Betting on cotton: Potential payoffs and economic risks of adopting transgenic cotton in West Africa

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Abstract

Cotton is the largest source of export receipts in several West African nations where yields are declining and pesticide use is rising. Although there may be payoffs to introducing genetically modified Bt (*Bacillus thurigiensis*) cotton, limited information is available to predict its potential economic impact and there is uncertainty about its performance. Recognizing these constraints, we use an economic surplus model augmented with stochastic simulation to estimate ex ante the impact and distribution of benefits from Bt cotton. We consider the effects of adoption on both yields and abating crop damage, and offer scenarios depicting the policy options faced by West African stakeholders. The findings indicate that although the total net benefits of adopting Bt cotton may be relatively small for the countries studied, these countries would be worse off without the technology. Our approach, which incorporates variability and uncertainty, may be useful in decisions about investments in crop biotechnology.

Keywords: Crop biotechnology; Bt cotton; Economic surplus model; West Africa; Agricultural development; Risk

*Dans plusieurs pays ouest africains où le rendement est à la baisse et où l'usage de pesticides est à la hausse, le coton représente la source la plus importante des recettes générées par l'exportation. Bien que le fait d'introduire un coton génétiquement modifié Bt (*Bacillus thurigiensis*) puisse s'avérer profitable, l'information disponible à ce sujet reste limitée et ne permet pas d'en prédire l'impact économique potentiel. De surcroît, sa performance reste incertaine. Prenant en considération ces contraintes, nous utilisons un modèle de surplus économique augmenté d'une simulation stochastique afin d'évaluer à priori l'impact et la distribution des bénéfices issus du coton Bt. Nous prenons en considération les effets de l'adoption à la fois sur le rendement et sur la réduction des dommages causés aux cultures, et nous proposons des scénarios qui décrivent les options politiques auxquelles les décideurs politiques de l'Afrique de l'Ouest font face. Les conclusions indiquent que l'adoption du coton Bt pourrait entraîner un total de bénéfices*

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nets relativement bas pour les pays étudiés mais que sans la technologie ces pays seraient dans une situation pire. Notre approche, qui utilise variabilité et incertitude, pourrait aider les prises de décisions concernant les investissements en matière de biotechnologie des plantes .

Mots-clés : *Biotechnologie des plantes ; Coton Bt ; Modèle de surplus économique ; Afrique de l'Ouest ; Développement agricole ; Risque*

1. Introduction

The prospect of cotton growers in West Africa adopting genetically modified Bt (*Bacillus thurigiensis*) has generated controversy about the uncertain impacts of the technology on the economy and the environment. However, despite the controversy, some West African governments and farmers' associations have expressed interest in producing the crop – especially when they observe the economic gains earned elsewhere. In this study, we conduct an ex ante assessment of the impact of Bt cotton on five major cotton-producing countries in West Africa: Benin, Burkina Faso, Mali, Senegal and Togo. We augment the economic surplus model with a stochastic simulation analysis, in order to address both the limitations of existing data and the economic risk that may be associated with adoption caused by variability in prices, yields and costs of pest control. This analysis can better inform decision makers about the 'stakes' involved in deciding whether or not to adopt genetically modified crops.

Cotton production is the main source of income for smallholders in West Africa. According to the Sahel West Africa Club (SWAC) Secretariat / OECD (2005), a significant share is planted by approximately one to two million smallholder farmers, largely using household labor. SWAC also reports that cotton production on household farms engages an estimated six million persons directly and around 16 million persons off-farm. Furthermore, cotton has long played a crucial role in the economic development of West Africa, as an export crop and a source of hard currency. West Africa currently accounts for approximately 10% of world cotton exports (FAO, 2004). The region has had a comparative advantage in terms of lower production costs, consistent quality of fiber, strong farmers' associations and a vertically integrated industry (Bingen, 1994; Baffes, 2005). Yet this comparative advantage is rapidly eroding due to market constraints, competition from abroad and other factors such as the incidence of pests and diseases.

Cotton producers in West Africa spend approximately 194 million dollars annually on insecticide applications to control lepidopterans alone (CAB International, 2001). Yield losses due to lepidopterans in the region reach an average of 23% to 34% without control (Oerke et al., 1995). Ajayi et al. (2002) report that cotton yields have declined in West Africa at the same time as pesticide use has increased. This is partly due to the increased resistance of pests, such as cotton bollworm, to commonly used pesticides (Martin et al., 2002). Changes in pest management strategies, such as the use of control thresholds early in the season, have been proposed in order to reduce costs and improve control (Ochout et al., 1998) but have not been widely adopted (Silvie et al., 2001).

While Bt cotton offers an alternative means of controlling target pests and increasing cotton productivity in West Africa, decision makers in the region lack evidence about the potential impact of this technology. Ex ante analysis based on the economic surplus model can provide relevant information to support risk assessment during the biosafety analysis and related decision-making process.[1] Ex ante assessment can also provide useful information about the potential costs and benefits of: a) institutional arrangements for delivering genetically modified crops, b) technology use fees, c) the pattern of technology diffusion within and among countries, and d) regulatory delays that result from additional years of testing to comply with biosafety regulations.

The primary purpose of this study is to illustrate an ex ante approach that can be applied when data are sparse and which accounts for risk induced by variability in yields, yield losses, prices and other factors that affect adoption rates. We consider two effects of adoption: 1) yield changes that reflect the genotype into which the Bt gene is introduced, and 2) damage abatement that results from the Bt gene. Five scenarios are developed to highlight the effects of government policy and institutional factors on the distribution of economic benefits and risks. Comparison of the structure of benefits and risks across scenarios lends insights into issues that are critical for advancing biosafety processes and deploying crop biotechnology in West Africa.

2. Previous literature

While thousands of articles related to the economic impact of crop biotechnologies were published between 1996 and 2006, fewer than 100 were peer reviewed studies that applied a stated economics method to a data set collected in non-industrialized countries (Smale et al., 2008). Among these, the most frequently studied crop-trait combination was Bt cotton. (In this case the trait is the resistance to Lepidoptera pests conferred by the Bt gene to the cotton.) The majority of the articles about Bt cotton (44 out of 56) examined impacts on farmers. Five articles presented economic evaluations of impacts on the industry. An additional three articles included analyses of both farm and industry impacts. Four assessed impacts on international trade.

Only two of these articles addressed the potential economic impact of Bt cotton in West Africa. Cabanilla et al. (2005) developed a linear-programming model to assess the potential cost to West Africa (with a focus on Mali) of not adopting Bt cotton. The authors used parameters from detailed farm-level studies already conducted in Mali and published results of studies implemented in China, South Africa and Mexico. The analysis generated estimates of optimal allocations of land area, output, farm profit and whole farm income. Estimates were then aggregated to the national level. The effects of various technology fees were tested using sensitivity analyses. Cabanilla et al. (2005) concluded that even with a high technology fee countries will forego substantial economic benefits if Bt cotton is not adopted.

