

Bt Cotton Adoption in The United States and China: International Trade and Welfare Effects

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Many studies report that Bt cotton has led to significant yield gains, reduced insecticide use, or both in different countries. With rare exception, these studies examine adoption in one region in isolation from adoption in others. This article summarizes the global impacts of Bt cotton adoption in the United States and China based on results from a three-region model of the world cotton market. In 2001, adoption of Bt cotton in China and the United States increased world cotton production by 0.7% and reduced the world cotton price by 1.4 cents per pound. Global economic benefits were \$836 million. Consumer surplus increased \$63 million. Chinese producers gained by \$428 million and US producers by \$179 million. The fall in world price reduced rest-of-world (ROW) producer surplus by \$349 million. Net rest-of-world benefits were \$69 million, however, because purchaser gains outweighed producer losses.

Key words: biotechnology, Bt cotton, China, spillovers, trade, United States, welfare.

Introduction

In 2001, roughly 4 million hectares of cotton were planted to Bt cotton. This includes Bt-only varieties and stacked Bt and herbicide-tolerant varieties. With nearly 2.4 million hectares of Bt cotton planted in 2001, the United States accounted for about 60% of world Bt cotton acreage (Williams, 2001). China planted nearly 1.5 million hectares (Huang, Hu, van Meijl, & van Tongeren, 2004; James, 2001) and Australia roughly 0.1 million hectares (Cotton Research and Development Council [CRDC], 2002). Smaller areas of Bt cotton were also planted in Argentina, Indonesia, Mexico, and South Africa (Ismael, Bennett, & Morse, 2002; James, 2001; Qaim & de Janvry, 2003, 2005). A now-large body of literature reports that Bt cotton has led to significant yield gains, reductions in conventional insecticide sprays, or both throughout the world. These include studies of Argentina (Qaim, Cap, & de Janvry, 2003; Qaim & de Janvry, 2003, 2005), Australia (CRDC, 2002; Doyle, Reeve, & Barclay, 2002), China (Huang et al., 2004; Huang, Hu, Fan, Pray, & Rozelle, 2002; Huang, Hu, Pray, Qiao, & Rozelle, 2003; Huang, Hu, Rozelle, Qiao, & Pray, 2002; Huang, Rozelle, Pray, & Wang, 2002; Pray, Huang, Hu, & Rozelle, 2002; Pray, Ma, Huang, & Qiao, 2001), India (Barwale, Gadwal, Zehr, & Zehr, 2004; Bennett, Ismael, Kambhampati, & Morse, 2004; Bennett, Kambhampati, Morse, & Ismael, 2006; Qaim, 2003; Qaim, Subramanian, Naik, & Zilberman, 2006; Qaim & Zilberman, 2003), Mexico (Magaña, García, Rodríguez, & García, 1999; Traxler & Godoy-Avila, 2004; Traxler, Godoy-Avila, Falck-Zepeda, &

Espinoza-Arellano, 2002), South Africa (Bennett, Morse, & Ismael, 2006; Gouse, Pray, & Schimmelpfennig, 2004; Ismael et al., 2002; Shankar & Thirtle, 2005; Thirtle, Beyers, Ismael, & Piesse, 2003), and the United States (Carpenter & Gianessi, 2001; Falck-Zepeda, Traxler, & Nelson, 2000a, 2000b; Frisvold & Tronstad, 2002; Gianessi, Silvers, Sankula, & Carpenter, 2002; Klotz-Ingram, Jans, Fernandez-Cornejo, & McBride, 1999; Marra, 2001; Price, Lin, Falck-Zepeda, & Fernandez-Cornejo, 2003; Traxler & Falck-Zepeda, 1999).

Studies of farm-level impacts of Bt cotton adoption do not examine effects on world or domestic cotton prices. With rare exception, studies of Bt cotton impacts examine adoption in one region, in isolation of adoption impacts in others. Two exceptions are Falck-Zepeda et al. (2000a), who considered a case where productivity gains in the United States were matched in the rest of the world, and Elbehri and MacDonald (2004), who considered ex ante the potential impacts of Bt cotton adoption in West and Central Africa (WCA). Elbehri and MacDonald (2004) compared the impacts of adoption and nonadoption by WCA, given adoption elsewhere.

