Facts Series

Cotton in Africa

VIB International Plant Biotechnology Outreach

Table of contents

Source: *Bruno Tinland, personal collection*

3

Abstract

Cotton represents a crucial source of income in Sub-Saharan Africa, both for rural populations and for national economies. It is one of the most widely produced cash crops grown by African smallholder farmers, ranking only second in value after cocoa. Despite its economic potential, the cotton industry is subject to a number of risks, such as price fluctuations of both inputs and cotton on the world market, changing weather conditions, pest attacks and also problems related to pests becoming resistant to pesticides. All these risk factors threaten the sustainability of cotton production in Africa.

In most Sub-Saharan African countries, yields of 500-700 kg/ha of seed cotton produced under rainfed conditions are typical for varieties with a yield potential close to 3,000 kg/ha. Cotton is subject to damage by an extraordinarily wide range of insect pests, which causes significant losses to cotton production and impacts fiber quality. The larva of the cotton bollworm is the main cotton pest throughout Africa, which can cause damage in up to 90% of bolls when untreated. Due to strong bollworm pest pressure, cotton is heavily sprayed with chemical pesticides. This poses significant health hazards for many farmers and laborers and generates extensive environmental pollution.

In 2014, cotton was planted on 35 million hectares globally, 64% (22.3 million hectares) of which was insect-resistant genetically modified cotton, referred to as Bt cotton. In 2016, a total of 8 African countries either planted, actively evaluated field trials or moved towards grant approvals for the general release of Bt cotton. South Africa was the first country on the African continent to adopt Bt cotton for commercial production in 1998, followed by Burkina Faso in 2008 and Sudan in 2012. In these countries, Bt varieties spread rapidly because they provided a significant reduction of insecticide use and bollworm damage, an increased yield and higher farmer profits, and they allowed conservation of beneficial natural enemies.

However, in 2016, Burkina Faso government temporarily suspended the growing of Bt cotton to address a concern about fiber length observed with the varieties farmers have grown over the last eight years. This decision shows the important role that technology developers and breeders must play in incorporating traits and qualities well-adapted to local conditions in order to meet farmer and market needs.

In Africa, smallholder cotton growers often lack access to productivity-enhancing inputs such as improved seed, fertilizers, water and information. The credit needed to finance investment in these inputs is the major constraint. The implementation of reforms that are in line with local realities that cotton farmers face is required to enhance efficiency in cotton production and to revitalize Sub-Saharan African cotton sectors, while inducing economic growth and alleviating poverty. Donors and governments that invest in the hope that genetically modified crops will bring significant improvements to the livelihoods of resource-poor farmers without first paying attention to the fundamental institutions that support broader agricultural development and technology generation (with or without genetically modified crops) are in danger of misallocating their resources. The local key institutions include those that support public and private capacity for technology generation, technology delivery through markets, extension and regulations, and farmer capacities to demand services, participate in markets and understand the technology they are using.

Facts and figures

Cotton is predominantly a smallholder crop, mainly grown on small family farms of less than 4 hectares in size, and is a crucial source of cash income (60%) for millions of farmers and their families in more than 20 countries across all regions of Sub-Saharan Africa.

Among export crops with substantial smallholder farmer involvement in Sub-Saharan Africa, cotton ranks second in value after cocoa.

During the decade of 2004-2014, the African continent contributed 6% to the world's total seed cotton production (world production was about 1.4 million metric tons).

In most Sub-Saharan African countries, yields of 500-700 kg/ha of seed cotton produced under rainfed conditions are typical for varieties with yield potential close to 3,000 kg/ha.

The larva of the cotton bollworm is the main cotton pest throughout Africa, causing damage in up to 90% of bolls when untreated, leading to lost cotton production.

Half of the insecticides used in Africa are sprayed onto cotton, posing significant health hazards for many farmers and laborers and causing extensive environmental pollution.

In 2014, cotton was planted on 35 million hectares globally, 64% (22.3 million hectares) of which was insect-resistant genetically modified cotton, referred to as 'Bt' cotton.

In 2016, a total of 8 African countries either planted, actively evaluated field trials or moved towards grant approvals for the general release of Bt cotton (Cameroon, Ethiopia, Kenya, Malawi, Nigeria, South Africa, Sudan, Swaziland).

South Africa was the first country on the African continent to adopt Bt cotton for commercial production in 1998. Burkina Faso was the second country to adopt Bt cotton in 2008, and Sudan became the third in 2012.

In 2016, the government of Burkina Faso temporarily suspended the growing of Bt cotton to address a concern about fiber length observed in the varieties farmers have grown over the last eight years.

Smallholder cotton growers often lack access to productivity-enhancing inputs such as improved seed, fertilizers, water and information, and credit needed to finance investment in these inputs is the major constraint.

The implementation of reforms that are in line with local realities that cotton farmers face is required to enhance efficiency in cotton production and to revitalize Sub-Saharan African cotton sectors while inducing economic growth and alleviating poverty.

Cotton, an important cash crop for African smallholder farmers

Cotton and cotton textile industries are central to the economic growth of both developed and developing countries. Cotton cultivation has been an important economic activity for thousands of years across all continents. Cotton occupies a relatively small percentage (3%) of the world's crop acreage, a fact that may seem at odds with the prevalence of cotton in home textiles and clothes. However, cotton is one of the most significant crops in terms of land use after food grains and soybeans (FAOSTAT, 2017).