The second study, conducted by Elbehri and Macdonald (2004), assessed the potential impact of Bt cotton in West and Central Africa on international trade. The authors used a multi-region, applied general equilibrium model and multi-country estimates of productivity after Bt cotton adoption. Elbehri and MacDonald (2004) found that adoption of Bt cotton in West and Central Africa would raise returns to growers, land values and social welfare. The

[1] Article 18.2 of the Cartagena Protocol on Biosafety allows member countries the possibility of considering socio-economic assessments in making decisions. Socio-economic assessments are not needed to determine the safety of products entering the regulatory system. Biosafety assessments concentrate on evaluating food/feed and environmental safety.

potential gross benefits were substantial for this region, while the economic costs of not adopting the technology were also significant.

Ex post impact evaluations at the industry level have been carried out in a few other developing countries. The approach used by Falck-Zepeda et al. (2000a,b) has provided the foundation for these assessments. This approach consists of an adjusted economic surplus model (Alston et al., 1995) that accounts for temporary monopolies derived from intellectual property (Moschini & Lapan, 1997). Pray et al. (2001) applied this approach in China and reported that smallholder farmers gained major economic benefits from Bt cotton adoption. Similar results were obtained in North-Central Mexico, where Traxler et al. (2003) found that Bt cotton reduced costs and raised revenues for farmers. Cotton growers in Mexico earned a two-year average of 85% of total estimated benefits.

A major disadvantage of the economic surplus approach is that the reliability of the findings depends on the extent to which the underlying parameters represent local conditions. Often, for ex ante studies, parameters are adapted from related research conducted in other countries, or elicited through interviews with local experts. Because so few crop-trait combinations have been released, this disadvantage is particularly evident when assessing the potential impact of crop biotechnologies in developing economies.

In addition, the conventional economic surplus model fails to incorporate the risks that are characteristic of agricultural production and marketing. Farm-level assessments of the impact of Bt cotton in China, India and South Africa indicate that there is considerable variability in economic returns, which is associated with both the germplasm and the production environment (Fok et al., 2005; Bennett et al., 2006a; Bennett et al., 2006b; Qaim et al., 2006). Analyses conducted in South Africa (Gouse et al., 2005), Mexico (Traxler et al., 2003) and Argentina (Qaim & De Janvry, 2005) confirm the importance of institutional arrangements in determining the economic benefits earned by farmers. Institutional factors include, for example, the nature of grower contracts, the magnitude of the technology fee, the availability of credit and the extent of competition in the seed and product markets.

While evaluating Bt technologies it is important to take into account the damage abatement effect (Waibel et al., 2003; Pemsl et al., 2005). Damage abatement is defined as the proportion of the destructive capacity of the damaging agent eliminated by applying a given level of a control input. By ignoring this abatement effect economic surplus models would overestimate the benefits of insect protection technologies (Waibel et al., 2003).

3. Model

3.1 Augmented economic surplus model

The economic surplus model is based on Falck-Zepeda et al. (2000a,b). As detailed in Alston et al. (1995), the model consists of a set of equations that depict the cotton market in an economy, including equations for producer and consumer surplus, prices and quantities. On the basis of the stream of yearly estimates, we calculated the Net Present Value (NPV) and, when appropriate, the Internal Rate of Return (IRR) to society. Expected yield increases were converted to equivalent cost changes by dividing the percent yield change by the elasticity of supply. The five countries included individually in this study were Benin, Burkina Faso, Mali, Senegal and Togo. The rest of the cotton producing countries in West Africa were grouped with other countries under Rest of the World (RoW).

The innovator surplus was defined as the benefit appropriated by the institution that delivered the technology. Innovator surplus was estimated by multiplying the area planted to Bt cotton by the technology fee or premium (Falck-Zepeda et al., 2000a). The price difference between the conventional and Bt cotton seed is known as the technology fee or premium. The monopoly rents generated by the innovator can be estimated by multiplying the technology fee or premium times the quantity of seed sold.

The underlying model was augmented to account for risk, uncertainty and sparse data by replacing single-point values with probability distributions for selected parameters (technology fee, supply elasticity, yield and cost differences between Bt and non-Bt varieties). For each of these parameters, we generated triangular distributions based on values cited in published articles. Widely used in the analysis of agricultural risk and uncertainty, the triangular distribution is a continuous probability distribution that is fully described by the minimum, maximum and mode and approximates the normal distribution (Hardaker et al., 2004). The @Risk™ program calculates and saves values of designated output variables (for example, producer surplus, consumer surplus, total surplus, net present value, internal rate of return) from repeated draws ('iterations') of the specified triangular distributions. To our knowledge, only a few studies have applied a stochastic approach (for example, Pemsl et al., 2004; Hareau et al., 2006) and this study is the first to apply the approach to the case of Bt cotton in West Africa.

After repeated sampling the average variation across all simulations will tend to decrease. Thus, a recommended practice while running simulations is to monitor the convergence to a stable 'steady' state for selected outcome variables. On the one hand, researchers need to ensure that sufficient iterations are run so that the statistics describing all the iterations are deemed to be reliable because they are stable. On the other, after a certain point, additional iterations will not yield new information because there is little variation in the average statistics that summarize all iterations. We chose a minimum cut-off point of less than 1.5% change in the value for the average statistics calculated after each iteration.

Changes in adoption rates over time were modeled using a logistic curve with a maximum adoption rate that depended on the country and the scenario. Information on cost of production and cotton prices was obtained from the International Cotton Advisory Committee surveys (ICAC, 2004, 2006).

3.2 Parameters

We formulate five scenarios to highlight the policy options and institutional factors available to West African governments. Across all scenarios, we address risk and uncertainty in parameter values by including probability distributions that replace single values for elasticities, yield and cost differences between Bt cotton and the conventional counterpart. Simulations allow for random sampling for these parameter values and estimation of the change in producer, consumer and total surplus as well as its distribution. The assumptions associated with each scenario are summarized in Tables 1a and 1b, along with the literature that was consulted to obtain parameter values.

The time lag parameter is understood as the total time required for completing research and development, as well as compliance with biosafety regulations in the adopting country. Even when there is no time lag for adaptive research because varieties are transferred directly, varieties may enter regular performance trials or Plant Protection Quarantine processes while biosafety information is compiled.