This article reports on estimates of production, price, trade, and welfare impacts of Bt cotton adoption in the United States and China, using a three-region, output price endogenous model of the world cotton market calibrated to 2001. These two countries accounted for roughly 40% of world cotton production and over 95% of Bt cotton production in 2001. Although modest adoption occurred in the third region (i.e., the rest of the world, or ROW), these impacts would be small on a

world scale. In this study, ROW is affected by Bt cotton adoption only via changes in the world price of cotton.

Modeling Approach

A 28-region quadratic programming model of US cotton production is combined with linear supply and demand functions for cotton in China and a third region (ROW). Model equations are reported in the Appendix, and more detailed discussion of the model structure is provided in Frisvold and Tronstad (2002) and Frisvold, Tronstad, and Reeves (2006). A trade balance equation requires that net exports equal net imports. The model also accounts for Loan Deficiency Payments and Marketing Gain Payments received by US producers to support the price of cotton and, following Moschini and Lapan (1997), monopoly rents captured by suppliers of Bt cotton seeds.

Model Calibration and Data

The model is calibrated so that the equilibrium solution replicates observed conventional and Bt cotton acreage, average yields, pest control costs, cotton prices, Bt adoption costs, and cotton program payments for the base year 2001 in each US production region. The baseline model also replicates the world cotton price as well as aggregate production, consumption, imports, and exports for the United States, China, and ROW.

US regional and aggregate data sources used in the model are discussed in Frisvold and Tronstad (2002) and Frisvold et al. (2006). Estimates of domestic and export demand elasticities were based on Isengildina, Hudson, and Herndon (2000), Meyer (1999), Price et al. (2003), and Sullivan, Roningen, and Waino (1989). ROW consumption, production, and demand for US exports were derived from the Production Estimates and Crop Assessment Division of the United States Department of Agriculture's (USDA) Foreign Agricultural Service, the International Cotton Advisory Council (ICAC), and from various issues of the USDA Economic Research Service *Cotton and Wool: Situation and Outlook Yearbook*. The 28 regions within the United States correspond to those reported in the *Cotton Insect Losses* database (Williams, 2001), with the addition of a Southern California region.

Modeling Supply Shocks from Bt Cotton Adoption

In the baseline model, US acreage, yields, prices, program payment rates, exports, and costs are calibrated to actual USDA data. China and ROW cotton production,

consumption, demand for US cotton exports, and the world price of cotton are also set equal to USDA and cotton industry data. Implicitly, this data already accounts for the impacts of US and Chinese Bt cotton adoption.

To estimate the impact of Bt cotton adoption, we ask the counterfactual question, "What would the US and Chinese cotton supply functions look like if Bt cotton had not been adopted?" For the United States, the programming model is constrained so producers can only grow conventional cotton. The impacts of US Bt cotton adoption are measured by the differences between the baseline and constrained models. This approach is similar to previous analyses of pesticide cancellations (Deepak, Spreen, & Van Sickle, 1996; Sunding, 1996). The effect of Bt cotton adoption on the US supply step function is shown in Figure 1. For a high effective price (market price plus LDP payments) the supply function is perfectly inelastic. If the effective price falls sufficiently, the marginal region-technology combination (highest marginal cost combination) will reduce production first, followed by other region-technology combinations as the price falls further. In the baseline calibration and after simulated shocks, the effective price of cotton remains in the range where the US supply function is perfectly inelastic.

