The success story of Bt cotton in Burkina Faso: a role model for sustainable cotton production in other cotton-growing countries?

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Abstract

The West-African cotton (*Gossypium hirsutum*) industry has a huge economic potential. In particular, Benin, Burkina Faso, Ivory Coast, and Mali play an important role as exporter on the world market. Still, the cotton sector is also subject to a number of risks that can threaten the sustainability of the cotton production in West Africa. This chapter overviews the challenging pest problems and assesses how biotechnology and, more specifically, insect-resistant cotton (*Bt* cotton), overcome these problems. Introduction of *Bt* cotton in Burkina Faso and South Africa resulted in important benefits regarding yield, farmer income, pesticide use, and environmental and health impacts. When structural and institutional limitations are suppressed to realize its full potential, *Bt* cotton can clearly contribute both to the economic and environmental sustainability of the cotton production.

Introduction

Cotton (*Gossypium hirsutum*) is an important industrial crop worldwide and the predominant natural fiber in the textile industry. Despite competition with artificial fibers, cotton remains important and accounted for 30% of the more than 82 million tons of textile fibers processed in 2013 (www.icac.org/tech/Overview/100-facts-about-cotton). In 2000, the world production of cotton was twice that of 1960. Even though the production is subject to fluctuations, it still increases (http://faostat3.fao.org/home) (Figure 1). Farmers produce seed cotton that is processed into cotton lint, mainly for the textile industry to produce fabrics for clothing, furniture applications, or money bills. From the seeds derived from the seed cotton less than 1% is used to plant cotton again (www.icac.org/tech/Overview/100-facts-about-cotton). Cotton seeds are mainly applied in food and feed. The protein-rich seeds can be used as feed for ruminants, but, because they contain the toxic gossypol, they are not suited for consumption as such by humans and monogastric animals. Processing of the cotton seeds yields an edible oil that is suitable for cooking and human consumption as well as additional byproducts utilized in soaps and cosmetics (www.vib.be/en/about-vib/plant-biotech-news/Documents/ BackgroundReport_BT_Cotton.pdf).

Cotton is a subtropical crop and is grown either under irrigation or in sub-humid and semi-arid locations with an annual rainfall between 50 and 150 cm (ECOWAS-SWAC/OECD, 2006). Because of the high vulnerability to insect infestations, cotton is currently grown in a few tropical locations only. In 2013, the top producers of seed cotton were China (18.93 million tons [Mt]), India (18.91 Mt), USA (7.63 Mt), and Pakistan (6.24 Mt) (http://faostat3.fao.org/home). The West-African production levels are quite low (2.35 Mt). Nevertheless, the four main cotton-producing countries in West Africa, Benin, Burkina Faso, Ivory Coast, and Mali, play an important exporter role on the world market. Export of high-quality cotton accounts for approximately 80% of the total production of the entire region. The cotton industry is seen as an important source of economic growth as well as a social safety net for the region, especially in rural areas because it secures farmers' income and generates employment. As a result, cotton is often referred to as 'white gold' (Redifer *et al.*, 2014; Vitale and Greenplate 2014; http://faostat3.fao.org/home).
Despite its economic potential, the cotton industry is also subject to a number of risks, such as price fluctuations of inputs (i.e. fuel, fertilizers, and pesticides) and cotton on the world market, changing weather conditions, and emergence of pests and/or pesticide resistance. All these can threaten the sustainability of the cotton production in West Africa (Redifer *et al.*, 2014, Vitale and Greenplate, 2014). In this chapter, we look at the pest problems that challenge the cotton production and how biotechnology and, more specifically, insect-resistant cotton (*Bt* cotton), can play a role to overcome these problems. Furthermore, we aim to evaluate the contribution of *Bt* cotton to sustainable cotton production in Burkina Faso and South Africa. Specifically reviewing the introduction of *Bt* cotton into these countries, we will take into account the lessons learned and analyze whether it can serve as a role model in other cotton-growing countries in West Africa to increase the sustainability of the cotton sector.

Cotton production sustainability and the role of *Bt* cotton

Cotton production is subject to a number of risks, among which its susceptibility to a wide range of insect pests, such as the caterpillars *Helicoverpa armigera* (cotton bollworm), *Pectinophora gossypii* (pink bollworm), and *Heliothis virescens* (tobacco bollworm), was responsible for the largest eco-

