bt cotton observations. Greene (2000) stated that if the individual effects are strictly uncorrelated with the model regressors, it might be appropriate to model the individual specific constant terms as being randomly distributed. In the crop production literature, at least three approaches have been used to remedy (as best as possible) the potential for self-selection bias. Shankar and Thirtle (2005) used the instrumental variable approach to correct for self-selection bias. Crost et al. (2007) used a fixed-effect model with seasonal data to reduce self-selection bias. Ali and Abdulai (2009) used a propensity score-mating approach to find out different characteristics between the type of cotton grown by Pakistani producers so at least some aspects of self-selection could be controlled. The other alternative in panel data setting is a fixed-effect model which estimates each fixed parameter for each farm observation, causing reducing degrees of freedom. This article used a random-effects model, which separated unobserved individual heterogeneity from the error term by estimating one random error parameter with the panel data. The random-effect model (Equation 5) is chosen to remedy the unbalanced design of the panel data and its relatively short time period.

Endogeneity Problem for Insecticide Use. The endogeneity problem occurs when inputs are not independent from yields and are correlated to one another. For example, as farmers observe pests in fields and anticipate yield loss, they are expected to respond to the information by applying pesticides. This dynamic between field observations, insecticide applications, and yield outcomes results in a simultaneous relationship between cotton yield and insecticide use. This creates an endogeneity problem that violates the OLS assumption. Specifically, in this model it is likely that the independent variables are correlated with the error term due to missing variables such as farm efficiency or the asymmetric information of Bt cotton performance among producers.

Farmers in Burkina Faso typically follow a regimented pest-management schedule, applying pesticide sprays at pre-determined times of the year when pest infestations are expected to occur based on prior experience. This is a preventative approach that is encouraged by the extension services of the national cotton companies, and field visits confirm that producers follow this practice with only minimal deviation from the prescribed spraying regiment. This is supported by Shankar and Thirtle (2005), who found there was no significant endogeneity problem in the South African smallholder case. As this study does not have data—or even any reason to believe—that producers made spray decisions based on scouting fields in current time, the assumption that farmers apply insecticides at predetermined times of the year independent of pest pressure is maintained. Thus, the cotton production function's assumption that endogeneity did not play any bias in our production function seems justified for this study.

Farm Survey Data

To determine the overall effect of output and all inputs, a CD production function was estimated using six years (2009-2014) of household survey data. Data was collected from 3,071 farms, which included roughly an equal number of observations from conventional (1,402) and Bt (1,669) cotton farms in each of the three zones: Faso Coton, Socoma, and Sofitex (Table 1). The number of surveyed farms increased over the six-year study period, from 135 Bt farms in 2009 to 720 farms in 2014, with an equal number of Bt and conventional farms (Table 2). Many farms produced both conventional and Bt cotton to satisfy refugia requirements, while others

Table 1. Summary statistics of the explanatory variables used in the Cobb-Douglas production function.

Explanatory variable	Total	Conventional cotton	Bt cotton
Cotton yield (kg/ha)	1,015.3 (343.5)	923.5 (329.2)	1,091.1 (336.7)
Year	2009-2014	2009-2014	2009-2014
Zone	Faso Cotton, Sofitex, Socoma	Faso Cotton, Sofitex, Socoma	Faso Cotton, Sofitex, Socoma
Type of cotton	0.54 (0.49)	0	1
Farm size (ha/farm)	2.87 (2.80)	2.17 (1.79)	3.46 (3.31)
Cow (number/farm)	2.74 (1.73)	2.65 (1.74)	2.81 (1.72)
Active family labor (person/farm)	6.68 (4.45)	5.64 (3.14)	7.21 (4.91)
Number of sprays	2.85 (1.96)	4.2 (2.03)	1.66 (0.76)
Number of observations	2,578	1,060	1,517

Note: Standard deviation of the mean is in parentheses.

Table 2. Summary statistics of the explanatory variables over times.