Table 1a: Assumptions used in the estimation of economic surplus model for the adoption of Bt cotton in West Africa

Assumptions	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Source(s) of assumptions
Maximum adoption rates (%)	0% in WA 20% in RoW	30% in WA 20% RoW	30% in WA 20% RoW	50% in WA 20% RoW	Fluctuating adoption in Benin and Mali, 30% in rest of WA, 20% RoW	Based on Cabanilla et al., 2005. For fluctuating adoption patterns see Figure 3.
Total R&D & Biosafety lag (years)	0	5	6 Burkina Faso, 9 other WA countries	6 Burkina Faso, 9 other WA countries	6 Burkina Faso, 9 other WA countries	Own (subjective) assumptions
Adoption lag (years)	0	5	5 Burkina Faso, and other WA countries	5 Burkina Faso, and other WA countries	5 Burkina Faso, and other WA countries	Own (subjective) assumptions
Year at maximum adoption level	7	7	7	7	7	Own (subjective) assumptions
Years to dis-adopt	0	5	5	5	5	Own (subjective) assumptions
Total years simulation	23	23	24	24	24	Sum of all components of adoption pattern

Notes: WA = West Africa, RoW = Rest of the World, Scenario 1 = No adoption in West Africa, adoption in the rest of the world, Scenario 2 = WA adopts available private sector varieties, Scenario 3 = WA uses West African varieties backcrossed with private sector lines, Scenario 4 = WA uses West African varieties backcrossed with private sector lines plus a negotiated premium Scenario 5 = WA uses West African varieties backcrossed with private sector lines with irregular adoption.

Table 1b: Assumptions for probability distributions used in the estimation of economic surplus model for the adoption of Bt cotton in West Africa

Assumptions	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Source(s) of assumptions
Technology fee (US$/ha)	Triangular (15, 32, 56) for RoW	Triangular (15, 32, 56) for WA and RoW	Triangular (15, 32, 56) for WA and RoW	Triangular (9, 19, 34) for WA and (15, 32, 56) for RoW	Triangular (15, 32, 56) for WA and RoW	Falck-Zepeda et al., 2000a,b; Huang et al., 2003, 2004; Bennett et al., 2004

Supply elasticity (Units)		Triangular (0.3, 1, 1.5)	Triangular (0.3, 1, 1.5)	Triangular (0.3, 1, 1.5)	Triangular (0.3, 1, 1.5)	Minot & Daniels, 2005; Dercon, 1993, Delgado & Minot, 2000; Alston et al., 1995
Yield advantage of Bt over conventional varieties (%)	Triangular (0, 0.2, 0.4) for RoW only	Triangular (0, 0.2, 0.4) for WA and RoW	Triangular (0, 0.25, 0.45) for Burkina Faso and WA (0, 0.2, 0.4) for RoW	Triangular (0, 0.25, 0.45) for Burkina Faso and WA (0, 0.2, 0.4) for RoW	Triangular (0, 0.25, 0.45) for Burkina Faso and WA (0, 0.2, 0.4) for RoW	Falck-Zepeda et al., 2000a,b; Huang et al., 2003, 2004; Bennett et al., 2004;
Cost advantage of Bt over conventional varieties (%, net of technology fee)	Triangular (0, 0.06, 0.12) equivalent to a reduction of 0, 7, 14 applications for RoW only	Triangular (0, 0.06, 0.12) for RoW and (0, 0.13, 0.26) for WA equivalent to a reduction of 0, 7, 14 applications	Triangular (0, 0.06, 0.12) for RoW and (0, 0.13, 0.26) for WA equivalent to a reduction of 0, 7, 14 applications	Triangular (0, 0.06, 0.12) for RoW and (0, 0.13, 0.26) for WA equivalent to a reduction of 0, 7, 14 applications	Triangular (0, 0.06, 0.12) for RoW and (0, 0.13, 0.26) for WA equivalent to a reduction of 0, 7, 14 applications	Cabanilla et al., 2005; Bennett et al., 2004; Huang et al. 2004
Adaptive R&D / Biosafety regulatory costs (US$ total)	0	$120,000 distributed over 4 years in BF, $90,000 distributed over 3 years rest adopting countries in WA	$120,000 distributed over 4 years in BF, $90,000 distributed over 3 years rest adopting countries in WA	$120,000 distributed over 4 years in BF, $90,000 distributed over 3 years rest adopting countries in WA	$120,000 distributed over 4 years in BF, $90,000 distributed over 3 years rest adopting countries in WA	Quemada, 2003; Pray et al., 2005; Falck-Zepeda & Cohen, 2006

Note: The triangular probability distributions used in the simulations are fully described by minimum, mode and maximum values. In the table above, values for these three parameters are included in parentheses in each cell of this table, when appropriate.

We used published data from other developing countries such as India and China to obtain preliminary data on the cost compliance with biosafety regulations and/or adaptive research and development (R&D). We also used estimates reported in conferences and publications for any Bt crop (for example Quemada, 2003; Pray et al., 2005; Falck-Zepeda & Cohen, 2006). When the cost of compliance with biosafety regulations is excluded from our simulations, the benefit values generated represent the present value of gross benefits to producers and consumers. We assume that cost of regulations will be charged to total surplus and thus become a 'social cost'.

Technology fees, represented by triangular distributions, are applied in all scenarios. In the base scenario, they are incorporated only for the RoW because there is no adoption in West Africa. The technology fee implies that varieties of Bt cotton are developed or adapted via joint ventures between the gene and germplasm innovators and West African organizations. The technology fee is paid by producers as part of the seed price, representing an additional cost that reduces the leftward shift of the supply curve. In terms of the technology diffusion pattern, we assume that Burkina Faso leads in promoting the Bt cotton technology, and is followed later by Benin, Mali, Senegal and Togo (except in the baseline scenario).

Other model parameters where we substitute a deterministic value with a distribution are the supply elasticity of cotton, the yield difference between Bt and non-Bt cotton varieties, and the cost advantage of using Bt varieties relative to non-Bt varieties. Given limited information about the supply elasticity of cotton in West Africa, the unitary elasticity is assumed to be the most likely value. To set the range of the supply elasticity values, we consulted Minot and Daniels (2005), who employed a lower value of 0.5 and a maximum of 1.5, with an intermediate value of 1.0. Deliberately, we chose a more conservative minimum value ($\varepsilon = 0.3$).

We adopted relatively conservative estimates of yield differences between Bt and conventional cotton, drawn from published findings (Falck-Zepeda et al., 2000a,b; Huang et al., 2003, 2004; Bennett et al., 2004). The maximum yield difference was fixed at 40% and the mode at 20%. The minimum value was fixed at 0% to allow for the possibility that there is no discernible pest pressure in some years. Yield differences will be observed only when the target pest attacks the crop. When there is no pest attack, any difference between a Bt variety and a non-Bt variety is related to yield performance of genotypes rather than to the trait.