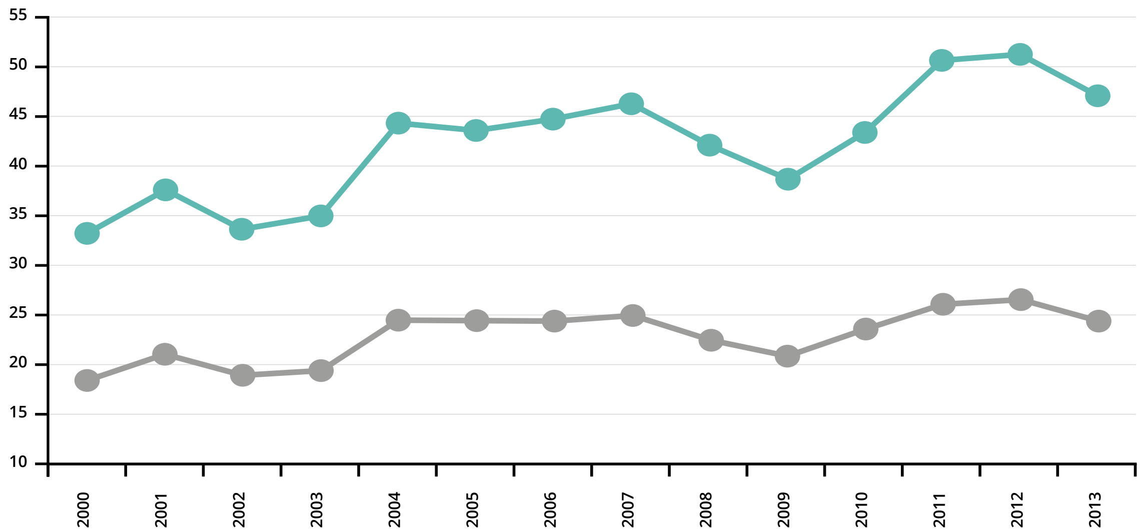

Figure 1. Global production of cotton seed (green) and lint cotton (grey) (M tonnes) (source: FAOSTAT, 2015)

nomical losses before efficient management strategies were put in place (www.cottoninc.com/fiber/Agricultural Disciplines/Entomology/). For West Africa, the cotton bollworm has been reported to be the main threat and to be able to cause up to 90% damage when untreated (Vitale and Greenplate, 2014). The larvae feed on cotton terminals, small squares, such as blooms, large squares, and bolls, provoking important losses (Boyd *et al.*, 2004). As traditional pest control measures have become less efficient, other alternatives have been explored.

The common Gram-positive soil bacterium *Bacillus thuringiensis* (*Bt*) produces crystal (Cry) proteins with an insecticidal activity. Large-scale screening of different *Bt* strains has revealed over 700 *cry* gene sequences, of which some without known invertebrate target, but many effective against insect pests (Palma *et al.*, 2014). More importantly, these Cry proteins that are specific to a limited number of insect species belonging to the orders of *Lepidoptera*, Diptera, Coleoptera, Hymenoptera, Homoptera, Othoptera, and Mallophaga, are not toxic to humans (Bravo *et al.*, 2012). The Cry proteins are ingested as protoxins and processed in the insect gut into Cry toxins, which recognize and bind specific receptors in the insect gut wall, with pore formation (Bravo *et al.*, 2012) or apoptosis (Zhang *et al.*, 2006) as a result. Eventually, the insect dies due to starvation and to bacterial or other infections (www.vib.be/en/about-vib/plant-biotech-news/Documents/BackgroundReport_BT_Cotton.pdf).

As Cry proteins of *B. thuringiensis* are highly effective as well as specific against a number of insect pests, they were used as bioinsecticides already at the end of the 1930s (Schnepf *et al.*, 1998; Bravo *et al.*, 2012), but these commercial preparations that often contained a mixture of spores and crystals were not widely adopted. Inefficiency was high because of the non-optimal spray coverage and because rain showers washed off the pesticides. Moreover production costs were relatively high and the formulation was sensitive to UV degradation (Krattiger, 1997). The plant genetic transformation technology triggered the interest in *Bt* applications because they can bypass these disadvantages: spraying is no longer required, because the crops produce the Cry proteins themselves and, thus, are protected throughout their life cycle (www.vib.be/en/about-vib/plant-biotech-news/Documents/ BackgroundReport_BT_Cotton.pdf). Biotechnology can greatly contribute to agricultural challenges. *Bt*-mediated insect resistance was one of the first commercialized traits, namely in 1995, when the *Bt* potato (*Solanum tuberosum*) resistant to the Colorado potato beetle (*Leptinotarsa decemlineata*) was the first *Bt* crop approved for commercialization in the USA (James and Krattiger, 1996). Since then, the *Bt* trait has been successfully introduced into a number of crops, such as maize (*Zea mays*), brinjal or eggplant (*Solanum melongena*), poplar (*Populus* sp.), potato, and cotton and has resulted in a worldwide adoption. In 2014, 55 million hectares of insect-resistant *Bt* crops were planted (James, 2014). In 1996, *Bt* cotton was grown for the first time in the USA on 1.7 million acres (approximately 688,000 ha). BollgardTM (Monsanto, St. Louis, MO, USA) cotton produced one Cry protein (Cry1A[c]) that conferred resistance against *Helicoverpa armigera* (cotton bollworm), *Pectinophora gossypii* (pink bollworm), *Bucculatrix thurberiella* (cotton leaf perforator), *Trichoplusia ni* (cabbage looper), and *Estigmene acrea* (*Drury*) (saltmarsh caterpillar) (Krattiger, 1997). Since this first successful introduction, biotech cotton has been adopted by many cotton-growing countries and new biotech cotton varieties have been developed, such as herbicide-tolerant (HT) cotton or biotech hybrid cotton that produces two or more *Bt* toxins with different action modes or combined with herbicide tolerance (James, 2014). BollgardII cotton synthesizes two proteins from *Bacillus thuriengiensis:* Cry1Ac and Cry2Ab and was developed by introducing the *cry2Ab* gene into transgenic cotton that already contained the *cry1Ac* gene. These two Cry toxins are recognized by different receptor sites on the midgut wall of the insects. Cry1Ac is effective against *Helicoverpa armigera* and *Helicoverpa punctigera* (Australian bollworm) as well as against *Earias vittella* (rough bollworm), *Pectinophora gossypii*, and some other *Lepidoptera* spp. The addition of Cry-2Ab increases the efficacy by extending the period in which it effectively controls *Helicoverpa* spp. (www.monsanto.com/global/au/products/documents/bollgard-ii-technical-manual.pdf). An additional advantage is that the possibility that a target insect develops resistance simultaneously against the two different Cry toxins will be extremely rare (www.vib.be/en/about-vib/plant-biotech-news/Documents/BackgroundReport_BT_Cotton.pdf).