Explanatory variable	2009		2010		2011		2012		2013		2014	
Type of cotton	**Bt**	**CV***	**Bt**	**CV**	**Bt**	**CV**	**Bt**	**CV**	**Bt**	**CV**	**Bt**	**CV**
Cotton yield (kg/ha)	1,106	-	1,083	991	1,184	988	1,136	877	1,052	920	1,033	901
Farm size (ha/farm)	3.51	-	3.38	1.60	3.41	2.68	3.71	2.27	3.39	1.94	3.34	1.96
Cow (number/farm)	3.42	-	2.90	2.95	2.68	2.50	2.83	2.74	2.75	2.67	2.71	2.62
Active family labor (person/farm)	7.28	-	-	-	7.02	5.89	7.95	5.94	5.92	4.97	7.92	7.61
Number of sprays	1.16	-	1.77	5.40	1.79	5.24	1.70	5.22	1.76	5.08	1.55	4.85
Number of observations	117	-	205	45	250	279	360	360	359	358	360	360

**CV indicates conventional farms*

grew Bt only and used communal plots of conventional cotton for refugia. The sample was selected randomly within each of the farm categories—manual, small, medium, and large (Vitale, Vognan, Ouattarra, & Traoré, 2010). Summary statistics for the explanatory variables used in the CD production function are listed in Table 1. Bt farms had 18% higher yields on average than conventional farms over the six years (Table 1). Bt cotton farms were 60% larger in field size than conventional farms and also had a larger household supply of agricultural labor and working animals than conventional farms (Table 1). Conventional farms sprayed more insecticide than Bt farms, with Bt cotton farms typically applying two-thirds less insecticide (Table 2).

A CD production function is presented in the next section that allows for an investigation of how variables such as cotton type, insecticide spraying, and farm structure explain yields. However, the CD function approach has been criticized for over-estimating damage-control inputs such as pesticides and varieties of cotton as mentioned earlier in the methods section. So, a damage-control function was also estimated to provide a potential remedy for econometric issues.

Econometric Model Results and Analysis

A pair of functional forms for the CD cotton production function were tested and compared: OLS vs. the random effect model (Table 3). Breusch and Pagan (1980) developed a statistical procedure which tests whether including the random effect variance structure provides a more consistent estimation than an OLS model with a standard variance structure of iid (independent identically distributed) error terms. Specifically, Breusch and Pagan (1980) tested the hypothesis that the variance term from the random-effect model is different from zero, i.e., σ_V^2

Table 3. Cobb-Douglas production function by type of cotton and without damage control.

Explanatory variable	CD with OLS	CD with random effect	CD with conventional	CD with Bt
Constant	6.61*** (0.05)	6.78*** (0.02)	6.46*** (0.02)	6.68*** (0.05)
Year				
2009	0.10** (0.04)	0.12*** (0.02)	0.38*** (0.02)	0.13*** (0.04)
2011	0.06** (0.03)	0.06*** (0.01)	-	0.03 (0.03)
2012	-0.01 (0.02)	0.02 (0.01)	-0.09*** (0.01)	0.06** (0.03)
2013	-0.01 (0.02)	-0.03** (0.01)	0.03*** (0.01)	-0.01 (0.02)
2014	0	0	0	0
Zone				
Faso cotton	-0.18*** (0.02)	-0.21*** (0.01)	-0.28*** (0.01)	-0.16*** (0.02)
Socoma	-0.01 (0.03)	-0.02 (0.01)	0.02 (0.01)	0.04 (0.03)
Sofitex	0	0	0	0
Type of cotton				
Bt	0.20*** (0.03)	0.19*** (0.01)	-	-
Conventional	0	0		
Size	0.04*** (0.01)	0.04*** (0.004)	-0.03*** (0.01)	0.038*** (0.01)
Cow	0.08*** (0.02)	0.08*** (0.007)	0.11*** (0.01)	0.10*** (0.02)
Labor	0.03 (0.02)	-0.01 (0.008)	-0.02*** (0.006)	0.05** (0.02)
# of sprays	0.06*** (0.02)	0.07*** (0.007)	0.19*** (0.01)	0.13*** (0.03)
Model statistics				
Var. of residual	0.09***	0.001*** (0.00)	1.01** (0.11)	0.02 (10.0)
Var. of rand. effect	-	0.08*** (0.001)	6.56*** (0.11)	0.06 (10.0)
Loglikelihood value	-1,375.4	-1,184.2	-641.8	-536.2
Number of obs.	1,572	1,572	598	974

≠ 0. The variance of the random farm effect was estimated at 0.08 and was significant ($P < 0.01$), rejecting the hypothesis that the variance of farm random effect is zero (Table 3). This statistic indicates that the more elaborate variance structure of the random effect model better conforms to the data than the OLS model. The loglikelihood test, which compares model fit of the restricted model (OLS) vs. unrestricted model (random-effect model), confirmed that the random-effect model has a better fit than the OLS model (Table 2). Hence, the analysis and discussion of model results is based on the random-effects error models.