7

Source: *Bruno Tinland, personal collection*

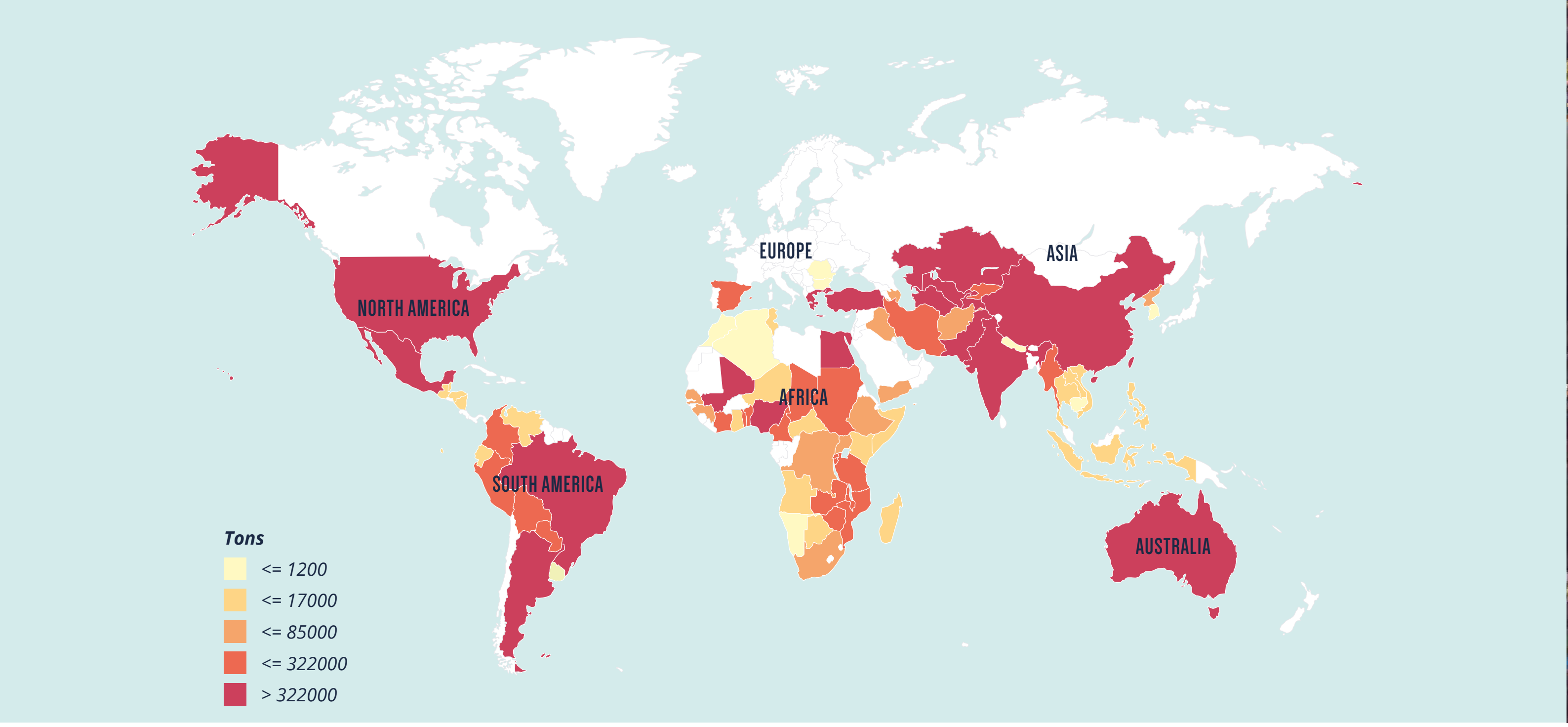


Figure 1.1: *Cotton-producing countries (seed cotton, 2004-2014 average) (source: adapted from FAOSTAT, 2017 and reproduced with permission).*

Cotton is a perennial plant that has been domesticated to grow as an annual crop. Natural acclimatization processes have impacted cotton throughout its history, but exactly when the domestication process began is unknown. Cotton is grown around the world, from the tropics to latitudes higher than 40° (Uzbekistan and Xinjiang Province in China) (Figure 1.1), either as dryland (reliant on rainfall) or as irrigated cotton (requiring supplemental water supply). The basic conditions required for the successful production of cotton include a long frost-free period, a temperature range of 18–32° C and 600–1200 mm of water over the growing cycle, which typically lasts 125–175 days (FAO, 2012). Cotton exhibits a certain degree of tolerance to salt and drought and can therefore be grown in arid and semi-arid regions. However, higher and consistent yield and fiber quality levels are generally obtained with irrigation or sufficient rainfall.

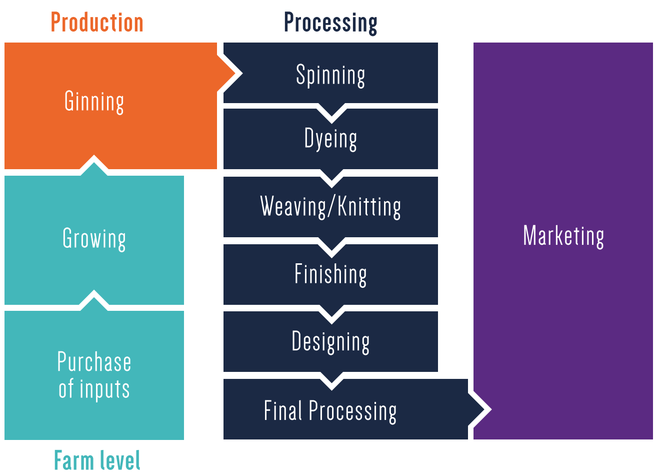


Figure 1.2: *Schematic representation of the cotton textiles value chain (source: adapted from FAO and ICAC, 2015 and reproduced with permission).*

Figure 1.3: *(A) Burkinabe women picking cotton bolls (source: Bruno Tinland, personal collection); (B) spinning cotton into thread by hand; (C) transforming yarns into fabric by weaving.*

Cotton is simultaneously an agricultural product and industrial raw material. The cotton market is one of the most diverse commodity industries worldwide and the processing, transport and by-product industries create significant opportunities for employment to hundreds of millions of farmers and processors (Kooistra *et al.*, 2006). The value chain begins with the farmer, who grows and harvests seed cotton from the bolls of the plant. Cotton production systems range from labor-intensive systems in Africa and Asia to highly mechanized systems in the United States, Australia and Brazil. By weight, seed cotton is composed of roughly one-third cotton lint and two-thirds cottonseed. The cotton lint is separated from the cottonseed (a process known as ginning) using a cotton gin. Cotton lint is then sold to spinners who produce yarn. Textile manufacturers transform yarns into fabric by knitting or weaving the yarns and applying dyes and finishes. In the final stage, end products (garments, home textiles etc.) are made from fabrics (Figures 1.2 and 1.3).

Cotton has hundreds of applications, from blue jeans to soap. Most parts of the plant are useful, the most important being the fiber or lint, which is used to make yarn for cotton cloth. The linters (the short fuzz on the seed) provide, among other products, cellulose for making plastics, explosives and other goods. The cottonseed itself is crushed into three separate products: oil, meal and hulls. The oil is primarily used for cooking oil and salad dressing; the meal and hulls that remain are mainly used either separately or in combination as livestock, poultry and fish feed, and also as fertilizer. The protein-rich seeds can be used as feed for ruminants. Cottonseed contains gossypol, a polyphenolic aldehyde, which can make cottonseed toxic to monogastric animals (e.g. pigs, poultry, fish). In ruminants (e.g. cattle and sheep), it is unlikely that enough cottonseed meal would be ingested to result in the animal suffering from gossypol toxicity (Gadelha *et al*., 2014).

As textile industries grew and became more specialized during the Industrial Revolution at the end of the 18th century, increasing demand was placed on cotton production worldwide. In Africa, the demand for cotton was also a primary driving force of many colonial regimes (Isaacman and Roberts, 1995). This often led to the enforced cultivation of cotton and the disruption of traditional economic and farming systems. Today, although continually threatened by synthetic fibers, demand for cotton remains strong. With a total production of 21 million metric tons of cotton fiber lint during the 2015-2016 growing season across more than 75 countries (the majority in developing countries), the social and economic importance of cotton on a global scale is self-evident (ICAC, 2017).

Cotton is predominantly a smallholder crop. It is grown mainly on small family farms less than 4 hectares in size (Gouse *et al.*, 2003). From 2004-2014, the African continent contributed 6% to world seed cotton production (world production was about 1.4 million metric tons) (Figure 1.4) (FAOSTAT, 2017). Cotton is a major source of foreign exchange earnings in more than 20 countries across all regions of Sub-Saharan Africa and a crucial source of cash income for millions of smallholder farmers and their families. Therefore, the crop is critical in the fight against rural poverty.