In 2014, 15 countries, namely India, USA, China, Pakistan, Australia, Burkina Faso, Brazil, Argentina, Paraguay, South Africa, Myanmar, Mexico, Colombia, Sudan, and Costa Rica, grew a total of 25.1 million hectares of *Bt* cotton, constituting 68% of the global cotton planted area (James, 2014). In Africa, *Bt* cotton had already been introduced in 1998 (Gouse *et al.*, 2004), when it had been approved for commercialization in South Africa. It took another 10 years for the first commercial release in Burkina Faso and in 2012, Sudan was the third African country to adopt *Bt* cotton (James, 2014). To date, 73.8% of the cotton planted in Burkina Faso and 80% in Sudan is *Bt* cotton. Even though South Africa grows a relatively low acreage of cotton, the adoption rate of *Bt* cotton is high and reached 95%, whereas the remaining 5% is HT cotton planted as refuge area to manage insect resistance development (James, 2014).

The wide-scale adoption of insect-resistant (IR) cotton has resulted both in a positive environmental and economic impact when compared to conventional farming practices. In 2012, the global farmer income gains from the use of IR cotton have been estimated at US$ 5.3 billion. These gains resulted mainly from increased yields thanks to reduced crop damage, especially in developing countries, but also from decreased input costs, mostly in developed countries (Brookes and Barfoot, 2014). The number of insecticide sprays could be reduced significantly, corresponding to important savings in insecticide-active ingredients: 205.4 million kg cumulatively from 1996 to 2012 or a reduced environmental impact of 28.2% (as measured by the Environmental Impact Quotient). An additional positive effect from using biotech IR cotton is the decreased fuel usage, namely 17 million liters in 2012 (Barfoot and Brookes, 2014).

The cotton industry in Burkina Faso

Cotton was already produced in West-Africa during the colonial period at the beginning of the 20th century. In 1949 under the French administration, the Compagnie française pour le développement des fibres textiles (CFDT) was founded and contributed to the development of the cotton industry (Perret, 2009). The CFDT applied the parastatal industry model: a vertical coordination between producers and company. Under a parastatal structure, the company provides inputs, such as seeds, pesticides, and fertilizers, and technical advice to the farmers. After the growing season, the company buys the yield at fixed prices from the farmers, who in this manner pay off their input credit, and takes up transportation, ginning, and marketing (Theriault and Serra, 2014; Tumusiime *et al.*, 2014).

After independency in the early 1960s, state-owned enterprises set up the parastatal model and promoted cotton production (Theriault and Serra, 2014; Tumusiime *et al.*, 2014). After the independence of Haute-Volta, renamed Burkina Faso in 1984, the CFDT partnered with the government and private investors to found the Sociéte Voltaïque/Burkinabé des Fibres Textiles, abbreviated SOFITEX (Redifer *et al.*, 2014). The cotton production increased as producers gained access to chemical fertilizers, insecticides, herbicides, and improved cotton seeds. Land expansion also contributed to intensify the cotton production (Vitale and Greenplate, 2014), namely from 74,000 ha in 1981 to 406,000 ha in 2003 (Redifer *et al.*, 2014). This was of great importance for the economic development and rural livelihoods.

However, in the late 1990s, the world prices collapsed and the sector faced an economic crisis. The sector was also subject to bad governance and mismanagement. Input credits were given also to non-cotton farmers, even though cotton revenue remained the principal mean to cover the loans. In addition, some farmers sold their inputs on the black market without repaying their loans (Theriault and Serra, 2014). The economic crisis led to structural and market-oriented reforms. The sector was partially liberalized and two new additional ginning companies, Faso-Coton and Société Cotonnière du Gourma (SOCOMA) were established. This however did not result in a price competition between the three companies (Tumusiime *et al.*, 2014) because they each manage their own production zone and retained a parastatal structure. SOFITEX controls the West and approximately 80 to 90% of Burkina Faso's total cotton production, SOCOMA the East, and Faso-Coton the center (Bassett, 2014; Redifer *et al.*, 2014). Market coordination and contract enforcement were improved by installing regional cooperatives restricted to cotton farmers only, whereas a national inter-professional association grouped the unions of the farmers, the Union Nationale des Producteurs de Coton du Burkina Faso (UNPCB; the national cotton producer association or growers' union) and the ginners, Association Professionnelle Des Sociétés Cotonnières du Burkina (APROCOB, the professional association of cotton companies of Burkina) (Theriault and Serra, 2014; Redifer *et al.*, 2014; Vitale and Greenplate, 2014). As a consequence, the involvement of the producers in the companies increased, while the government's role in decision making was reduced (Tumusiime *et al.*, 2014).