Estimates of changes in US insecticide application rates from Bt cotton adoption were derived from surveys of empirical studies of Bt cotton adoption impacts (Carpenter & Gianessi, 2001; Gianessi et al., 2002; Marra, 2001). Data on costs per insecticide treatment for target pests and Bt cotton technology fees were obtained from the *Cotton Insect Losses* database. The Bt cotton technology fees, per-acre insecticide cost savings, and yield advantages assumed in the simulations are reported in Table 1. Individual regional impacts were aggregated to obtain a national supply shift. In the simulations, Bt cotton adoption reduced insecticide use by a weighted-average of 2.4 applications per acre in the United States. In a survey of empirical studies, Marra (2001) reported large variations in the impact of Bt cotton on insecticide use. In most major Bt cotton adopting areas, however, the mean impact was a reduction of between two and three applications per acre. So, our simulation assumptions seem in line with this overall finding. Although Bt cotton reduces costs for insecticide applications, adopters must pay higher prices for Bt seed. In our simulations, US insecticide cost savings exceeded higher seed costs by only about \$1 million. This came out to a per-acre net pest-control cost saving of only \$0.23 per acre. Gianessi et al. (2002) estimated

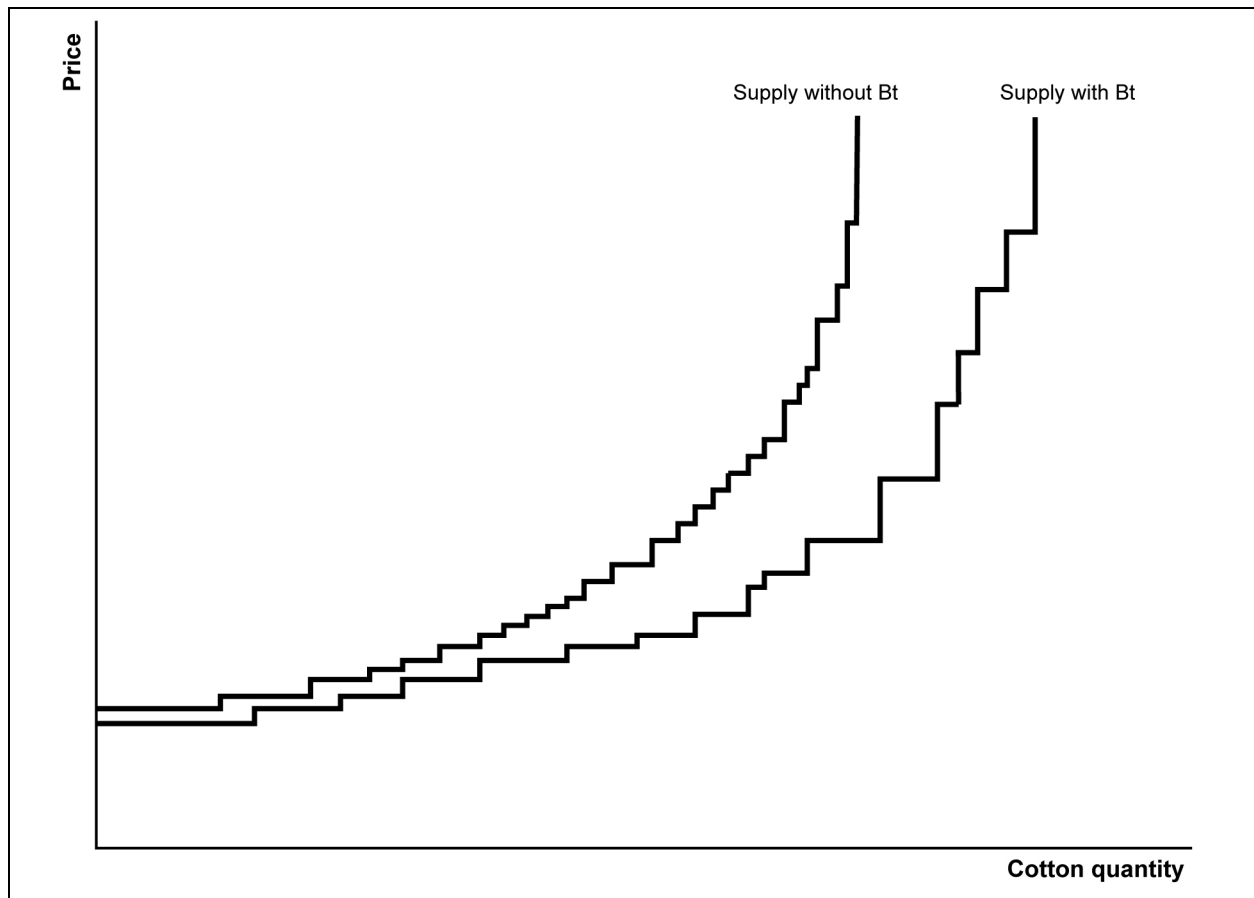


Figure 1. Impact of Bt cotton on US cotton supply.

that Bt cotton actually led to a \$2.00 per acre increase in net pest-control costs, with technology fees exceeding insecticide cost savings.