The cost advantage of adopting Bt cotton is the per unit cost savings from reduced pesticide use. We consulted the literature in order to set the values of the triangular distribution. The minimum cost difference was fixed at zero. The implication of this assumption is that Bt adoption does not necessarily reduce the need for insecticide applications. Bt has economic advantages only when there are pest pressures sufficient to cause economic damage.

Even when the Bt technology is successful in controlling primary pests, there are secondary pest populations that can become important. The cost of controlling secondary pests could offset the benefits from reducing pesticide applications to control lepidopterans. The cost increase may be greater for production systems using Bt varieties than for systems using conventional varieties. In the absence of data that would enable us to model negative yield and cost differences, we truncate the distributions at a 0% difference for yields and costs.[2]

In summary, the simulations in our study include cases where distributions of changes in yield and cost have no effect on the displacement of the supply curve (values equal to zero). In such cases, farmers would potentially be worse off using Bt cotton seed since they still have to pay the technology fee included in the seed price.

3.3 Scenarios

Scenario 1 is the point of reference to which we compare the other four scenarios. In Scenario 1, there is no adoption of Bt cotton in the region because no country in West Africa allows its commercial release. The counterfactual in this scenario is the use of conventional seed with no adoption of Bt cotton in West Africa. On the other hand, cotton-producing countries in the RoW adopt at a constant rate of 20% of cotton area. The 20% RoW adoption is the current global rate of adoption of Bt cotton (James, 2007). Maximum adoption rates are achieved in the RoW in year seven, and the total time simulated is 23 years. For the RoW countries, we assumed a distribution with a minimum technology fee of US$15 per hectare, a most likely technology fee of US$32 per hectare and a maximum technology fee of US$56 per hectare.

[2] This assumption can easily be changed when information becomes available.

Note that these are relatively high estimates of the technology fees to be charged to producers.

In Scenario 2, adoption begins in 2012 in Burkina Faso, followed by other countries three years later. Cabanilla et al. (2005) assumed adoption rates of up to 100% in West Africa given the severity of the lepidopteran problem. We employ a more conservative estimate of 30% as a maximum in each country. If the maximum adoption ceiling value is raised, there is a tendency for the benefits earned by farmers to rise in both absolute and relative terms. In this scenario, the five West African countries choose to use existing varieties that are available in international markets.

In this scenario the distribution of the technology fee for the countries studied in West Africa is the same as for the RoW in Scenario 1 (varying from US$15 to US$56 per hectare). The range reported in the literature is between US$15 and US$80 per hectare (see Falck-Zepeda et al., 2000a,b; Huang et al., 2003, 2004; Bennett et al., 2004). We use a lower 'upper bound' for technology fees than the maximum previously reported. No developer is likely to charge the maximum technology fee in West Africa because the region is a new market and countries have alternative sources (Falck-Zepeda et al., 2000a). Yield advantages are a minimum of 0%, a mode of 20% and a maximum of 40% for the countries of West Africa as well as the RoW. Cost advantages are a minimum of 0%, a mode of 13% and a maximum of 26% in West Africa. For the RoW, cost advantages are 0%, 6% and 12%.

In Scenario 3, countries in West Africa only allow commercialization of Bt cotton varieties developed in West Africa. This implies that existing Bt lines will need to be backcrossed into local varieties before release, thus increasing the time needed to clear regulatory and performance evaluation hurdles. This decision delays the stream of benefits because of a longer process of research and biosafety approval. The research lag extends to six years in Burkina Faso and nine years in the other countries of study. One positive consequence of adapting local varieties is that yield advantages are greater, due to the combined effect of host germplasm and Bt expression. The mode and maximum yield differences have been increased to 25% and 45%. The total period of simulation in Scenario 3 is 24 years.

In Scenario 4, we explore the possibility that farmer unions and marketing associations in West Africa are able to negotiate a lower technology transfer fee. We reduced the technology fee for minimum, mode and maximum values by 40% (to 9, 19 and 34 dollars per hectare respectively). Adoption rates rise to a maximum of 50% as a consequence of the lower price of Bt cotton seed. Other assumptions remain the same as those used in Scenario 3.

In Scenario 5, we allowed for a pattern of adoption, disadoption and readoption in Mali and Benin. This scenario is included to emphasize: 1) the importance of institutional and governance considerations, 2) the effect that ongoing reforms may have on the strength of seed demand, and 3) the vulnerability of farmers to fluctuations in seed-to-product price ratios and farm income. We use this example to illustrate how abrupt policy or institutional changes, by causing fluctuating adoption rates, can affect the size and distribution of the benefits that are generated. Experience has shown that the diffusion paths of new technologies are often irregular (Gouse et al., 2005) rather than smooth and sigmoid as usually assumed. Except for the irregularity in adoption rates, all other assumptions in Scenario 5 are the same as those made in Scenario 3.

The number of iterations was set to 10,000 for Scenarios 1 to 4 and 25,000 for Scenario 5. The higher number of simulations in Scenario 5 was necessary to ensure convergence to a stable state, a result of fluctuating adoption rates.

4. Results

The results are shown in Table 2, expressed in actual and present values of the change in economic surplus due to the introduction of the technology. Burkina Faso has taken the lead in West Africa and has conducted confined field trials of Bt cotton in 2004–2006. Reflecting this fact, this country was assigned a 'first mover' role in our simulations. A leader role translated into a greater potential to capture higher increases in producer surplus. In contrast, gains in consumer surplus are low because West African countries are largely net exporters with low rates of internal consumption. The largest rate of consumption in-country is in Senegal (13% of the total produced), but in absolute numbers the highest consumption of locally produced cotton is in Benin, which benefits from the highest consumer surplus changes in each of the scenarios.