The CD cotton production functions were also estimated separately, with and without the cotton-type variable, but including either all of the Bt or conventional cotton observations (Table 3). In the CD production function with the random-effect model and both Bt and conventional cotton observations, the cotton-type variable was significant ($P < 0.01$), indicating that Bt cotton provided significantly higher yields than conventional cotton (Table 2). Interpreting the estimated coefficient on the cotton-type variable implies that if a farm were to shift one hectare of cotton from conventional to Bt, cotton yield would increase by 19% (Table 3). This result provides an initial ground-truthing of the production function since the 19% yield increase is consistent with the annual yield increases based on descriptive statistics and ANOVA models, where yield increases of 22% were found during the first three years of commercial Bt cotton use in Burkina Faso (Vitale & Greenplate, 2012).

Farm size (cotton acreage) had a significant effect ($P< 0.01$) on farm productivity for both Bt and conventional cotton (Table 3). For the CD model with random effect error and both Bt and conventional cotton, the farm size parameter was estimated at 0.04 (Table 3). The farm size parameter is interpreted as a 1% increase in cotton acreage would, on average, increase cotton yield by 4% (Table 3). The productivity of farm operating size is, however, significantly different between Bt and conventional cotton (Table 3). The estimated parameter of operating size is negative for conventional cotton, -0.03, but positive for Bt cotton, 0.038 (Table 3). The model results imply that conventional cotton farms are less efficient in their land use when compared to Bt cotton farms, who use their land more efficiently according to the CD model estimates (Table 3). The CD model findings on farm size are consistent with Shankar and Thirtle (2005) and Theriault and Serra (2014); results from these field studies in South and West Africa found that farm size had a positive effect on Bt cotton productivity. Ali and Abdulai (2010) also found a significant difference of land productivity between Bt and conventional cotton in Pakistan. Results from this study and previous ones indicate that Bt cotton increases land productivity compared to conventional cotton, which (all else equal) provides a positive impact on the environment by reducing pressure on agricultural land.

Farm equipment (e.g., animal traction) had a significant effect (P < 0.01) on farm productivity for both Bt and conventional cotton (Table 3). For the CD model with random effect, the Bullock variable was estimated at 0.08 in the complete model (with Bt and conventional cotton), 0.11 for conventional only model, and 0.10 for the Bt-cotton-only model (Table 3). The estimated parameter is interpreted as a 1% increase in bullock holdings would correspond to an 8% increase in cotton yield, indicating the availability of additional bullocks is effective in increasing cotton yield.

Active labor was not significant in the model that pooled Bt and conventional cotton observations, but had significant and mixed effects in the CD models that estimated Bt and conventional cotton separately (Table 3). The Active Labor variable was estimated at -0.01 (P > 0.05) in the complete CD model (with Bt and conventional cotton), -0.02 (P < 0.01) for conventional-cotton-only model, and 0.05 (P < 0.01) for the Bt-cotton-only model (Table 3). For conventional cotton, the Active Labor parameter is interpreted as a 1% increase in labor would correspond to a 2% reduction in yield, whereas for Bt cotton a 1% increase in labor would increase yield by 5%. The negative relationship between labor and farm size found for conventional farms is more consistent with previous findings than the Bt cotton findings. According to the development literature, the negative relationship is explained by an excess in household labor and the general low productivity of conventional cotton. Additional labor placed on conventional cotton fields is not able to contribute to any meaningful increased productivity. In this study, productivity actually declines according to the CD model results (Table 3). Crost et al. (2007) and Shankar and Thirtle (2005) also found that labor was overused on family farms in India and South Africa.

The positive effect of active labor on productivity for Bt cotton is an important finding and suggests that Bt cotton substantially increases demand for labor. So, unlike conventional cotton that attracts labor like traditional smallholder farming, Bt cotton is able to absorb increased farm labor like larger, commercial farms. With greater pest protection, Bt cotton farms are able to increase productivity with additional labor, perhaps through more intensive weeding, enhanced secondary pest protection, and other farm management practices.