Despite these reforms, the cotton production level decreased between 2006 and 2011 (http://faostat3.fao.org/home). One reason is that the costs for fertilizers had increased and simultaneously the cotton prices dropped, imposing a serious pressure on the sector. To tackle these short-term risks, two publicly managed schemes were installed: the "Stabilization Fund" in 2007 and the "Input Fund" in 2012. In short, farmers receive subsidies from the Stabilization Fund when cotton prices are low and funds are returned in years with high cotton prices. The Input Fund ensures that input costs, in particular fertilizers, are affordable by supplying credits at reduced costs (Redifer *et al.*, 2014).

In the last years, Burkina Faso's cotton production has recovered, reaching 766,000 tons in total in 2013 (http://faostat3.fao.org/home), representing 3.5% of Burkina Faso's gross domestic product in real terms. Cotton accounted for 18% of the export earnings in 2013 and 15-20% of the labor income is estimated to derive directly from it (Redifer *et al.*, 2014). Nevertheless on the long term, cotton prices might still continue to drop. Currently, there is a production surplus, resulting in significant stock volumes. The International Cotton Advisory Committee predicts that "Even assuming reasonably lower production and higher consumption in the next few years, it will take several seasons for the significant volume of stocks to reach a more sustainable level, and low cotton prices are likely to persist while the market adjusts" (www.icac.org/Press-Release/2015/PR-1-Low-Cotton-Prices-A-Long-term-Problem#zoneTopWrap). This situation could threaten the sustainability of the cotton sector in Burkina Faso and concerns raise that under continuing low prices producers might shift away to other crops.

Bt cotton introduction in Burkina Faso

Input costs arise not only from the acquisition of seeds and fertilizers, but also from pesticides. In conventional cotton cultivation, farmers typically spray 6 times throughout the season and in Burkina Faso annually the aggregate insecticide costs can roughly be as high as US$ 60 million. In addition, insecticide resistance had emerged in Burkina Faso, with, as a consequence, not only an intensified insecticide use, but also a shift towards broad-spectrum, more toxic insecticides that pose significant health hazards. The decreasing efficiency of the conventional pest control measures triggered the interest of Burkina Faso in biotechnological applications as a new pest control option. In collaboration with Monsanto, two regional Bolgard II varieties were generated. In parallel, the government developed a legal framework to regulate field testing and commercialization of genetically modified (GM) crops. After several years of field trials (2003-2007), the National Biosafety Agency authorized the two *Bt* cotton varieties for seed production and commercialization in 2008 (Vitale and Greenplate, 2014), which were distributed that year by the three cotton-producing companies and planted on approximately 8,500 ha for seed multiplication. One year later, the adoption rate already increased to 29% and reached 70% in 2014 or a total of 454,124 ha, demonstrating the success of *Bt* cotton in Burkina Faso (Figure 2) (James, 2009, 2014).

The parastatal structure of the cotton industry in Burkina Faso facilitated the introduction of *Bt* cotton (Vitale and Greenplate, 2014). The large number of smallholders, approximately 300,000, who grow cotton would result in numerous contracts and agreements under the typical marketing model, but the vertical coordination through APROCOB allowed the upstream introduction of the technology and reduced the number of agreements to enforce the legal compliance and prevent resale and reuse of the *Bt* cotton seeds. In addition, the legal burden was shifted from the producers to the company. The royalties were set up in such a manner that the fee for the Monsanto technology depended on the farmer's income. The gross income is calculated as the value of increased yield plus savings in insecticides and is divided between the farmers (two-thirds) and Monsanto and the seed companies (one-third) (James, 2014). Burkina Faso continues to support *Bt* cotton and a new authorization for 10 years for Bollgard II has been issued in 2013. Meanwhile, other cotton biotech varieties are explored: for example, Roundup Ready® Flex cotton (Monsanto) was in its fourth year of field trials in 2014 and field trials have started with the stacked Bollgard II x Roundup Ready® Flex cotton (ABNE, 2015).

The introduction of *Bt* cotton into Burkina Faso in 2008-2009 has also created a research pool regarding socioeconomic, environmental, and health impacts. Several studies have been conducted over a period of five years (2009-2013) and annually reported to the Agence Nationale de Biosécurité, the National Biosecurity Agency (ANB). The following paragraphs summarize the main findings of these reports (I.R.E. Sanou, G. Vognan, J. Vitale and I. Brants, personal communication).

Yield performance (kg ha^{-1})

In the 2013 growing season, the yield of growers of *Bt* cotton was 14.3% higher than that of conventional cotton growers (Figure 3). Moreover, such yield gain has been observed for each agricultural campaign from 2009 to 2013, albeit with yearly variations that may be essentially due to two factors, namely raining season fluctuations and fertilizer mixtures. Nevertheless, it is clear that cultivation of *Bt* cotton created a substantial yield gain of at least 14%.