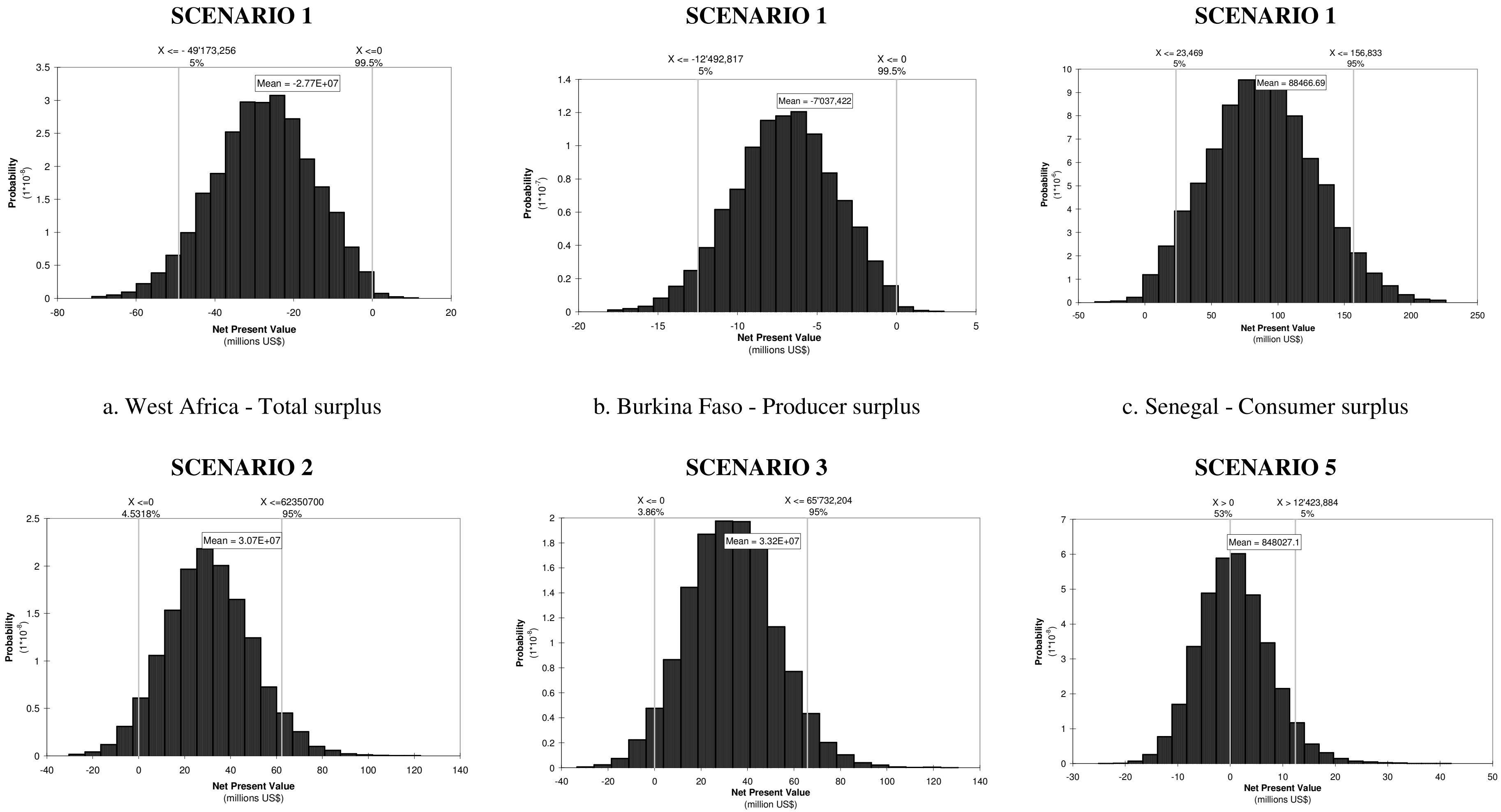
In the reference scenario, West Africa chooses not to adopt Bt cotton while the RoW does. According to Paarlberg (2006) this implies a pre-emptive rejection of GM technologies. Remaining 'GM-free' foregoes any potential benefit of the technology in West Africa. The RoW countries, and particularly cotton producers in these countries, benefit from cost savings and reduced yield damage. Based on the economic surplus model used, adoption of Bt cotton in the RoW results in a decrease in cotton prices, which leads to a reduction in producer surpluses in all five of the West African study countries. Producer losses are not compensated by the positive gains in consumer surplus since domestic consumption of cotton in the study countries is relatively low. As a result, the total change in economic surplus is negative in each of the study countries.

Table 2: Level and distribution of the present and actual value of the change in economic surplus in West Africa and Burkina Faso, by scenario (millions US$)

Actors	Present values					Actual values				
	S 1	S 2	S 3	S 4	S 5	S 1	S 2	S 3	S 4	S 5
West Africa										
Producers	-28.1	30.4	32.9	33.6	20	-77.6	190.5	199.7	208.3	145.9
Consumers	0.5	0.5	0.6	0.6	0.5	1.4	1.5	1.56	1.7	1.5
Innovators	0	47.9	48.	28.8	37	0	219.3	219.3	131.5	188.7
Total surplus	-27.7	78.7	81.1	62.8	58	-76.2	410.9	420.1	341.1	335.7
Burkina Faso										
Producers	-7.0	10.9	13.4	13.8	13.5	-19.3	47.4	56.7	58.6	51.2
Consumers	0.1	0.1	0.1	0.1	0.1	0.4	0.4	0.4	0.4	0.4
Innovators	0	14.8	14.7	8.9	14.7	0	54.9	54.9	32.9	54.9
Total surplus	-6.9	25.7	28.3	22.7	28.3	-19.0	102.6	111.9	91.9	106.5

Note: The values for producer, consumer and innovator surplus do not add up to the value for total surplus shown in the table because the values presented in each cell of this table are the average of the thousands of iterations undertaken in each scenario.

Examples of probability distributions for change in total, producer and consumer surplus are shown in Figures 1a–c in present value terms for Scenario 1. In this scenario (Figures 1a and 1b), there are high probabilities of negative changes in both economic surplus in West Africa as a whole and in producer surplus in Burkina Faso (99.5%). Similar results to the Burkina Faso and West Africa region as a whole, are observed in the other four countries studied. On the other hand, benefits to consumers tend to be positive, depending on how much cotton they demand on domestic markets. For instance, Senegal is a large domestic consumer of cotton (Figure 1c). Thus, the expected increase in consumer surplus in Senegal is positive, with a small probability of a negative outcome.



a. West Africa - Total surplus
b. Burkina Faso - Producer surplus
c. Senegal - Consumer surplus
d. West Africa - Total surplus
e. West Africa - Total surplus
f. Mali - Producer surplus

Figure 1: Distribution of present value of total surplus, West Africa

In Scenario 2, the total variation in economic surplus is positive for the study countries (see Table 2). Not surprisingly, the probabilities of decreases in the present values of the total economic surplus in Scenario 2 (4.53%) in Figure 1d are much lower than in Scenario 1 (99.5%). Although specific results are not reported here, similar results are obtained for a change in producer surplus in Burkina Faso and other adopting countries in the region. Similarly, consumers continue to gain from Bt cotton adoption in West Africa, with only a very small probability (< 0.4%) of loses.

The increase in economic surplus recorded for Scenario 2 in Table 2 masks significant variability at the individual country level. The probability that producer surplus will decrease (downside risk) varies significantly among countries. In fact, the simulations suggest that Scenario 2 generates considerable financial risk for farmers in West Africa. We have assumed a 100% probability of success in the research and biosafety approval processes. Lower probabilities of success (i.e. a longer lag period for biosafety assessments and adaptive R&D) would further increase the financial risk. At the same time, we have assumed high technology fees comparable to those charged globally to farmers, which may not be the case in West Africa. This creates an artificially high downside risk.