Burkina Faso and Mali are by far the biggest cotton producers in Africa (Table 1.1). In Burkina Faso, more than 2 million Burkinabe citizens derive a majority of their income (60%) from producing,

Figure 1.4: *Production share of seed cotton by region (average 2004-2014) (source: adapted from FAOSTAT, 2017 and reproduced with permission).*

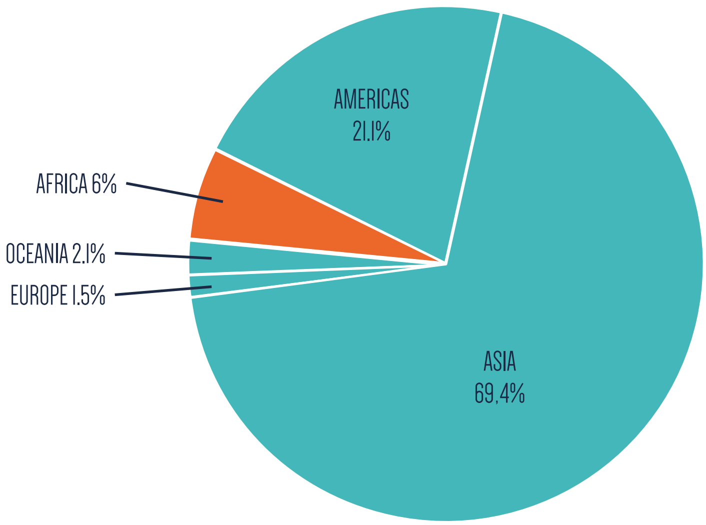


Figure 1.5: *(A) Field cotton and (B) harvested cotton in Burkina Faso (source: Bruno Tinland, personal collection).*

ginning, or transporting cotton (Figure 1.5). Public services such as schools, roads, public health, and a variety of agricultural extension services have traditionally been provided via cotton revenues.

Moreover, studies in Ivory Coast and Zimbabwe have shown a positive synergy between cotton cultivation, on the one hand, and food production and household nutrition, on the other. This is because the income and experience gained through cotton cultivation are applied to the rest of the farm (Sahn, 1990; Govereh and Jayne, 1999). In West Africa, many cotton-producing regions have also experienced significant growth in cereal production because of the development of input provision (i.e. energy, water, fertilizers and pesticides) and the emphasis on agricultural innovation (OECD, 2006). Among export crops with substantial smallholder farmer involvement in Sub-Saharan Africa, cotton ranks second in value after cocoa, and its production is spread across the African continent (FAOSTAT, 2017). In some countries, especially in the Sahel, there is no short- to medium-term cash crop substitute to cotton for smallholder farmers.

Country	Production (tons of lint)	Yield (kg/ha of seed cotton)
Benin	102,600	941
Burkina Faso	256,500	1374
Cameroon	81,000	1250
Chad	48,000	415
Egypt	113,000	3386
Ethiopia	38,000	951
Ghana	5,600	875
Guinea	15,000	977
Ivory Coast	132,000	976
Kenya	4,450	554
Malawi	53,800	644
Mali	232,748	1017
Mozambique	33,000	618
Nigeria	105,000	682
Senegal	11,000	1060
South Africa	8,741	2954
Sudan	95,000	2683
Swaziland	600	508
Tanzania	81,000	790
Togo	37,000	815
Uganda	26,600	1056
Zambia	39,700	963
Zimbabwe	75,000	507

Table 1.1: *Leading cotton producers in Africa in 2014 (source: FAOSTAT, 2017).*

2 Threats to the sustainability of cotton production in Africa

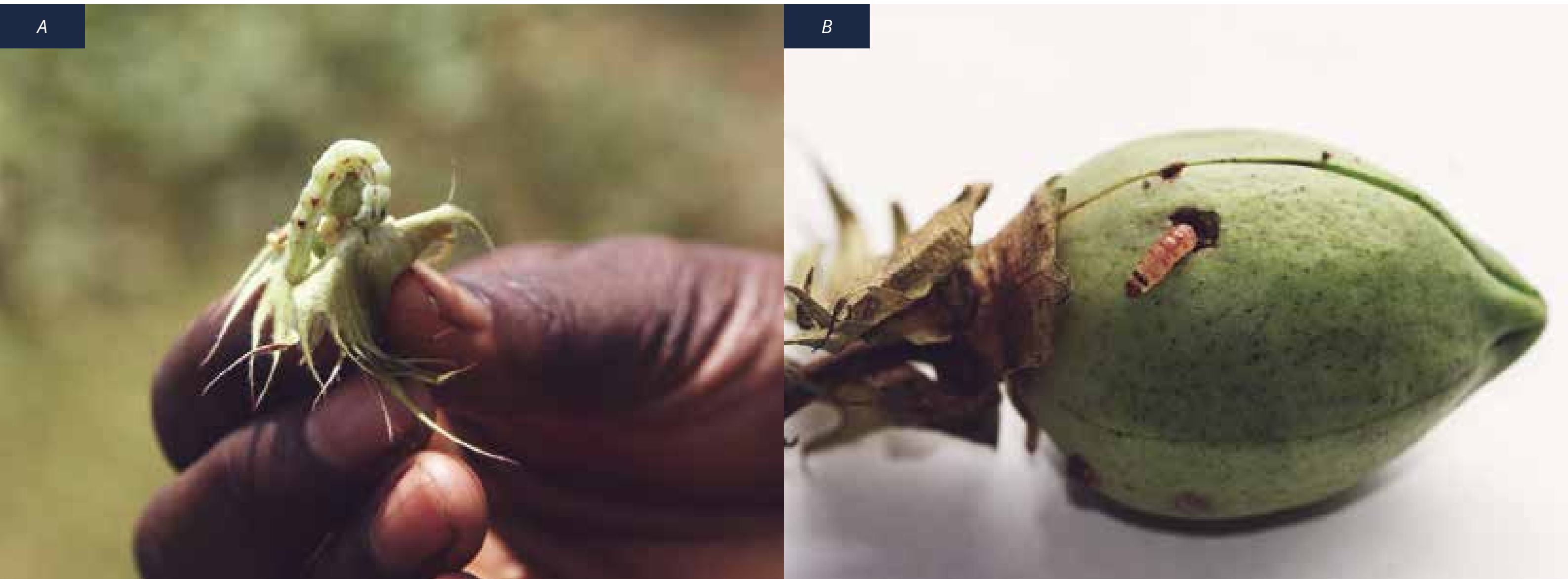
Despite its economic potential, the cotton industry is also subject to a number of risks, such as input price fluctuation, cotton price fluctuations on the world market, changing weather conditions, pest attacks and problems related to pests becoming resistant to pesticides. All these risk factors threaten the sustainability of cotton production in Africa (Vitale and Greenplate, 2014).