In either case, it is yield gains—not per-acre cost savings—that are the major economic incentive for adopting Bt cotton (Table 1). To estimate the impacts of Bt cotton adoption on US producer yields, percent yield increases were taken from the moderate impact scenario developed in Frisvold, Tronstad, and Mortensen (2000) and Frisvold and Tronstad (2002). Although in the simulations Bt cotton had little impact on per-acre costs, it had more of an impact on per-pound cost as yield increased. In the simulations, total US cotton production was 2.7% greater with Bt cotton adoption.

If Bt cotton were not adopted in China, the China supply function would shift upward in a parallel fashion. This is the approach used by Lichtenberg, Parker, and Zilberman (1988) to estimate impacts of pesticide cancellations and also follows the standard, proportional k -shift assumption of studies of returns to research (Alston, Norton, & Pardey, 1994). Through the market

equilibrium equation, these shifts induce a shift in the equilibrium world price of cotton. One can then simulate how much higher the world price would have been had there been no US or Chinese Bt cotton adoption.

To construct estimates of the k -shift parameter, we rely on information and data provided in Huang et al. (2004) for China. Bt cotton accounted for 31% of total cotton acreage (Pray et al., 2002). Econometric studies have examined the farm-level impact of Bt cotton adoption on Chinese cotton production costs and yields (Huang, Hu, Rozelle, et al., 2002; Huang, Rozelle, et al., 2002; Pray et al., 2001, 2002). Based on these studies, Huang et al. (2004) reported a yield advantage of Bt cotton of 8.3% in Hebei, Henan, and Shandong provinces. These provinces accounted for 86% of Bt cotton acreage and 43% of all cotton acreage in China in 2001. The yield advantage in Anhui, Jiangsu, and Hubei provinces was 5.8%. These provinces accounted for 12% and 24% of Bt cotton and total cotton acreage. The reported yield advantage in the remainder of China was 3%. This area accounted for a third of total cotton acres but only 2.5%

Table 1. Bt cotton insecticide cost savings per acre, technology fees, and yield advantages assumed in model simulations.

Region	Bt cotton insecticide cost savings (\$/acre)	Bt cotton technology fee (\$/acre)	Bt cotton yield advantage (%)
Alabama – North	\$16.80	\$25.00	7
Alabama – Central	\$18.00	\$28.00	7
Alabama – South	\$17.11	\$25.00	7
Arizona	\$41.49	\$31.90	5.5
Arkansas – North	\$18.00	\$22.00	7
Arkansas – South	\$27.60	\$22.00	7
California – Southern	\$41.49	\$31.90	5.5
California – San Joaquin Valley	\$13.83	\$12.00	1
Florida	\$36.99	\$26.50	8
Georgia	\$27.00	\$26.00	8
Louisiana	\$34.42	\$29.75	6
Mississippi Delta	\$23.52	\$26.00	5
Mississippi Hills	\$23.52	\$26.00	5
Missouri	\$13.50	\$24.50	4
New Mexico	\$36.00	\$32.00	7
North Carolina	\$18.72	\$19.25	4.5
Oklahoma	\$35.70	\$20.00	8.5
South Carolina	\$22.50	\$22.50	8
Tennessee	\$20.24	\$23.79	8
Texas – Coastal Bend	\$19.73	\$19.99	4
Texas – Northern Rolling Plains	\$20.50	\$23.00	4
Texas – High Plains	\$21.50	\$20.00	4
Texas – Far West	\$20.00	\$17.62	4
Texas – Rio Grande Valley	\$16.00	\$19.99	4
Texas – Southern Rolling Plains	\$19.00	\$14.40	4
Texas – Northern Blacklands	\$30.00	\$21.50	4
Texas – Southern Blacklands	\$15.00	\$18.00	4
Virginia	\$20.00	\$12.00	6.5

Note. Data from Williams (2001) and authors' calculations.

of Bt cotton acres. Based on these numbers, we assumed that Bt cotton adoption in China shifted supply in such a way to increase production 2% (at baseline price) and to reduce the marginal cost of production (at baseline quantity) by 24%. These assumptions appear in line with other studies (Huang et al., 2004; Huang, Rozelle, et al., 2002; Pray et al., 2001, 2002).