The two control variables—*year* and *zone*—are both significant (P < 0.05) in the random-effects model (Table 3). Year is a control variable that captures inter-year differences in weather, pest pressure, etc. Farms in 2009 and 2011 obtained significantly higher yields than 2014, while yields in 2012 and 2013 were similar to 2014 (Figure 2). Although cotton yields varied across years, none of the years (2009-2014) experienced abnormal weather patterns (e.g., drought) or pest pressure.[5] Zone is a control variable that captures variability in pest density, agro-ecological conditions, and weather that persists across the cotton-producing regions. Socoma and Sofitex zones had higher cotton yields, averaged across cotton type and year, than Faso Cotton, by an average of about 21% according to the model (Table 3).

Insecticide use had a significant effect (P < 0.01) on cotton yield (Table 3). The estimates ranged from 0.07 in the CD model, with both Bt and conventional cotton to 0.19 in the CD model with only conventional cotton (Table 3). For Bt cotton, insecticide use was estimated at 0.13, which is interpreted as a unit increase in the number of sprays would increase cotton yield by a corresponding amount of 13%. The significance of the CD estimates for insecticide use is consistent with earlier findings based on the first three years of Bt cotton production in Burkina Faso. Vitale and Greenplate (2012) reported—using an ANOVA model—that cotton producers who didn't follow the prescribed regiment of two late-season insecticide sprays had significantly lower cotton yields (18%) compared to producers who followed the regiment. The greater productivity of spraying conventional cotton, estimated at 0.19 versus 0.13 for Bt cotton, is likely explained by the substantial control efficacy of Bt cotton's cry proteins that control early season pests (e.g., bollworms) without spraying and is not captured in the insecticide spray estimate. Hence, the control efficacy of Bt cotton versus conventional cotton is more accurately assessed in the CD model that includes both Bt and conventional cotton observations. Insecticide sprays were estimated at 0.07, but in this model with both cotton types it reflects the average effectiveness of insecticide sprays for both Bt and conventional cotton. The more appropriate variable to use is the dummy variable for cotton type, which measures the productivity differences between Bt and conventional cotton for factors that are not included in the other variables. This includes the effect of Bt cotton's cry proteins, which control pests without insecticide sprays.

5. *The significance of the year variable leaves open the possibility that parameters could vary significantly across years as well. While interaction terms could be used to test for this type of relationship, the resulting model was considered too complicated.*

The dummy variable was estimated at 0.19, a large component of which is expected to be from improved pest protection, although its effect is confounded with other latent factors such differences in soils, management practices, germplasm, etc., between Bt and conventional cotton (Table 3).

This positive effect of number of sprays was further examined with a CD production function that included a damage-control component (see the Methods and Materials section above). This damage-control approach more accurately reflects productivity measures of production inputs since damage-control inputs (e.g., sprays and cry proteins) are estimated in a separate component of the production function that can only mitigate damage (Table 4). The coefficients of most inputs are similar to those coefficients estimated from the more traditional CD, i.e., without damage control (Table 3). Estimates from the CD models with the damage-control function are in general slightly higher than those in the corresponding models without damage control, and there was little change in the significance of variables. In the damage-control function focusing on the size, the positive effect of size is not different from the random-effect model (Table 3), but the size effect in the conventional model (Column 2) is positive and has a greater effect, 0.04, than Bt model, 0.02 (Column 3). This confirms that small farms used land more intensively than large farms. Hence, this comparison highlights the robustness of the estimation procedures across fairly different functional forms.

The damage-control function provides meaningful insight into the extent of crop loss pest damage (Table 4). In the damage-control function with both Bt and conventional cotton observations, the negative coefficient of the constant term in the damage-control function (-2.29) implies that there is only a modest quantity of damage resulting from insect attacks on uncontrolled fields. The damage is visually evident in Figure 4, which reveals that on uncontrolled fields, Bt and conventional cotton had 4% and 9% losses to pests (Figure 4). The CD production function model appears to be understating pest pressure since most reports from field crop researchers place losses on unprotected fields at higher levels, more likely in the range of 25-35%. The low level of pest damage estimated by the CD production model is more noteworthy for conventional cotton since Bt cotton fields are never actually unprotected. The cry proteins in Bt cotton are always present in the plant and provide pest control even without any sprays. Hence, estimating a 4% yield loss on unsprayed Bt cotton fields is much closer to expectations than the loss on conventional fields.

Table 4. The Cobb-Douglas estimated production function with damage control function.