Source: *Bruno Tinland, personal collection*

By far the most visible issue related to cotton cultivation, particularly in African countries, has been the relationship between low international prices and domestic support of cotton production. To be specific, subsidies offered by the USA, China and the European Union to their cotton growers cause significant market distortions. In 2003, a group of West African cotton-producing countries (Benin, Burkina Faso, Chad and Mali) has filed a case with the World Trade Organisation asking for the removal of producer support by the USA, China and the European Union (Baffes, 2011). The issue has captured public attention as an example of how protection of agriculture by industrialized countries can affect the livelihoods of producers in developing countries. A study in Benin estimated that a 40% drop in cotton prices (like the one that occurred in 2002) caused an 8% rise in rural poverty, where cotton accounted for 22% of the gross value of crop production in Benin (Minot and Daniels, 2005).

Cotton is subject to damage by an extraordinarily wide range of insect pests, which causes significant losses to cotton production and impacts fiber quality. As extensive areas of cotton have been planted, the call for higher yields and more uniform fiber resulted in monocultures, increasing cotton's susceptibility to pests and diseases. Pests are a significant problem in Sub-Saharan Africa, with climatic conditions favoring multiple pest generations per year and heavy pest densities. About 15% of cotton produced worldwide is lost due to insect attack every year (Oerke, 2006). In West Africa, the numbers are higher, with about 25-35% of cotton lost because of insects (Vitale *et al.*, 2016). Among insects, the larva of the cotton bollworm is the main cotton pest throughout Africa. It has been reported to damage up to 90% of bolls when untreated (Vitale and Greenplate, 2014) (Figure 2.1). Other bollworms vary from country to country and include pink bollworm, tobacco bollworm, spotted and spiny bollworms, and red bollworm. Damage to cotton plants is characterized by feeding activity on squares (flower buds), flowers and cotton bolls. These forms of damage are the most severe, as they destroy the plant's reproductive parts and drastically reduce yield (Abhiyan and Abhiyan, 2012).

Figure 2.1: *(A) Larva of the cotton bollworm (source: Bruno Tinland, personal collection); (B) larva of the pink bollworm (source: Peng Wan, personal collection).*



Large-scale cotton production also has serious environmental consequences. The expansion of cotton in 19th century USA led to widespread erosion and soil exhaustion (Stoll, 2002). Although the widespread use of chemical insecticides for cotton throughout the world has helped farmers producing higher yields, it is also the source of many problems, particularly in developing countries and more specifically in Africa. About a quarter of the world's insecticide use is devoted to cotton and half of the insecticides in developing countries are used on cotton. Several of those insecticides are classified by the World Health Organisation as 'highly hazardous' (Kooistra *et al.*, 2006). In Africa, cotton producers spray about six times per year, although as many

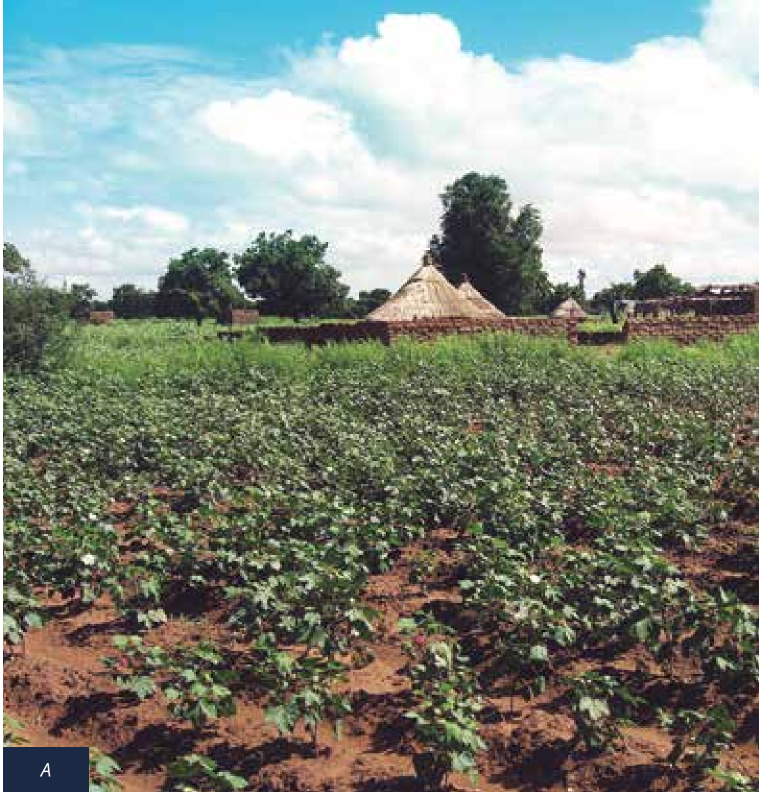


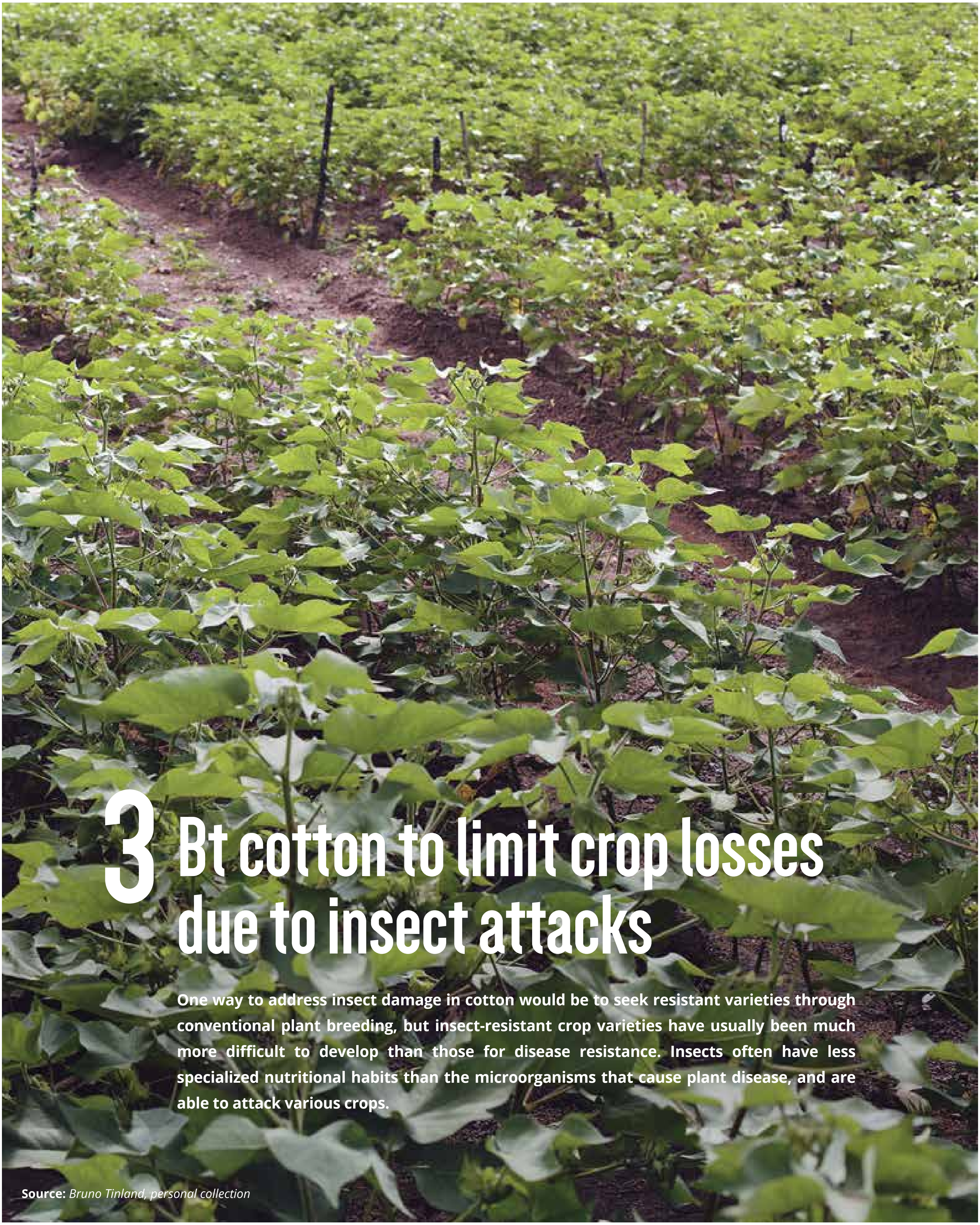
Figure 2.2: *(A) Field cotton of a smallholder farmer in Burkina Faso (source: Karim Maredia, personal collection); (B) harvested cotton being piled up in traditional reed stockage in Benin.*