Impacts on Price, Production, Consumption, and Trade

We consider three scenarios: (a) Bt cotton adoption in the United States only, (b) adoption in the China only, and (c) adoption in both the United States and the China. Bt cotton increases cotton production and consumption and reduces world and US prices. The effects are great-

est with adoption in both areas, followed by adoption in the United States alone, then China alone (Table 2). Under joint US-Chinese adoption, increased production contributed to a 1.4 cent per pound reduction in the world price of cotton.

In all scenarios, the rest of the world increases consumption, reduces production, and increases its cotton imports, with the effects stronger with combined adoption. China's production increases (and imports decrease) the most if it is the sole adopter, but production declines (and imports increase) if the United States is the sole adopter. US exports rise 4.3% if it is the sole adopter. With adoption also occurring in China, US exports increase by only 3.6%. If adoption occurred only in China, US exports would fall by -0.7%. US production is unaffected because of the highly inelastic US

Table 2. Impact of Bt cotton adoption on cotton prices, production, consumption, and trade, 2001.

	Bt cotton adoption in:		
	US only	China only	Both US and China
	Change in US cents per pound		
World price	-0.7	-0.7	-1.4
US LDP^a rate	0.7	0.7	1.4
US farm price received	-0.6	-0.5	-1.1
	% change		
US consumption	0.9	0.8	1.7
US production	2.7	0.0	2.7
US exports	4.3	-0.7	3.6
China consumption	0.6	0.5	1.1
China production	-0.3	1.8	1.5
China imports^b	60.2	-82.9	-22.7
Rest-of-world consumption	0.2	0.2	0.4
Rest-of-world production	-0.2	-0.2	-0.3
Rest-of-world imports	2.3	2.2	4.5
World cotton production	0.4	0.4	0.7

^a LDP: Loan Deficiency Payment.

^b In 2001, net imports of upland cotton in China were small, about 1% of consumption. Large percentage changes represent small changes in import levels.

supply function combined with the LDP payments maintaining the US effective price at a relatively constant level.

The results reported in Table 2 and the welfare impacts reported in Table 3 suggest that adoption of Bt cotton in the United States and China have a near-additive effect. That is, the impact of joint adoption is quite close, if not identical, to the sum of effects of individual country adoption. There are small differences in ROW and global production (Table 2) and Chinese and US welfare measures (Table 3), yet the remainder of the impacts appear additive.

Two things account for this result. First, near-additive impacts are not unusual in models estimating spillovers. For example, in Edwards and Freebairn (1984) and Frisvold (1997), the difference between joint adoption impacts and the sum of individual adoption impacts are often negligible. Second, we have rounded numbers up to avoid overstating the precision of our results.

Welfare Impacts

The change in economic welfare in ROW and China are measured as the sum of changes in producer and consumer surplus (Table 3). For the United States, the change in welfare is measured as the sum of the change in US producer surplus, consumer surplus, and innovator-monopolist rents charged to US producers for seed, minus the change in US government program payments to cotton producers. Including innovator-monopolist rents follows the approach introduced by Moschini and Lapan (1997). Ideally, one would also want to include measures of these rents captured in China. There, Bt seed varieties are supplied both by Monsanto/Delta and Pine Land and the Chinese Academy of Agricultural Science (CAAS). At the time of writing, we did not have access to information about any monopoly rents captured in China in 2001. For 1999, however, Chinese suppliers just covered their costs, while Monsanto/Delta and Pine Land received less than \$2 million in gross revenue (Pray et al., 2001). Besides greater formal competition in the seed sector in China, farmers also save and replant Bt seed. Saved seed thus competes with new seed, exerting downward pressure on rents. Bt cotton acreage has roughly tripled in China from 1999 to 2001 (Huang et al., 2004), so it would be interesting to include estimates of seed sales rents captured in future analysis.