Explanatory variable	CD with logistic damage function	Conventional cotton	Bt cotton
Constant	6.82*** (0.03)	6.94*** (0.03)	6.90*** (0.08)
Year			
2009	0.12*** (0.02)	-	0.15*** (0.01)
2011	0.05*** (0.02)	0.15*** (0.02)	0.08*** (0.01)
2012	-0.02** (0.01)	-0.26*** (0.01)	0.13*** (0.01)
2013	-0.005 (0.01)	-0.09*** (0.01)	0.03*** (0.01)
2014	0	0	0
Zone			
Faso cotton	-0.22*** (0.01)	-0.21*** (0.01)	-0.16*** (0.01)
Socoma	-0.05*** (0.01)	-0.03 (0.02)	0.07*** (0.01)
Sofitex	0	0	0
Type of cotton			
Bt	0.22*** (0.03)	-	-
Conventional	0		
Size (ha/farm)	0.03*** (0.004)	0.04*** (0.005)	0.02*** (0.005)
Cow (number/ha)	0.08*** (0.007)	0.08*** (0.008)	0.10*** (0.01)
Labor (number/farm)	-0.02 (0.008)	-0.01 (0.008)	0.07*** (0.008)
Damage abatement function			
Constant	-2.29* (0.48)	-0.89*** (0.15)	-1.05*** (0.30)
Type of cotton	-0.36 (0.41)	-	-
# of insecticide sprays	0.92 (0.50)	0.99*** (0.17)	0.72*** (0.25)
Model statistics			
Variance of residual	14.56*** (1.19)	11.53*** (1.04)	13.65*** (1.30)
Variance of random farm effect	7.87*** (0.14)	8.34*** (0.18)	7.70*** (0.14)
Loglikelihood value	-1,184	-508.8	-511.0
# of observations	1,572	598	974

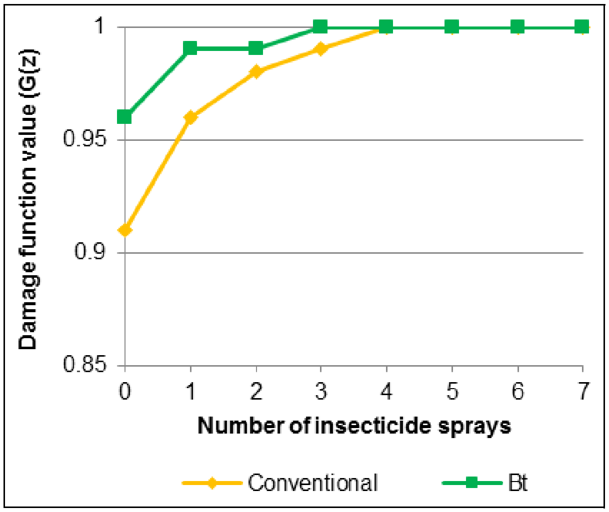

Figure 4. Pest damage control component of the Cobb-Douglas production function estimated using both Bt and conventional cotton observations.

The crop damage model can also be used to estimate the control efficacy of each cotton type by calculating $G(z)$ using the average number of sprays applied. Based on the average number of sprays, 2.85 (late season) sprays for Bt cotton and 4.2 sprays (early and late season sprays) for conventional cotton, the CD production model shows that $G(z) \approx 1$ for both Bt and conventional cotton, indicating they have effectively controlled pests, i.e. no crop damage. This is likely a consequence of the pest-damage model estimating only a small quantity of crop damage on unsprayed fields, which is eliminated once the pest-damage function includes the effect of sprays.

The other two variables—the cotton type dummy variable and the number of sprays—were not significant ($P > 0.10$) in the model with both Bt and conventional cotton, but in the Bt and cotton models the number of sprays variable was significant (Table 4). The lack of significance of the dummy variable in the crop-damage function is contrary to prior expectations since Bt cotton was anticipated to provide better crop protection than conventional cotton. This is also likely explained by the low level of pest pressure the model estimates for unsprayed fields, which substantially understated the pest protection that insecticides would need to provide on conventional cotton to provide equivalent performance to Bt cotton. Shankar and Thirtle (2005) also found Bt cotton had a highly significant effect on mitigating insect damage. Qaim (2003) found Bt cotton had only a weak statistical significance in the damage-control function.