CASE STUDIES IN CHINA – THE BEWILDERING ARRAY OF COMMERCIAL INSECTICIDE PRODUCTS FROM WHICH FARMERS MUST CHOOSE

In China, the insecticide market consists of many small, local companies. Until mid-2008, China only recognized process-based and not substance-based patents (molecules or any active compound). Thus, manufacturing products based on molecules patented elsewhere has been common. The large number of formulators led to a plethora of products (often mixtures of two or more active ingredients) and farmers face a pesticide market that includes thousands of trade names (Tripp, 2009). Despite the fact that state regulatory agencies monitor the market, there are concerns about the quality of many available products (Meng et al.*, 2006). A survey of 150 farmers in Shandong Province recorded 448 different pesticide products (of which the vast majority are insecticides) used in Bt cotton fields, many of which were not officially registered. In 15% of the cases, researchers were even unable to identify the active component (Pemsl, 2006). Thus, it is a challenge for farmers to distinguish between trusted and fraudulent input sources.*

as ten sprayings can be required. Moreover, the availability and promotion of cheap, low-quality insecticides combined with sub-optimal agricultural practices have led to the emergence of insecticide resistance in a number of pests and the decline or disappearance of natural enemies of cotton pests that formerly helped in maintaining an ecological balance (Tabashnik *et al.*, 2013). In Burkina Faso, cotton yield losses often surpass 30% in fields treated with recommended insecticide applications (Vitale *et al.*, 2016). In addition, the emergence of insecticide resistance triggers intensified insecticide use that poses significant health hazards for many farmers and laborers and is the source of extensive environmental pollution (Kooistra *et al.*, 2006).

In most Sub-Saharan African countries, yields of 500-700 kg/ha of seed cotton produced under rainfed conditions are typical for varieties with a yield potential close to 3,000 kg/ha. With irrigation, cotton farmers can obtain yields of 4,000–5,000 kg/ha with high-yielding varieties (ICAC, 2017) (Figure 2.2). While the world market price for cotton remains low, smallholder farmers who rely on family labor to cultivate their cotton and obtain yields of 600 kg/ha would probably not cover their input cost if labor was included in the calculation of net cost benefit. Under these circumstances, it is not surprising that national annual cotton production varies greatly from year to year in most Sub-Saharan African countries. And, although weather plays an important part in the variation, the farm gate price per kg of seed cotton in the previous season has a strong influence on farmers' decisions to plant cotton the following season. The low yields also reflect the reality that many African agricultural systems are far from best practice (Tripp, 2009).



3 Bt cotton to limit crop losses due to insect attacks

One way to address insect damage in cotton would be to seek resistant varieties through conventional plant breeding, but insect-resistant crop varieties have usually been much more difficult to develop than those for disease resistance. Insects often have less specialized nutritional habits than the microorganisms that cause plant disease, and are able to attack various crops.

Source: *Bruno Tinland, personal collection*

WEST AFRICAN COTTON FARMERS IN A CHANGING WORLD

"Under a clear November sky, a group of West African farmers takes a break from harvesting their cotton. The men survey the crop and dare to hope that the harvest will be better than last year, when drought meant they were barely able to repay their loans for the expensive inputs used to produce cotton. The women participate in the harvest even though some of their own food crop fields still need attention and there are scores of tasks to be done at home. They need a good harvest, because cotton offers one of the few possibilities to earn the cash that is used to pay school fees and buy medicine and other essentials.

In addition to their concerns about the harvest and the price they will receive, these farmers now find themselves at the center of a worldwide controversy about agricultural biotechnology. The news they hear on the radio and in discussions with other farmers is difficult to interpret, and the debates mostly take place in distant locations. The farmers hear there is a new type of cotton that resists some insects and reduces the need to buy insecticides. Some people argue that this will help them save money and keep up with other cotton-producing countries, while others say that it will put them at the mercy of powerful foreign companies and untested technologies." (Quoted from 'Biotechnology and Agricultural Development. Transgenic Cotton, Rural Institutions and Resource-Poor Farmers' by Robert Tripp, 2009)

A major breakthrough in plant breeding for insect-resistance in cotton was achieved only with the use of genetically modified (GM) varieties that produce a protein toxic to specific insects. Indeed, the soil bacterium *Bacillus thuringiensis* (usually abbreviated to 'Bt') produces proteins (for instance, Cry1Ac and Cry2Ab) that are only toxic to some moth and butterfly caterpillars and/or larvae of beetles and mosquitoes. They are harmless to other insects and animals, including humans. Once ingested by, for example, the cotton bollworm, the Cry proteins bind to specific receptors in the lining of the caterpillar's gut, where they create holes and quickly cause death (Höfte and Whiteley, 1989). Bt toxins have been known for a long time and are the basis of a number of commercial insect control products that are particularly popular with organic farmers. In this case, when Bt is used as a spraying agent, it also kills sensitive insects that do not feed on the plant (for more information, see VIB Facts Series issue 'Bt cotton in India'). Moreover, the Bt toxin has a short half-life when placed under field conditions due to degradation by UV light and other environmental factors. Thus, many types of insect larvae may escape control by these products if spray coverage is not optimal, because they are washed off when applied or because the insect is already feeding inside the plant and is thus protected from spraying (Aronson, 1986).

Researchers reasoned that if the gene producing the Bt protein could be inserted into the plant's DNA, the plant could produce its own toxin, killing only the insects that feed on the crop without the need for external insecticide spraying. By the early 1980s, a number of public and private research entities were attempting to produce GM tobacco plants containing a Bt gene. At the same time, there was increased pressure to patent the genes coding for various Bt toxins. Early successes were registered at Washington University in St. Louis and at Plant Genetic Systems, a Ghent University spin-off company in Belgium. Although it was possible to demonstrate the presence of the Bt gene in the GM plants, its insecticidal performance was very modest. When the laboratories of Monsanto discovered in 1988 that the sequence of the bacterial gene needed to be optimized to be compatible with those of plant systems, the resulting insecticidal activity increased significantly (Charles, 2001).