The world economic surplus from Bt cotton adoption in the United States and China was \$836 million in 2001. Chinese producers capture 51% of this gain with a \$428 million increase in producer surplus, while Chinese consumers capture 20% of world economic surplus a \$167 million increase in consumer surplus. ROW captured 8% of the gain, with consumer gains slightly exceeding producer losses. Losses to ROW producers accrue because of the falling world price of cotton. US producers captured \$179 million and consumers \$48 million.

US commodity program payments shelter US producers from the impact of the falling world price, but at a budgetary cost. Under joint US-Chinese adoption, US producer surplus would have declined if not for commodity program payments of \$198 million. This result is similar to one obtained by Sobelevsky et al. (2002) in their analysis of global adoption of transgenic soybeans. They found that US producers gained from global adoption of biotechnology with loan deficiency payments in place, but, in general, not when they were absent. When the United States adopts Bt cotton alone, program payments account for 82% of producer surplus gains.

Table 3. World welfare effects of Bt cotton adoption in the US and China, 2001 (million \$).

		Bt cotton adoption in:		
		US only	China only	Both US and China
Rest of world	Change in consumer surplus	217	201	418
	Change in producer surplus	-181	-168	-349
	Change in welfare	36	33	69
China	Change in consumer surplus	87	81	167
	Change in producer surplus	-84	514	428
	Change in welfare	3	595	595
United States	Change in consumer surplus	25	23	48
	Change in producer surplus	164	14	179
	Change in government payments	134	63	198
	Seed supplier US profits	143	0	143
	Change in welfare	198	-26	172
Global welfare		237	602	836

The United States captured 21% of the increase in world economic surplus, with 17 of this 21% going to seed suppliers as profit. Relative gains in China were larger, in part, because China was starting from a base of less effective pest control. Bt cotton adoption led to greater yield increases and greater reductions in insect control costs in China than in the United States.

Table 3 also highlights the consequences of falling behind technologically. If Bt cotton were adopted in the China but not the United States, US export share falls and welfare falls by \$26 million from a no-adoption baseline. The declines are even more pronounced compared to a case where both countries adopt. Moving from joint adoption to China-only adoption, US welfare falls by \$198 million. If Bt cotton were adopted in the United States, but not China, then welfare in China would only increase by \$3 million, instead of \$595 million with combined adoption. With only US adoption, producer surplus in China falls by \$84 million. These results reinforce those of Elbehri and MacDonald (2004) that found that costs of not adopting Bt cotton in Africa could be quite significant.

Under joint adoption, ROW producers are worse off by \$349 million. ROW producers were almost entirely nonadopters of Bt cotton in 2001. (Producers in Australia are a notable exception.) Unlike Bt cotton adopters in China and the United States, ROW producers do not benefit from higher yields and lower per-pound production costs. They are only negatively affected by US-Chinese adoption through the falling world price of cotton.

In simulation exercises, Edwards and Freebairn (1984) found that technological spillovers across regions reduce the gains from technological change in net exporting regions, while increasing the gains to net-

importing regions. Our results are consistent with these earlier findings. In the case of cotton, the United States is a net exporter, while the rest of the world and China are net importers. US welfare is highest when it adopts alone, while welfare is highest for ROW and China when there is combined adoption.

Conclusions

This article presented simulation results from a three-region output price endogenous model of the world cotton market to evaluate the global impacts of Bt cotton adoption in the United States and China in 2001. Bt cotton reduced insecticide use and per-pound production costs in both countries. Higher yields and production contributed to a 1.4 cent per pound reduction in the world price of cotton. Net global benefits were \$836 million. China captured 71% of this benefit, the United States captured 21%, and the rest of the world captured the remainder. ROW cotton purchasers benefited from lower cotton prices, while returns to ROW producers fell.