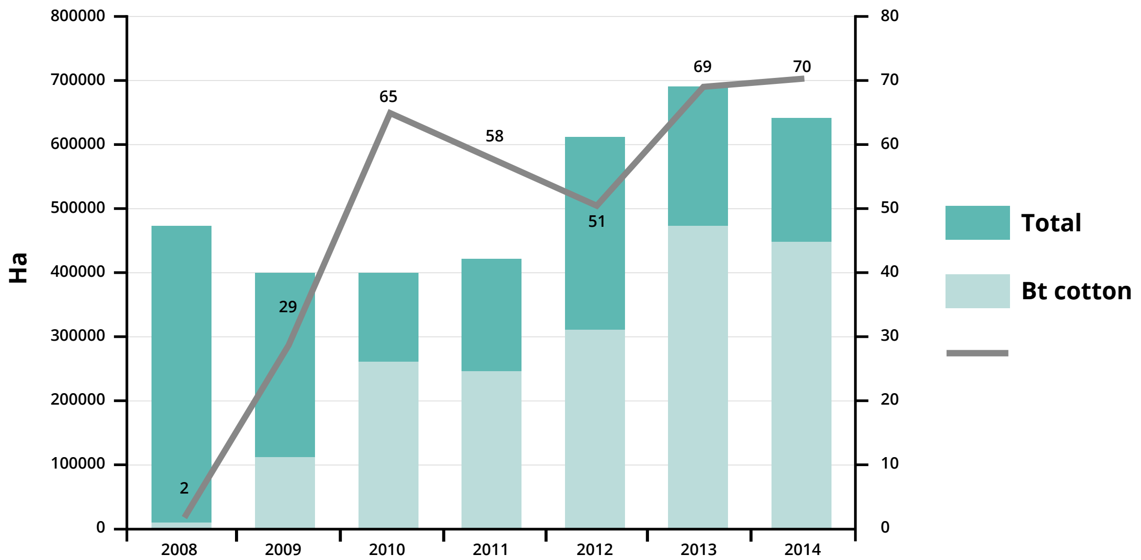

Figure 2. Adoption rate of Bt cotton in Burkina Faso.

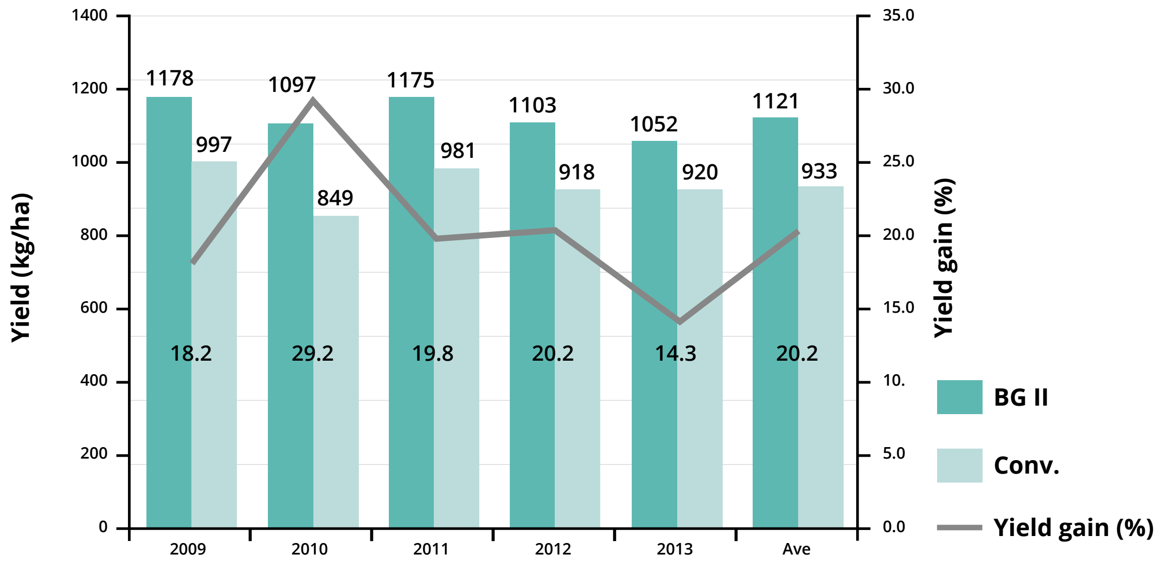

Figure 3. Yield performance (Kg.ha-1); BG II: BGII, Bollgard II (*Bt* cotton); conv., conventional cotton.

Bt cotton profitability (US$ ha-1)

In 2013, analyses indicated that farmers derive the majority of their income from growing *Bt* cotton (on average 63.1%), implying that *Bt* cotton is an economically important crop for the country. For the yearly reports to the ANB, the profitability of *Bt* and conventional cotton has been analyzed by comparison of net incomes, by taking into account the gross income based on yield, the sale price of cotton, as well as the average input costs for seeds, fertilizers, insecticides, herbicides, and labor. The average costs are considered because, besides seed cost, each cost is able to change from one agricultural campaign to another in Burkina Faso. In fact, during each campaign, a dialog framework is instituted between the government and the farmer's organization UNPCB that fixes all prices considering the cotton currency on the international market.

At the end of an agricultural campaign, a *Bt* cotton grower experiences on average a production cost quasi equivalent to a conventional cotton grower (US$ 319 ha-1 to US$ 312 .ha-1) (Figure 4). This insignificant difference in production costs is due to the fact that even though *Bt* cotton farmers have a relevant gain in insecticides treatments, they incur higher seed costs. As a result, the sum of seeds and insecticide costs is approximately the same for *Bt* cotton (US$ 78 ha-1) and conventional cotton (US$ 75 ha-1). Nevertheless, farmers growing *Bt* cotton have a 65.1% higher net income than conventional cotton growers that could be attributed to the yield gains and concurrently increased gross income.