In Scenario 3, despite a longer time lag (local Bt varieties), we observe a slight increase in the overall scale of benefits and in the surplus earned by producers and consumers (Table 2). The small increment in benefits with respect to Scenario 2 was 3% overall and 8% for producers in the five study countries. In the case of Burkina Faso, the increment was higher (10% overall and 20% for producers). There are two important implications of these findings. First, the benefits of having appropriate varieties may compensate for the additional time needed to develop them. Second, the benefits from this strategy could be even greater if countries in West Africa succeed in improving the efficiency of the R&D and biosafety regulatory system, thus reducing the time lags.

Total, producer and consumer surplus variation does not change much between Scenario 2 and Scenario 3, nor do the distributions of other outcomes. An example is the probability distribution of change in total economic surplus for West Africa under Scenario 3 (Figure 1e). A very small reduction in the probability of a decrease in total economic surplus is observed in Scenario 3 (3.86%) with respect to Scenario 2 (4.53%). An example at the country level, in Burkina Faso, demonstrates that the probability of obtaining a negative outcome for total economic surplus is reduced from 8.3% in Scenario 2 to 5.8% in Scenario 3. Similar reductions are observed for total, producer and consumer surplus in the other four countries studied. Informal consultations by the authors with regulatory authorities and scientists in West Africa have shown that Scenario 3 is the most likely when considering varietal choice.

In Scenario 4, overall, we observe an increase in the benefits earned by consumers and producers in West Africa, while innovators' benefits decline (Table 2). This pattern results from the lower technology fees paid to the innovators and higher adoption rates.[3] The lesson is that negotiating

[3] Notice that innovators may face two distinct effects from lower technology fees. On one hand, lower fees reduce revenue because the sales price is lower – holding the adoption rate constant. There may also be an increase in the adoption rate as a result of a lower seed price, contributing to higher revenues. Either effect on revenue might outweigh the other.

lower technology fees will have a positive impact on benefits to the cotton sector. Under Scenario 4, the probability of obtaining a negative outcome declines relative to the other scenarios, showing reduced financial risk to the cotton sectors in the study countries.

In Scenario 5, irregular adoption rates in Benin and Mali have a negative impact on both producer surplus and total economic surplus in West Africa as compared to Scenarios 2, 3 and 4. In comparison to Scenario 4, decreased consumer surplus and increased innovator surplus are observed. The probability distributions for producer surplus reveal that disrupted adoption causes a higher probability of a reduction in producer surplus. The probability of decrease in producer surplus can be as high as 50% in Mali (Figure 1f) and Benin. While this probability is lower for Senegal (20%), it still remains substantial. In the other study countries, effects on producer surplus appear to be more a consequence of the time lags assumed in the simulation. In contrast, consumer surplus remains almost unaffected by irregular adoption, because consumers still benefit from the adoption of Bt cotton in the RoW. Note that consumers are mostly located in the RoW.

Table 3 summarizes the average benefits to the various actors in the cotton sector (producers, consumers, innovators) in Scenarios 3, 4 and 5. If we compare Scenarios 3 and 4, we observe that the lower technology fee and greater scale of adoption may have a positive impact for producers and consumers both inside and outside the region. Producers and consumers in all countries are slightly better off in Scenario 4 than in Scenario 3. On the other hand, innovators are worse off. However, these losses do not affect increases in total surplus, which are also high in Scenario 4 (with and without innovator surplus). Comparing Scenarios 3 and 5, we see that producers in Benin and Mali are dramatically affected by irregular adoption patterns. Innovators also have lower returns in these countries when adoption fluctuates, although the returns they earn in Burkina Faso, Senegal and Togo remain stable. Essentially, consumers are unaffected by adoption patterns.

Table 3: Average present values of the change in economic surplus to the cotton sector, by sector actor and country (values in US$)

Country	Producer surplus	Innovator surplus	Consumer surplus	Total surplus without innovator	Total surplus
			SCENARIO 3		
Benin	7,397,656	11,381,600	203,629	18,931,930	7,550,328
BF	13,452,700	14,778,650	139,729	28,303,260	13,524,610
Mali	8,416,729	15,339,090	102,146	23,811,640	8,472,551
Senegal	553,824	1,305,254	91,535	1,904,289	599,035
Togo	3,045,468	5,172,745	20,321	8,192,210	3,019,465
RoW	4,073,093,000	2,794,727,000	1,477,385,000	8,345,204,000	5,550,478,000
			SCENARIO 4		
Benin	7,579,815	6,828,961	223,300	14,581,120	7,752,158
BF	13,789,120	8,867,198	153,230	22,747,890	13,880,690
Mali	8,525,793	9,203,451	112,017	17,794,940	8,591,486
Senegal	560,684	783,151	100,379	1,397,890	614,739
Togo	3,167,267	3,103,650	22,284	6,246,877	3,143,227
RoW	4,441,543,000	2,794,728,000	1,619,545,000	8,855,815,000	6,061,088,000
			SCENARIO 5		
Benin	2,307,335	7,415,446	202,151	9,873,975	2,458,529
BF	13,499,500	14,778,660	138,715	28,349,060	13,570,390
Mali	848,027	9,085,328	101,405	9,988,436	903,108
Senegal	557,971	1,305,253	90,870	1,907,769	602,517
Togo	3,065,317	5,172,746	20,174	8,211,913	3,039,167
RoW	4,078,755,000	2,794,726,000	1,465,509,000	8,338,990,000	5,544,264,000

Note: The values for producer, consumer and innovators surplus do not add up to the value for total surplus and total surplus without innovator shown in the table. Values for all the components of surplus presented in each cell of this table are the average of the thousands of iterations undertaken in each scenario

Table 4 shows the Internal Rate of Return (IRR) for individual countries in Scenarios 3, 4 and 5. The IRR is calculated by estimating the interest rate that would make the sum of the stream of annual net benefits (or Net Present Value) equal to zero. In most cases, although the IRR is higher than the interest rates used in our simulations, it is relatively low compared to estimates of rates of return to technology adoption found in other studies. This result reflects the conservative estimates we employed for the yield and cost advantages of Bt cotton, the relatively high technology fees we assumed, and our consideration of damage abatement as well as yield effects. A consequence of including damage abatement effects is that the average change in producer and consumer surpluses is calculated over positive and negative values.

Table 4: Internal rate of return (IRR) Scenarios 3, 4 and 5 (%)

Country	Scenario 3		Scenario 4		Scenario 5	
	TS	TSi	TS	TSi	TS	TSi
Benin	28	21	25	20	14	20
Burkina Faso	44	32	38	31	32	44
Mali	27	19	24	18	12	18
Senegal	29	19	25	19	19	29
Togo	28	20	24	19	20	28

Notes: 1) TS = Total surplus without innovator surplus, TSi= Total surplus including innovator surplus. 2) Shares have been rounded to next whole number.