The results provide an indication of the costs of not adopting Bt cotton. Both the United States and China were significantly worse off under scenarios when they did not adopt Bt cotton. These results mirror those of Elbehri and MacDonald (2004) that suggest significant costs of nonadoption of Bt cotton in Africa. Bt cotton adoption rates were negligible in the rest of the world in 2001 and assumed to be zero in the model. In the simulations, ROW producers lose from falling prices, but do not benefit from lower insecticide use or higher yields from adopting Bt cotton. In contrast, producers in China gained more than any other group examined in the simulations, gaining \$595 million.

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Appendix: Simulation Model Structure

We assume a “putty-clay” specification for US cotton production. Cotton planting decisions (acreage and seed variety choice) are flexible at the beginning of the crop year, but then production is characterized by a fixed-proportion technology. At the beginning of the crop year, growers in each region i choose how much cotton to plant A_i , subject to a capacity constraint \bar{A}_i , which limits the total acreage where cotton may be grown profitably. Growers allocate cotton acreage between conventional cotton acres A_{i1} and Bt cotton acres A_{i2} , where $\bar{A}_i \geq A_{i1} + A_{i2}$.

Bt seed varieties cost more than conventional seed varieties but reduce the need for conventional insecticide applications to control cotton bollworm, pink bollworm, and tobacco budworm. Bt varieties have higher yields, to the extent they reduce losses from these pests.

Growers choose conventional and Bt cotton acreage (A_{i1} and A_{i2}) to maximize profits, subject to constraints. The first is the overall capacity constraint, limiting total cotton acreage planted in a region, \bar{A}_i . Given the Leontief constant returns technology, if producers can earn profits from producing using either technology, the overall capacity constraint will be binding.

The second constraint is an adoption ceiling, \bar{A}_{i2} , that places a cap on the total acreage planted to Bt cotton in a region. Bt cotton may have a profit advantage over conventional cotton on only part of a region's cotton acreage. Within a region, there will be areas where

bollworm/budworm pressure neither exceeds insecticide treatment thresholds, nor causes appreciable yield losses. For example, in 1995, 15% of US cotton acreage was not infested by bollworm/budworms, while 37% of acreage did not receive insecticide treatments for these pests (Williams, 1996). On these acres, there is little scope for Bt cotton to reduce pest control costs or increase yields. The adoption ceiling is meant to capture this relationship. Regulation also limits regional adoption. To slow the development of pest resistance to Bt cotton, the US Environmental Protection Agency requires Bt cotton adopters to plant refuges of conventional cotton to allow susceptible and resistant pests to interbreed.

The Lagrangian, L_i , for profit maximization in region i is

$$L_i = (P_i + S_i)(A_{i1}Y_{i1} + A_{i2}Y_{i2}) - \{A_{i1}Y_{i1}[(C_{i1}/Y_{i1}) + G_i] + A_{i2}Y_{i2}[(C_{i2}/Y_{i2}) + G_i]\} + \lambda_i(\bar{A}_i - A_{i1} - A_{i2}) + \gamma_i(\bar{A}_{i2} - A_{i2}). \quad (1)$$

Yields and per-acre costs for conventional cotton are Y_{i1} and C_{i1} ; for Bt cotton they are Y_{i2} and C_{i2} . For each region, yields and costs are constant for each technology within a given crop year. Per-pound ginning costs (G_i) are the same for each technology. For every pound of lint produced, growers receive the market price P_i and a government support price payment, S_i . The terms λ_i and γ_i are the shadow costs of the land use constraints.

The market price (P_i) a grower receives for a pound of cotton lint is

$$P_i = P_f + z_i, \quad (2)$$

where P_f is the average US farm price and z_i is the regional price premium or discount that reflects difference in lint quality and transportation costs. The US farm price of cotton is a function of the endogenously determined world price, P_w :

$$P_f = \theta P_w^\epsilon, \quad (3)$$

where θ and ϵ are parameters. Domestic and world prices can differ because of quality difference, transportation costs, and government market interventions. The term ϵ is a price transmission elasticity that determines the percent change in the US farm price in response to world price changes. The transmission elasticity reflects how the domestic price is sheltered from changes in

world price. Following Sullivan et al. (1989), we assume $\epsilon = 1$.