Environmental impact

Bt cotton has been discredited at its adoption time due to the perception of possible environmental risks, but field observations show a clearly positive impact. Since its introduction in 2008, a significant reduction in the insecticide use has been observed (Figure 5) (http://faostat3.fao.org/home) with a beneficial impact on the environment. This reduction results from the reduced annual numbers of sprays from 6 to 2 as recommended to control sucking insects present in the field.

The yearly reports to the ANB also assessed the behavior of *Bt* cotton farmers regarding this recommendation. On average, 1.1% of the farmers do not spray their fields at all, 18.9% once a year, and 80% report to faithfully respect the two sprays. Nevertheless, disregard of the recommended number of sprays is not without consequences on yield performance (Figure 6). Indeed, two insecticide sprays to deal with the secondary insect pests improve yields on average by 17.9% and even 40.7% compared to one and no treatment, respectively.

Specific interviews under the research framework from 2011 to 2013 focused mostly on the identi-

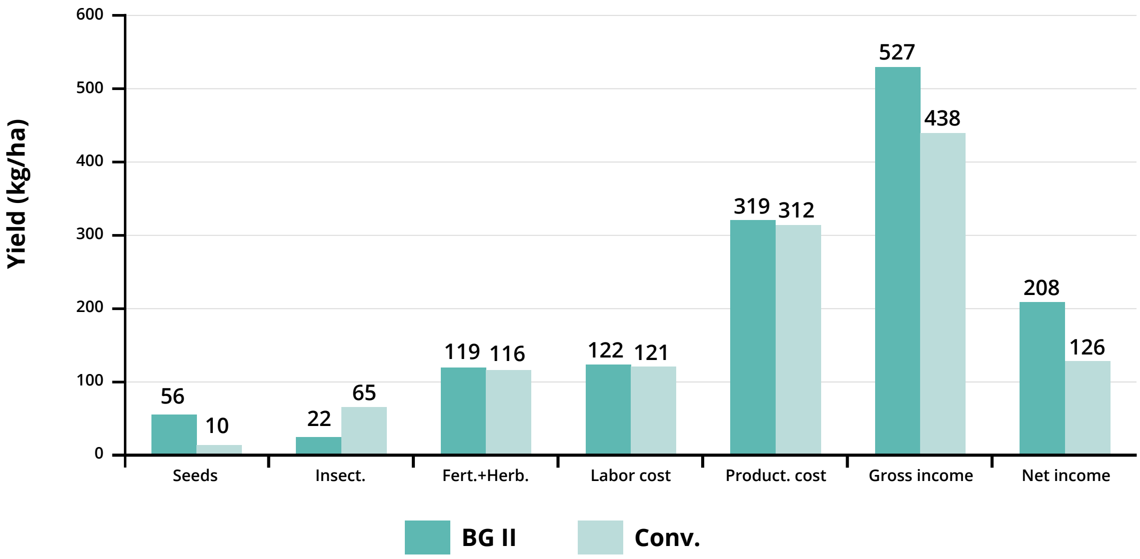

Figure 4. Average *Bt* cotton profitability (US$ ha⁻¹) from 2009-2013. BG II, Bollgard II (*Bt* cotton); conv., conventional cotton; insect., insecticides; fert., fertilizers; product., production.

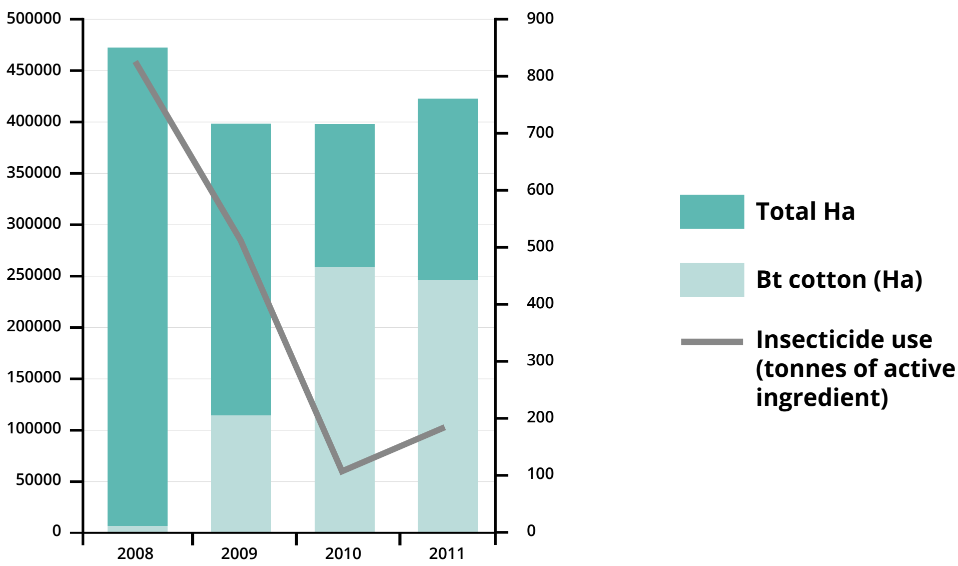

Figure 5. Use of insecticides in Burkina Faso since the introduction of *Bt* cotton in 2008.

fication of beneficial species present in *Bt* cotton fields, such as termites, bees, and ants that have a role in the agroecosystem equilibrium. All farmers interviewed certified the presence of these species. These results match outcomes of *Bt* cotton trials before commercialization, indicating that reduction of insecticide treatments would increase the presence of beneficial organisms.