Table 5 shows the proportion of benefits from Bt cotton adoption accruing to the various cotton sector actors. When the study countries are considered as a group, producers and innovators earn the largest share of the benefits, while consumers benefit little. Similar patterns have been documented in other studies of Bt cotton (Falck-Zepeda et al., 2000a,b). The situation is not uniform, however, either among countries or among scenarios. In Scenario 3, where West African varieties are backcrossed with private sector varieties, innovators tend to earn a larger share of the predicted surplus than producers. In part, this finding reflects the fact that Scenario 3 spans one more year because of delayed adoption. Given the way the innovator surplus is estimated, the nature of the innovation partnership does not affect the distribution of benefits between innovators and producers. Again, we attribute the partitioning of benefits that is evident in Scenario 3 to the fairly conservative assumptions used in our simulations of the potential farm benefits of Bt cotton in West Africa and our treatment of damage abatement. In Scenario 4, where premiums are reduced, we find the opposite result and producers earn a larger share of benefits. This finding underscores the need to negotiate a technology fee that is consistent with the internal economic situation of each country in West Africa.

Table 5: Percent (%) share of benefits to sector actors, by country, Scenarios 3, 4 and 5

Country	Scenario 3			Scenario 4			Scenario 5		
	PS	IS	CS	PS	IS	CS	PS	IS	CS
Benin	39	60	1	52	47	1	23	75	2
Burkina Faso	47	52	<1	60	39	<1	48	52	<1
Mali	35	64	<1	48	52	<1	8	91	1
Senegal	28	67	5	39	54	7	29	68	5
Togo	37	63	<1	50	49	<1	37	63	<1
5 countries WA	40	59	<1	53	46	1.0	35	65	<1

Note: Shares have been rounded to next whole number.

5. Policy implications

Our findings reinforce the perceived need for decision makers in West Africa to consider whether Bt technology needs to be adopted, if only to 'catch up' with major cotton-producing countries in the rest of the world. Under the assumptions of the model, all of the study countries are made worse off economically by not adopting Bt cotton. The downward pressure on global prices of high adoption rates in the RoW creates the possibility that West African countries will have to adopt the technology just in order to compete in a global market. Nonetheless, even after including the benefits earned by innovators in the calculation, the net benefits of adopting Bt in some scenarios are relatively small.

West African countries need to decide which institutional arrangements can bring larger benefits to the society. Arrangements for developing and transferring technology are key steps in this process. Delivery of the technology by the private sector would mean shorter time lags. The introduction of Bt cotton varieties developed for other conditions has been the market penetration strategy of seed companies in China, Mexico, South Africa and Colombia. The results of this study show, nevertheless, that society benefits most when the Bt gene is transferred to local varieties. This step would require greater participation of the public sector. As has happened in India, the development of public–private partnerships is probably the best option for West African countries.

In published studies on the impact of Bt cotton in countries outside West Africa, a significant share of the expected economic benefits from the adoption of the technology is earned by producers. This finding does not hold for West African countries in our simulations. Here, a larger share of the benefits often accrues to the innovator, except for the scenario in which producers are able to negotiate a reduced technology fee. Still, this finding underscores the need for West African stakeholders to focus on the mechanism for setting the price of the technology, and to consider the full range of options for transferring technology. Seed price, including the technology fee premium, is crucial for the appropriate deployment of the technology (Scenario 4). An example of such a negotiation process is the decision of the Government of India to impose a ceiling on the amount charged to farmers by seed companies for the technology fee. Clearly, a preferred course of action for West Africa is negotiation between suppliers and clients until a notional equilibrium price is reached.

Policies and institutional arrangements in the cotton value chain may also support the continuity of the adoption process in countries, counteracting the fluctuating adoption rates depicted in Scenario 5. There is a need for West African policy makers to address technical, biophysical and institutional issues that could cause disadoption before (rather than after) Bt cotton is released. A drop in producer surplus caused by disadoption affects not only total benefits but also the distribution of benefits, shifting a larger share to the innovator.

Can farmers in West Africa gain from the introduction of Bt cotton technology? Taking into consideration the limitations of this study and the caveats enumerated, there is a real potential for farmers in the region to gain from adopting the technology. Our model suggests that these farmers would lose by not adopting Bt cotton while farmers in the rest of the world benefit. Although we find the changes in economic surplus to be smaller than those previously reported in the literature, we believe that our estimations are relatively robust because the underlying assumptions are conservative, damage abatement effects have been considered, and we have applied stochastic simulation analysis to capture variability.

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References

Ajayi, O, Camara, M, Fleisher, G, Haidara, F, Sow, M, Troare, A & Van de Valk, H, 2002. Socio-economic assessment of pesticide use in Mali. Special Issue Publication Series No. 6. Pesticide Policy Project, Hannover.

Alston, JM, Norton, GW & Pardey, PG, 1995. Science under scarcity: Principles and practice for agricultural research evaluation and priority setting. Cornell University Press, Ithaca and London.

Baffes, J, 2005. The cotton problem. World Bank Research Observer 20 (1), 109–43.

Bennett, R, Ismael, Y & Shankar, B, 2004. Reductions in insecticide use from adoption of Bt cotton in South Africa: Impacts on economic performance and toxic load to the environment, Journal of Agricultural Science 142 (6), 665–74.

Bennett, R, Kambhampati, U, Morse, S & Ismael, Y, 2006a. Farm-level economic performance of genetically modified cotton in Maharastra, India. Review of Agricultural Economics 28(1), 59–71.

Bennett, R, Morse, S & Ismael, Y, 2006b. The economic impact of genetically modified cotton on South African smallholders: Yield, profit and health effects. Journal of Development Studies 42 (4), 662–7.

Bingen, RJ, 1994. Agricultural development policy and grassroots democracy in Mali. African Rural and Urban Studies 1 (1), 57–72.

CAB International, 2001. Crop protection compendium. CAB International, Wallingford, UK.

Cabanilla, L, Abdoulaye, T & Sanders, J, 2005. Economic costs of non-adoption of Bt-cotton in West Africa: With special reference to Mali. International Journal of Biotechnology 7 (1/2/3), 46–61.

Delgado, C & Minot, N, 2000. Agriculture in Tanzania since 1986: Follower or leader of growth. World Bank Country Study. The World Bank and IFPRI (International Food Policy Research Institute), Washington, DC.

Dercon, S, 1993. Peasant supply response and macroeconomic policies: Cotton in Tanzania. Journal of African Economics 2 (2), 157–93.

Elbehri, A & MacDonald, S, 2004. Estimating the impact of transgenic Bt cotton on West and Central Africa: A general equilibrium approach. World Development 32 (12), 2049–64.