The government price support payment rate (S_i) is

$$S_i = \sigma_i l_i (P_w), \quad (4)$$

where l_i is the weighted average of the Loan Deficiency and Marketing Gain Payment rates and σ_i is the share of production receiving payments. The payment rate (l_i) is determined by the difference between the adjusted world price ($P_w - \omega$) and the loan rate, R :

$$l_i = \max [0, R - (P_w - \omega)]. \quad (5)$$

Producers receive payments if the adjusted world price falls below the loan rate, which is set at 51.92 cents per pound. The adjustment factor ω is set by the US Department of Agriculture and is based on transport costs and cotton grade. It typically ranges from 12–14 cents. Payment rates, l_i , vary by region, ranging between 25–28 cents per pound in 2001.

The solution to the Lagrangian yields the optimal allocation of acreage to conventional and Bt cotton as functions of the regional market price received and program payment rates, $A_{i1}^*(P_i, S_i)$ and $A_{i2}^*(P_i, S_i)$. From Equations 2–5, optimal regional acreage allocations can be expressed as functions of the world price of cotton, $A_{i1}^*(P_w)$ and $A_{i2}^*(P_w)$. The regional supply of cotton Q_i^S is

$$Q_i^S = A_{i1}^*(P_w)Y_{i1} + A_{i2}^*(P_w)Y_{i2}. \quad (6)$$

The US supply of cotton lint is the sum of optimal production over all 28 production regions:

$$Q_u^S = \sum_{i=1}^{28} A_{i1}^*(P_w)Y_{i1} + A_{i2}^*(P_w)Y_{i2}. \quad (7)$$

Equation 7 generates a step-function supply curve, where each step represents marginal costs and production of cotton in each region for each technology (Figure 1).

The supply functions for China (Q_c^S) and ROW (Q_r^S) are linear:

$$Q_c^S = \alpha_c (1 + k) + \beta_c P_w \text{ and} \quad (8)$$

$$Q_r^S = \alpha_r + \beta_r P_w \quad (9)$$

where the α and β terms are scalar constants. To estimate the impact of China's adoption of Bt cotton, a supply shift parameter, k , is introduced into China's supply function. Yield increases and cost reductions from Bt cotton adoption are reflected in the size of k . A large value of k implies that more cotton will be supplied at any given market price.

US demand Q_u^D , Chinese demand Q_c^D , and ROW demand Q_r^D are linear functions:

$$Q_u^D = a_u - b_u \theta P_w \tag{10}$$

$$Q_c^D = a_c - b_c P_w \text{ and} \tag{11}$$

$$Q_r^D = a_r - b_r P_w \tag{12}$$

where the a and b terms are scalar constants. US supply equals domestic plus export demand:

$$Q_u^S = Q_u^D + Q_u^E \tag{13}$$

Export demand can be expressed as a function of the world price of cotton. The model is calibrated to 2001 data. In that year, ROW was a large importer of cotton. China was also a net importer, but imports were only about 1% of consumption. The trade balance equation requires that net exports equal net imports,

$$Q_u^E = (Q_c^D - Q_c^S) + (Q_r^D - Q_r^S), \tag{14}$$

where Q_u^E is US exports. The US export demand equation can be expressed as a function of the world cotton price and exogenous variables by substituting Equations 8, 9, 11, and 12 into Equation 14, thus:

$$Q_u^E = [(a_c + a_r) - (\alpha_c(1+k) + \alpha_r)] - P_w(b_c + b_r + \beta_c + \beta_r). \tag{15}$$

The equilibrium world price can be determined by substituting Equations 7, 10, and 14 into Equation 13 and solving for P_w :

$$\sum_{i=1}^{28} A^*_{i1}(P_w)Y_{i1} + A^*_{i2}(P_w)Y_{i2} = [(a_u + a_c + a_r) - (\alpha_c(1+k) + \alpha_r)] - [P_w(b_c + b_r + b_u\theta + \beta_c + \beta_r)]. \tag{16}$$

The equilibrium world price is the P_w that solves Equation 16.