Health impacts

Field surveys of the Institut National pour l'Etude et la Recherche Agronomiques indicated that over seven growing seasons (2004-2010), 50.8% of the cotton farmers experienced at least one pesticide poisoning incident, despite the extensive services in good management practices provided by the seed companies. Approximately 80.3% of these incidents could be attributed to the application of *Lepidoptera*-targeting insecticides. These incidents have se-

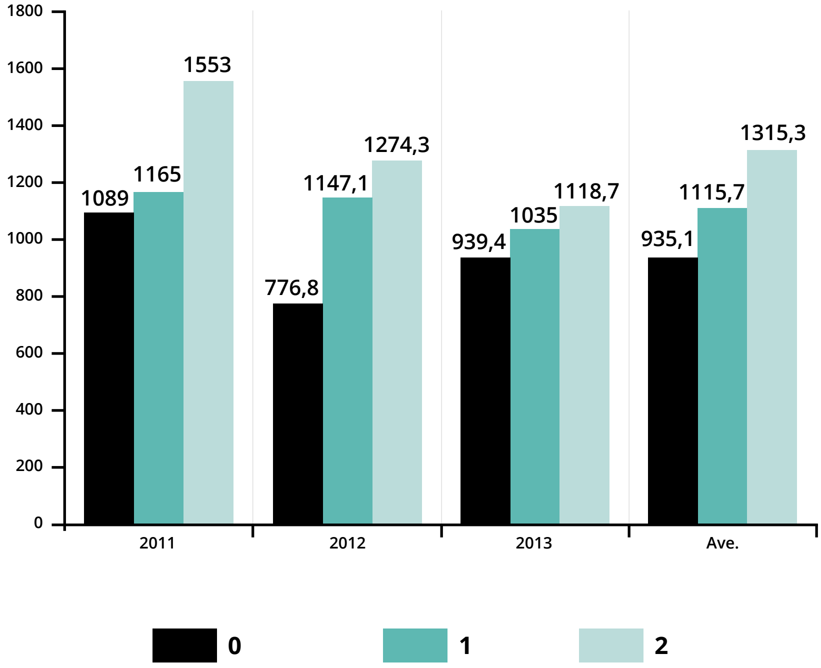

Figure 6. Yield performance (kg ha^{-1}) according to the insecticides sprays in *Bt* cotton fields.

rious health impacts, from symptoms ranging from dizziness to difficult breathing and vomiting and, additionally, they lead to economic losses as well due to medical costs and a loss of income, which have been estimated at US$ 39.22 per incident. However, with the introduction of *Bt* cotton, farmers were able to reduce the number of sprays. The 2011 survey showed a 75% decreased pesticide use for *Bt* cotton farmers, translating into a projected reduction of 30,380 poisoning incidents and a positive economic impact of US$ 1.09 million per year.

In conclusion, both the farmers and the environment have benefitted from the introduction of *Bt* cotton in Burkina Faso, not only by improving the safety of the working conditions but also by an increased net income from the yield gains. The 2011 survey indicated that the reduced pesticide use combined with the enhanced yields were perceived by 63.5% of the farmers as the most important motivation to adopt *Bt* cotton, whereas for an additional 16% the limitation in health risks was the single most important reason.

Bt cotton introduction in South Africa

South Africa planted *Bt* cotton for the first time in 1998. The adoption rate continued to increase and the *Bt* cotton coverage reached 95% in 2007 (with the remaining 5% HT cotton planted as refuge area) (James, 2007). *Bt* cotton was not only adopted by large-scale farmers, but also by smallholders. In the 1998/1999 season, 12% of the cotton-growing farmers in the Makhathini region planted *Bt* cotton. This grew to 40% in 1999/2000, 60% in 2000/2001, and 90% in 2001/2002 (Ismael *et al.*, 2002; Gouse *et al.*, 2005). Studies indicated that the yield increases had the highest impact on the income of both large-scale and small-scale farmers, with the largest yield increases obtained by the large-scale farmers who use irrigation. Furthermore, the reduced number of insecticide sprays additionally result in decreased application costs. Large-scale farmers save on diesel costs and tractor hours, whereas small-scale farmers benefit from labor savings that can be reinvested into other agricultural management practices, such as weeding and harvesting. Together, these benefits generate increased farming income for both groups, despite the high seed costs and additional technology fee (Gouse *et al.*, 2004). Of course, yield benefits can differ from one season to another, because they are also influenced by weather conditions and insect pressure. Analysis indicates that the yield increase from *Bt* cotton is higher during a wet season when insect pressure is higher and the pesticides are washed off by rain than in a dry year without significant yield advantage. Even so, the overall impact is positive and weather-related variation is reduced (Gouse *et al.*, 2005). Besides the economic benefits, the number of insecticide sprayings related to *Bt* cotton plantings had decreased between 1998 and 2001 with a beneficial impact on the environment (Morse *et al.*, 2006). Surprinsingly, this decrease resulted from a reduction not only in pesticides targeting *H. armigera*, but also in the highly toxic pesticides targeting secondary pests. The advantage would be less clear, when the applications of the latter would increase again.