Falck-Zepeda, J & Cohen, J, 2006. Biosafety regulation of genetically modified orphan crops in developing countries: A way forward. In Just, R, Alston, J, Zilberman, D (Eds), Regulating agricultural biotechnologies and policy. Springer, New York.

Falck-Zepeda, J, Traxler, G & Nelson, RG, 2000a. Surplus distribution from the introduction of a biotechnology innovation. American Journal of Agricultural Economics 82, 360–9.

Falck-Zepeda, J, Traxler, G & Nelson, RG, 2000b. Rent creation and distribution from biotechnology innovations: The case of Bt Cotton and herbicide-tolerant soybeans in 1997. Agribusiness 16 (1), 1-23.

FAO (Food and Agriculture Organization) Statistics, 2004. Imports and exports of selected agricultural commodities, Group III. FAO Statistics Division, FAO, Rome, Italy. http://www.fao.org/es/ess/yearbook/vol_1_1/pdf/c18.pdf Accessed July 2007.

Fok, M, Liang, W & Wu, Y 2005. Diffusion du coton génétiquement modifié en Chine : leçons sur les facteurs et limites d'un succès. Économie Rurale 285 (Janvier-Février), 5–32.

Gouse, M, Kirsten, J, Shankar, B & Thirtle, C, 2005. Bt cotton in KwaZulu Natal: Technological triumph but institutional failure. AgBiotechNet 7 (134), 1–7.

Hardaker, J, Huirne, R, Anderson, J & Lien, G (Eds), 2004. Coping with risk in agriculture. CABI Publishing, Wallingford.

Hareau, GG, Mills, BF & Norton GW, 2006. The potential benefits of herbicide-resistant transgenic rice in Uruguay: Lessons for small developing countries. Food Policy 31 (2), 162–79.

Huang, J, Hu, R, Meijl, vH & Tongeren, FV, 2004. Biotechnology boosts to crop productivity in China: Trade and welfare implications. Journal of Development Economics 75 (1), 27–54.

Huang, J, Hu, R, Pray, C, Qiao, F & Rozelle, S, 2003. Biotechnology as an alternative to chemical pesticides: A case study of Bt cotton in China. Agricultural Economics 29 (1), 55–67.

ICAC (International Cotton Advisory Committee), 2004. Survey of the cost of production of raw cotton. ICAC, Washington, DC.

ICAC (International Cotton Advisory Committee), 2006. World cotton trade 2005/06. International Cotton Advisory Committee. Washington, DC.

James, C, 2007. Global status of commercialized transgenic crops: 2007. ISAAA Briefs No. 37, ISAAA, Ithaca, NY.

Martin, T, Chandre, F, Ochu, OG, Vaissayre, M & Fournier, D, 2002. Pyrethroid resistance mechanisms in the cotton bollworm Helicoverpa armigera from West Africa. Pesticide Biochemistry and Physiology, 74, 17–26.

Minot, N & Daniels, L, 2005. Impact of global cotton markets on rural poverty in Benin. Agricultural Economics 33 (supplement), 453–66.

Moschini, G & Lapan, H, 1997. Intellectual property rights and the welfare effects of agricultural R&D. American Journal of Agricultural Economics 79 (4), 1229–42.

Ochout, GO, Matthews, GA & Mumford, JD, 1998. Comparison of different strategies for cotton insect pest management in Africa. Crop Protection 17 (9), 735–41.

Oerke, EC, Dehne, HW, Schonbeck, F & Weber, A, 1995. Crop production and protection: Estimated losses in major food and cash crops. *Crop protection* 14 (8), 689–90.

Paarlberg, R, 2006. RABESA regional workshop policy options paper: Toward a Regional policy on GMO crops among COMESA/ASARECA Countries: African Centre for Technology Studies (ACTS), Nairobi, Kenya. http://acts.or.ke/pubs/reports/rabesa_workshop_report.pdf Accessed July 2007.

Pemsl, D, Waibel, H & Gutierrez, AP, 2005. Why do some Bt-cotton farmers in China continue to use high levels of pesticides? International Journal of Agricultural Sustainability 3 (1), 44–56. http://www.earthscanjournals.com/ijas/003/ijas0030044.htm Accessed July 2007.

Pemsl, D, Waibel, H & Orphal, J, 2004. A methodology to assess the profitability of Bt cotton: Case study results from the state of Karnataka, India. Crop Protection 24 (12), 1249–57.

Pray, CE, Bengali, P & Ramaswami, B, 2005. The cost of regulation: The India experience. Quarterly Journal of International Agriculture 44 (3), 267–89.

Pray, C, Ma, D, Huang, J & Qiao, F, 2001. Impact of Bt cotton in China. World Development 29 (5), 813–25.

Qaim, M & De Janvry, A, 2005. Bt cotton and pesticide use in Argentina: Economic and environmental effects. Environment and Development Economics 10 (2), 179–200.

Qaim, M, Subramanian, A, Naik, G & Zilberman, D, 2006. Adoption of Bt cotton and impact variability: Insights from India. Review of Agricultural Economics 28 (1), 48–58.

Quemada, H, 2003. Developing a regulatory package for insect tolerant potatoes for African farmers: Projected data requirements for regulatory approval in South Africa. Paper presented at the symposium 'Strengthening Biosafety Capacity for Development', 9–11 June, 2003, Dikhololo, South Africa.

Silvie, P, Deguine, JP, Michel, NS & Vaissayre, M, 2001. Potential of threshold based interventions for cotton pest control by small farmers in West Africa, Crop Protection 20 (4), 297–301.

Smale, M, Zambrano, P, Falck-Zepeda, J, Gruère, G & Matuschke, I, 2008. Economic impact of transgenic crops in developing countries: A note on methods. International Journal of Biotechnology, (forthcoming).

SWAC (Sahel and West Africa Club) Secretariat / OECD (Organization for Economic Cooperation and Development), 2005. Economic and social importance of cotton in West Africa: Role of cotton in regional development, trade and livelihoods. SWAC Secretariat / OECD, SAH/D(2005)556.

Traxler, G, Godoy-Avila, S, Falck-Zepeda, J & Espinoza-Arellano, JdJ, 2003. Transgenic cotton in Mexico: Economic and environmental impacts of the first generation of biotechnologies. In Kalaitzandonakes, N (Ed.), The economic and environmental impacts of AgBiotech, A global perspective. Kluwer-Plenum Academic Publishers, New York.

Waibel, H, Zadoks, JC & Fleischer, G, 2003. What can we learn from the economics of pesticides? Impact assessment of genetically modified plants. In Laxminarayan, R (Ed.), Battling resistance to antibiotics and pesticides: An economic approach. Resources for the Future, Washington, pp. 137–57).