The development of Bt cotton cultivars is similar to conventional cotton breeding, with the exception of the first step involving the insertion of Bt genes. The insertion of the gene of interest is achieved using one of two methods: *Agrobacterium*-mediated transformation and particle bombardment (Potrykus *et al.*, 1998). The biggest drawback to these techniques is the required use of plant cell or *in vitro* tissue cultures to introduce a gene into the plant's DNA. Scientists often choose the American Coker cotton cultivar as the recipient plant because it can recover a plant from tissue culture, which is not the case for most cotton cultivars (Smith *et al.*, 2004). The new gene in the American Coker cultivar can then be transferred to local cultivars of interest through conventional breeding.

Herbicide tolerance was another major development of GM cotton technology, with the goal of producing cotton varieties able to tolerate appli-

Figure 3.1: In vitro *tissue cultures required to introduce a gene of interest into the plant's DNA (A) tissue culture; (B) growth chamber.*

A

cations of particular herbicides. Herbicides have been used for many years in industrialized countries, and increasingly in developing countries, to control weeds (Naylor, 1994). Many herbicides are so-called 'broad spectrum', killing a wide range of plants, and thus must be used before planting or by protecting the standing crop from contact. Herbicide-tolerant GM cotton fields can be treated with herbicide after the crop has emerged. The development of herbicide-tolerant varieties has made conservation tillage even more feasible (Thompson *et al.*, 2007). Conservation tillage is a crop management system that helps prevent erosion and reduces the number of times machines must enter the field. As a result, it lowers costs and reduces the risk of soil compaction. Cotton fields are increasingly planted under some type of conservation tillage, including the use of planting patterns such as 'skip row' that can help reduce down-the-row input costs and improve weed control through the wider distance between cotton rows. Cotton plants next to the skip will compensate by growing larger and producing more fruit (Thompson *et al.*, 2007).

In addition, there are GM cotton varieties with both insect resistance and herbicide tolerance, often referred to as 'stacked' Bt/herbicide-tolerant varieties. In industrialized agriculture, herbicide tolerance is the most important GM trait currently in use. Where stacked cotton varieties are available, they are often more widely used than just Bt or herbicide-tolerant varieties. For instance, 100%, 97%, 95%, 80% and 42% of cotton planted in 2016 was stacked cotton in South Africa, Australia, Mexico, USA and Brazil, respectively (ISAAA, 2016).

B

Development of Bt commercial cotton cultivars and hybrids

After Bt cotton plants have been recovered from tissue culture, a rigorous selection process is undertaken to identify plants with good agronomic characteristics and the highest and most consistent levels of Bt gene expression. The most suitable Bt plants are typically allowed to self-fertilize for a few generations to ensure that inheritance of the Bt gene is predictable and its expression remains stable (Skinner *et al.*, 2004). During this stage, plant breeders may also select individuals with particularly good agronomic characteristics. Another goal of the self-fertilization process is to produce cotton plants that are homozygous for the gene (i.e. plants that have a copy of the gene at the same locus on each homologous chromosome). Homozygous plants are sometimes called 'true-breeding'. The end result of this selection process is a true-breeding Bt cultivar.

This true-breeding Bt cotton cultivar is rarely commercially useful because of its Coker genetic background (Smith *et al.*, 2004). As described above, the American Coker cotton cultivar is suitable for GM methods, but it does not have good agronomic characteristics. To develop a commercial Bt cotton cultivar and eliminate the Coker genetic background, a series of backcrosses are conducted (for more information, see VIB Facts Series issue 'From plant to crop: the past, present and future of plant breeding'). This begins when the Bt Coker line is crossed with an established commercial cultivar (Figure 3.2). The initial progeny expresses the Bt gene, but still contains half of the Coker genes that may confer different characteristics than the ones of the desired cultivar. To purify the new cultivar, this progeny is backcrossed with the commercial parent cultivar. After five generations of backcrossing, about 98% of the undesired Coker genes are replaced by genes of the commercial cultivar. Thus, backcrossing for 5-10 generations eliminates nearly all Coker genes and produces a Bt cotton cultivar that is similar to the original commercial cultivar, except for the presence of the Bt gene (Duck and Evola, 1997). The next step is to self-fertilize plants that bear the newly inserted gene and retain progeny homozygous for the Bt gene. This yields a true-breeding commercial Bt cotton cultivar.

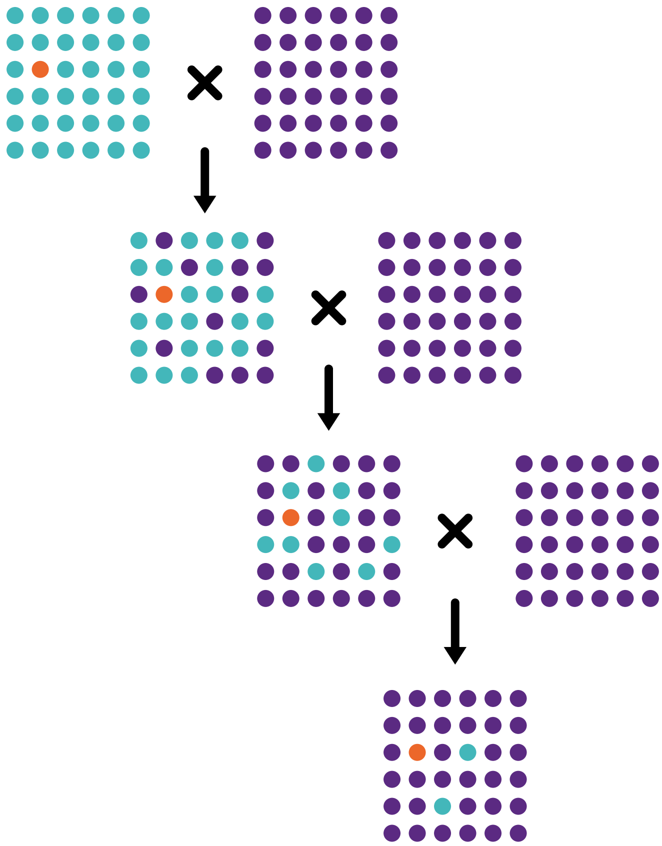


Figure 3.2: *An illustration of a backcrossing scheme aiming to transfer the Bt gene (shown as an orange dot) from one plant (e.g. the Bt Coker cotton cultivar, shown as green dots) to another plant (e.g. an established commercial cotton cultivar, shown as purple dots), while eliminating in the crossing product as many of the undesirable characteristics as possible.*

The development of Bt cotton hybrids can be a valuable option for growers in part because hybrids are often more vigorous than either of their parental cultivars and can increase cotton yield. Consequently, they can be planted at lower densities, saving labor and costs (Dong *et al.*, 2004). The process to develop such hybrids requires an additional step. The true-breeding commercial Bt cultivar (as described above) is crossed with a different cultivar to produce hybrid seed (for more information on hybrids, see VIB Facts Series issue 'From plant to crop: the past, present and future of plant breeding'). Until recently, commercial production of cotton hybrids was difficult to achieve. Because cotton plants mainly self-fertilize, hybrid seed production relies on careful hand pollination, a process that is labor-intensive and potentially uneconomical. Advances in breeding (e.g. inducing male sterility and fertility) have improved the efficiency of this process (Zhang *et al.*, 2000). In 2016, India was the only country that grew significant amounts of hybrid Bt cotton, with approximately 95% of cotton farmers planting and benefiting significantly from Bt cotton hybrids (ISAAA, 2016).