Implications on Economic Returns

Bt cotton increases farmers' income through increasing yield and reducing insecticide and labor costs. Vitale and Greenplate (2012) used partial budgeting to show that, on average, the additional cost of producing a hectare Bt cotton—$60 in seed cost—is offset by lower pesticide costs ($58) and labor costs ($4). The economic benefit of growing Bt cotton is thus the additional revenue generated from the yield advantage of Bt cotton relative to conventional cotton. Assuming the change in insecticide and seed costs cancels one another and ignoring secondary benefits and costs, the economic benefit to producers is given by cotton price × Bt cotton yield advantage. Since economic benefits are subject to the cotton price, an external factor not determined by Bt cotton performance, the yield advantage is a truer indicator of the benefit. This is particularly true for cotton, which has experienced tremendous price fluctuations over the past decade, including frequent world price collapses.

Conclusion

A Cobb-Douglas production function was estimated using data from six years of surveys (roughly 760 cotton farms) shows that Bt cotton significantly increased cotton yield and reduced insecticide use by approximately two-thirds. Additional benefits, often difficult to quantify, include lower labor costs, improved human and environmental health, and convenience. The model results suggest that farm structure plays an important role in determining productivity. According to the CD estimated production function, the Burkina Faso, having more animal traction (bullocks), operating farm size, and type of cotton seed has a significant effect on cotton yield. Findings from this article suggest that Burkina Faso smallholder farmers have benefitted on a commensurate level compared to their larger-scale counterparts in developed countries.

No evidence was found that farm size, however defined, had a negative effect on Bt cotton productivity or profitability. Rather, according to the CD model results, there was a negative relationship between farm size and productivity, i.e., smaller farms tended to have higher yields than larger ones. This result has been found quite often in previous research and should be highlighted in the GMO debate, where critics often decry GM crops as biased against smallholder farms. The effect of farm size and farm structure appears to be greatly reduced by the presence of the national cotton companies that provide input and output markets for

Burkinabé cotton producers. Their presence alleviates credit constraints and lowers input costs through economies of scale and provides extension services. One of the distinguishing features of the Burkina Faso cotton industry is the vertical integration in the input and output supply chains. While international donors have pushed for liberalization and the shift from parastatal to private ownership to improve efficiency, the vertical control of the Burkina Faso cotton industry by the cotton companies appears to make it better suited to introduce Bt cotton than a privately owned sector.

Burkina Faso is taking shape as a working example of how a business model can be successfully implemented in an industry heavily influenced by the public sector wherein credit is provided for seed and in return producers are obligated to buy their seed and inputs from and sell their cotton to a single entity. A stabilizing factor in Burkina Faso is the political and financial influence of the cotton growers' union (UNPCB) on cotton company policy due to its partial ownership status. Cotton prices are now negotiated prior to planting, and producers have had success in obtaining a greater share of the world price. Moreover, the legal framework has been greatly streamlined in the Burkina Faso cotton industry since contracting, and legal responsibility has been achieved through the national cotton companies and Monsanto. This bypasses the need to develop individual contracts with smallholder producers, which would be a daunting task in Burkina Faso given the large number of cotton producers (more than 300,000).

If GM cotton continues on its current trajectory in Burkina Faso, its success may create a gateway for the future introduction and development of other biotech crops in Africa. Other cotton-producing countries in the region, such as Mali and Benin, would likely benefit as much as Burkina Faso and could be next in line to introduce Bt cotton once, or if, legal frameworks are established. The commercialization of GM cotton in African countries such as Burkina Faso and South Africa can also serve as a gateway to facilitate other crops. The recent hesitance of certain African countries to accept food aid containing GM maize speaks to the tangible concerns that some African societies currently have over GM crops, particularly when they are intended for human consumption. The increased public awareness of the benefits from a crop such as Bollgard II could, however, enhance public perception and acceptance GM crops in general.

Bt cotton has already begun to play an important role in the developing economies of the world by decreasing poverty, increasing environment efficiency, and improving farmers' welfare. Its importance will remain strong, as insect problems are expected to worsen over the coming decades throughout the West Africa region. All of the major global climate change models forecast higher temperatures that will potentially promote higher pest populations within the region (Hulme, 2005; Pimentel, 1993).

Finally, a note on the modeling used to analyze the impacts of Bt cotton. In this study, employing a random effect model to correct a self-selection bias allowed for farm heterogeneity, typically associated with the cross sectional data, to be included in estimation. The random effect model was found to provide a better fit to the model data and the random error structure was significant according to the Breunch-Pagan test. The pest-damage function component included in the CD estimation provided additional insight into Bt cotton productivity and is a more accurate way of measuring input productivity when pest damage is present. Researchers studying Bt cotton should consider those approaches, including the awareness of the additional data that needs to be collected.

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