The issue of field-emerging *Bt* resistance and its solution

The main threat to the success of the *Bt* applications would be the development of insect resistance in the field. In the past, the cotton bollworm has been able to adapt to the chemical pesticides, hereby reducing their efficiency. The large-scale exploitation of *Bt* cotton increases the selective pressure and *Bt*-resistant insects have already been observed in the field (www.vib.be/en/about-vib/plant-biotech-news/Documents/BackgroundReport_BT_Cotton.pdf). Field-evolved resistance to Cry1Ac with reduced crop efficacy has been reported in cotton fields in the USA (in 2002) and India (in 2009), both within less than 10 years after their commercialization. In 2005, only 2 years after the commercialization of Cry1Ac and Cry2Ab hybrid cotton, Cry2Ab-resistant insect populations have been detected in the USA, possibly caused by Cry1Ac cross-resistance. Experiments have indeed indicated that resistance to plants that produce two Cry toxins evolves faster when they are grown alongside single-toxin plants (Tabashnik *et al.*, 2013).

It is widely recognized that the level of pest resistance to *Bt* crops will determine their long-term efficacy. Hence, proactive measures have been set up to delay and manage the evolution of pest resistance (Tabashnik *et al.*, 2013; www.vib.be/en/about-vib/plant-biotech-news/Documents/BackgroundReport_BT_Cotton.pdf). The United States Environment Protection Agency imposed a number of IR management practices, with planting of refuge areas as a key component (http://www3.epa.gov/pesticides/chem_search/reg_actions/pip/regofbtcrops.htm). Other measures include monitoring for resistance development or for increased tolerance to the *Bt* protein; education of and increased communication among growers, producers, researchers, and the public; development of a remedial action plan in case of identified resistance.

The refuge approach is based on the assumption that inheritance of resistance is recessive and that mating between susceptible and resistant insects will result in progeny susceptible to the *Bt* toxin(s). The success of this strategy does not only depend on the recessive nature of the resistance, but also on a low initial frequency of resistance alleles and the abundant presence of non-*Bt* host plant refuges. For example, Australia applies a very strict refuge requirement, namely 70% for one-toxin and 10% for two-toxin *Bt* cotton. The resistance frequency in Australia remained below 1% for *Helicoverpa armigera* and *Helicoverpa punctigera* after more than a decade since its first release. In addition, the dose of Cry toxins in *Bt* crops has to be high enough to eliminate more than 99% of susceptible insects under field conditions. This strategy is referred to as 'the high-dose rule' (Tabashnik *et al.*, 2013; www.vib.be/en/about-vib/plant-biotech-news/Documents/BackgroundReport_BT_Cotton.pdf). Indeed, studies on *Bt* maize in South Africa have shown that resistance development to *Busseola fusca* (maize stalkborer) has been enhanced because the crop did not conform with the high-dose requirement. Moreover, this was aggravated by the low compliance to refuge requirements by South-African farmers during the first 5-7 years after release (Kruger *et al.*, 2012; van den Berg *et al.*, 2013).

In theory, combining different *Bt* toxins targeting the same pest into one plant, the so-called pyramids or stacks, significantly lowers the chance of resistance development, but the example described above indicates that resistance develops faster when pyramids are grown alongside single-toxin plants. Resistance can emerge already after two years in the absence of appropriate insect resistance management practices and suboptimal design of the resistance gene(s) (Tabashnik *et al.*, 2013). Nevertheless, under optimal circumstances and when all factors influencing the development of insect resistance are taken into account, *Bt* crop efficiency can be sustained for 15 years or more. Even with the use of *Bt* pyramids, it is absolutely imperative that farmers are informed on and comply with insect resistance management practices when they adopt *Bt* crops to ensure their sustainability.

Bt cotton for the West-African cotton production

Before considering the introduction of *Bt* cotton into other West-African cotton production systems, it will be important to introduce the trait into local varieties adapted to the regional climatic conditions to fully gain the benefits observed for Burkina Faso and South Africa. In addition, the local farmers will need to be trained to implement resistance management practices to ensure a durable crop protection and to avoid or delay the development of insect resistance. When these important factors are taken into account, the examples described above clearly indicate that *Bt* cotton adoption into the cotton production systems is beneficial with regard to yield and farm income, pesticide use, and environmental and health impact.

However, it should be considered that the South-African farmers have been confronted with some limitations, such as difficult climatic conditions, failing credit system, and monopsonistic cotton companies, which can all put pressure on the sustainability of the cotton economy (Gouse *et al.*, 2005; Morse *et al.*, 2006; Witt *et al.*, 2006). Although Burkina Faso reformed its cotton sector, it did not create competition. As a result, world market prices are not always translated into producer prices which in 2011, led even to farmer protests (Bassett, 2014). In contrast, studies have shown that in the absence of a well-functioning credit market, parastatal structures improved growth in the cotton sector (Tumusiime *et al.*, 2014). In Burkina Faso, the reforms tackled the challenges on a global level by establishing a funding mechanism to balance the impacts of seasonal variations in input and/or international cotton prices (Redifer *et al.*, 2014).

In conclusion, it is clear that *Bt* cotton presents important benefits that contribute both to economic as well as environmental sustainability, but the structural and institutional limitations should be addressed appropriately to realize its full potential.

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