Production of Bt cotton cultivars and hybrids and their seed provision

True-breeding commercial Bt cotton cultivars are grown throughout the world (see table 3.1 below). Seed companies maintain pure lines of their varieties and grow them in carefully monitored fields to obtain subsequent generations of high-quality commercial seed. Most cotton farmers choose to buy fresh certified seed each year (Figure 3.3). Those who choose to save the seed of true-breeding commercial Bt cultivars from their own fields are usually able to preserve the qualities of the cotton variety. However, cross-pollination with other cotton varieties may cause an overall decline in seed quality if it occurs (Heuberger *et al.*, 2008).

In the case of the production of hybrid cotton seed (GM and conventional), seed companies must maintain both parental cultivars and cross the cultivars each year. If the seeds from a hybrid cotton are saved after harvest, they are unlikely to perform as well as the hybrids themselves, because the progeny of the hybrids will exhibit high genetic and phenotypic variation. Hybrid Bt cotton plants contain one copy of the Bt gene, which implies that approximately 25% of saved seeds from hybrids will not carry the Bt gene. Thus, saved seed from Bt hybrid cotton will not provide the same level of protection against insects as the previous year's hybrids (Kranthi *et al.*, 2005). To avoid these problems, hybrid seeds are advised to be obtained from seed companies each season to ensure high performance.

Cotton seed is somewhat more difficult to save from season to season than the seed of most field crops, as mechanical separation of the seed from the fiber is required. This means that farmers must either reserve and buy back a portion of their seed from the ginnery or have access to small, hand-turned gins that allow home processing of the seed. Such seed, even if it is the product of a single harvest, may be quite variable, because cotton is an indeterminate crop in which seed development is not synchronous, but rather spread over a period of time. Today, formal seed production by private and public entities accounts for the majority of farmers' cotton seed. In much of West Africa, seed is provided by parastatal enterprises and farmers have few incentives to save seed

Figure 3.3: *(A) Cotton seeds on the plant; (B) bales of cotton waiting to be exported in Burkina Faso (source: Bruno Tinland, personal collection); (C) cotton seeds after ginning.*

(Figure 3.3). India's strong public seed system has been largely replaced by private companies driven by the opportunity to sell hybrid seed, which farmers have difficulty saving because of the lower performance of hybrid progeny. Until the advent of hybrids, however, there was considerable seed saving. More than half of the cotton sown in India's Punjab was from farm-saved seed as recently as the 1990s (Sidhu, 1999).

Commercialization of Bt cotton in Africa is spreading more slowly than in other cotton growing regions

By 1990, Monsanto had the first experimental varieties of Bt cotton available for testing. The first commercial plantings of Bt cotton took place in 1996 in the USA, Mexico and Australia. Monsanto's first Bt cotton varieties were sold with the trademark Bollgard II® (containing two Bt genes, Cry1Ac and Cry2Ab). Since that time, several other types of Bt insect-resistant cotton have become commercially available (for more information, see VIB Facts Series issue ‘Bt cotton in India’).

Based on the latest FAOSTAT data of 2014 (FAOSTAT, 2017), cotton was planted on 35 million hectares globally, 64% (22.3 million hectares) of which was Bt cotton. A total of 14 countries grew Bt cotton in 2016 of the 26 GM crop countries worldwide (Table 3.1). India accounts for the largest area of Bt cotton in the world, with more than 10 million hectares planted in 2016 (ISAAA, 2016).

By 2016, at least four African countries have at some point in the past placed a GM crop in the market – Burkina Faso, Egypt, South Africa and Sudan. However, due to various political and technical setbacks, only South Africa and Sudan planted biotech crops, including Bt cotton, in 2016. In Egypt, a ban on Bt maize was imposed because of claims on safety problems, while the government of Burkina Faso temporarily suspended the growing of Bt cotton to address a concern about fiber length observed in the varieties farmers have grown over the last eight years (see page 25).

Country	Area (million hectares)
India	10.8
USA	3.7
Pakistan	2.9
China	2.8
Brazil	0.790
Australia	0.405
Argentina	0.380
Myanmar	0.325
Sudan	0.120
Mexico	0.097
Paraguay	0.010
Colombia	0.009
South Africa	0.009
Costa Rica	Only 210 hectares

Table 3.1: *Countries growing Bt cotton in 2016 (source: ISAAA, 2016).*

South Africa was the first country on the African continent to adopt GM crops for commercial production (Gouse *et al.*, 2003). The first field trials of GM crops were initiated in 1989, and South Africa released its first commercial GM crops in 1998 with insect-resistant Bollgard II cotton. The commercial release of Bt cotton was made possible by the Genetic Modified Organism Act of 1997, and, in the 1997-1998 season, a few farmers in the Makhathini Flats grew the variety as a trial. Adoption rapidly expanded following the first commercial release, and by 2001-2002, it was estimated that approximately 90% of farmers were growing Bt cotton. In 2016, 9,000 hectares of Bt cotton were planted, a 25% decrease compared to 2015 due to drought and low global cotton price. All cotton grown in South Africa is GM with 100% stacked Bt/herbicide-tolerant traits (ISAAA, 2016).

Cotton is one of the most important Sudanese crops and was the main foreign exchange earner before the development of a national oil industry. Sudan approved its first GM crop - insect resistant Bt cotton - for commercial planting in 2012, with a single variety under the trade name Seeni 1. Seeni is a Chinese Bt cotton genotype carrying the Cry1A gene from *Bacillus thuringiensis*. Continuous research over the last five years resulted in approval of two new insect-resistant cotton varieties in 2015, gradually increasing the hectarage from an initial launch of 20,000 hectares in 2012 to 120,600 hectares in 2016. In just five years, the country has recorded a 98% adoption rate of Bt cotton by Sudanese farmers. The two new insect resistant cotton varieties from India, Hindi 1 released for irrigated regions and Hindi 2 for rainfed areas, have recorded yields of two to three times those of local non-Bt varieties and significantly higher than the released Bt variety Seeni 1 (ISAAA, 2016).

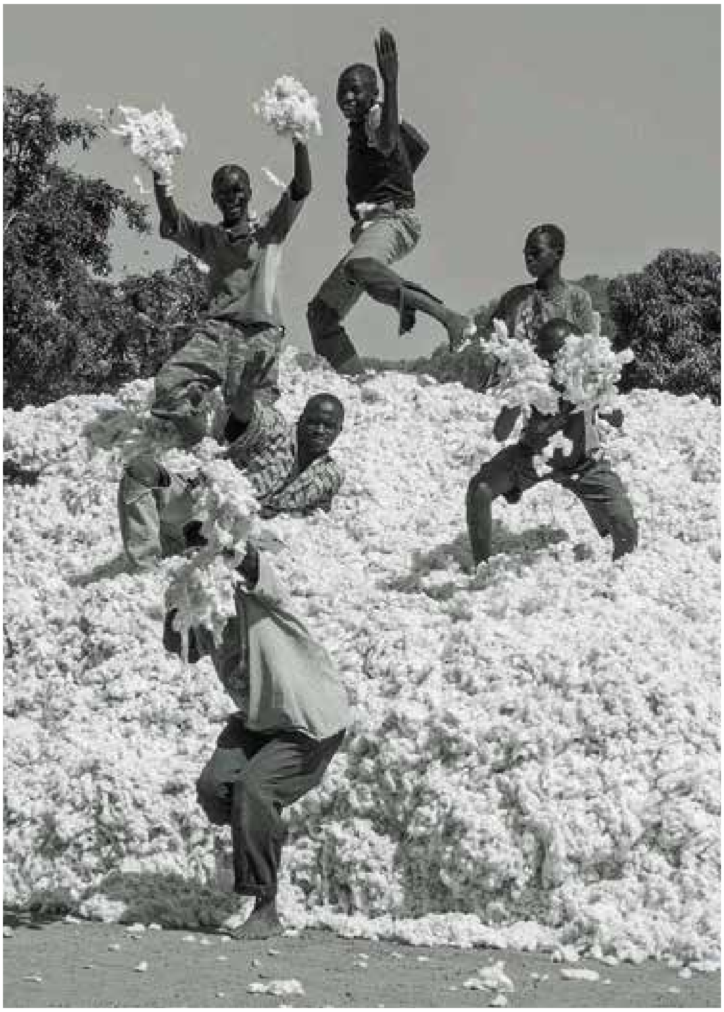


Figure 3.4: *Young Burkinabe farmers playing in cotton lint (source: Bruno Tinland, personal collection).*

At the beginning of the third decade of GM crop commercialization, the drive for research and regulatory support for GM crops in Africa remained focused on food security. Modernization of the agricultural sector to make it more efficient, competitive and adapted to climate change also dominated discussions at the policy level. On the other hand, many African governments prioritized Bt cotton as a strategically important crop to revive the once-vibrant textile industry and tap employment opportunities for young people within the cotton value chain (Figure 3.4)*.

Significant milestones in the GM research and biosafety policy landscape were achieved in 2016 in Africa (ISAAA, 2016). A total of 8 countries either planted, actively evaluated field trials or moved towards grant approvals for the general release of Bt cotton (Table 3.2). Kenya, Malawi and Nigeria moved from conducting experimental research or confined field trials to granting approvals for environmental release (open cultivation). This could lead to commercial planting in the next one or two years, after varietal and national performance trials are completed in different agro-ecological zones where the crops will be grown. Supportive policies are essential to make this happen. Ethiopia and Swaziland conducted multi-location trials in preparation for general release approvals that will take place after suitability is ascertained along various attributes such as yield, level of resistance and lint quality, among other parameters. A general release application for Bt cotton in Cameroon is under way (ISAAA, 2016). Table 3.2 also captures the developments within South Africa and Sudan, which sustained commercial planting of GM cotton in 2016.

** http://farmbizafrica.com/profit-boosters/african-governments-must-prioritize-agriculture-to-drive-inclusive-economic-growth-and-development.*

Country	Trait	Institutions/companies involved	Stage as of December 2016
Cameroon	Insect-resistance / herbicide-tolerance	Bayer Crop Science and SODECOTON (La Société de Développement du Coton)	Application for environmental release in process
Ethiopia	Insect-resistance	Ethiopian Institute of Agricultural Research (EIAR); seeds obtained from JK Agri Genetics-India	Multi-location trials in 6 sites
Kenya	Insect-resistance	Kenya Agricultural and Livestock Research Organization (KALRO), Monsanto	Conditional approval for environmental release; to conduct national performance trials
Malawi	Insect-resistance	Lilongwe University of Agriculture and Natural Resources (LUANAR), Department of Agricultural Research Services (DARS), Monsanto, Quton seed company	General release approved; variety registration trials underway to be planted in 9 sites
Nigeria	Insect-resistance	Monsanto	Approved for commercial release
South Africa	Insect-resistance / herbicide-tolerance	Bayer Crop Science	Trial permit granted
Sudan	Insect-resistance: 2 Indian hybrids 1 Chinese variety SCRC37	Biotechnology and Biosafety Research Center; China-aid Agricultural Technology Demonstration Center, the Sudan cotton company Elfaw	Multi-location trials completed for 3 additional Bt hybrid varieties; approved for commercial planting
Swaziland	Insect-resistance	Swaziland Cotton Board, JK Agri-Genetics	Confined field trials approval granted

Table 3.2: *Ongoing GM cotton research activities in Africa by December 2016 (source: ISAAA, 2016).*

What happened with Bt cotton in Burkina Faso?

Burkina Faso has emerged as one of the leading adopters of agricultural biotechnology in Sub-Saharan Africa. The introduction of Bt cotton in Burkina Faso corresponded with a severe crisis in the cotton sector. In the mid-2000s, a weak US dollar, high input costs, considerable cotton subsidies in the developed world and a declining world cotton market price all contributed to severe problems in West African cotton sectors. The adoption of Bt cotton in Burkina Faso took also place in the context of a severely underfunded public agricultural research sector. Burkina Faso's main research center INERA (Institut de l'Environnement et Recherches Agricoles) mostly relies on funds from the cotton sector to perform cotton research activities including cultivar selection and seed propagation. In addition, insecticide resistance had emerged in Burkina Faso and, as a consequence, the efficiency of conventional pest control measures has decreased. It is within this context that Bt cotton represented a potential benefit as a new pest control option for the struggling Burkinabe cotton sector.

The Burkinabe government developed a legal framework to regulate the field testing and commercialization of GM crops. After several years of field trials (2003-2007), the National Biosafety Agency authorized Bt cotton for seed production and commercialization in 2008 (Vitale and Greenplate, 2014). A key feature of this decision allowed INERA to cross

Monsanto's Bollgard II® Bt cotton with two locally used cultivars (Traoré *et al.*, 2008). This resulted in the domestic production of Bt cottonseed and improved the adaptability of Bt cotton to local growing conditions. By 2014, the adoption of Bt cotton had already approached 80%. 2015 was the eighth year that farmers could grow Bt cotton in Burkina Faso. A total of 350,000 hectares of a total cotton planting area of 700,000 hectares, or 50% of the total land available, were planted with Bt cotton. This represents a 23.8% drop in Bt cotton adoption from the 73.8% in 2014 (James, 2015). The anxiety created by two coups in a span of one year, subsequent government transitions, along with high Bt seed prices and governance issues including corruption and late payments may have persuaded cotton producers to reduce the size of their Bt cotton fields (Dowd-Uribe, 2014). Furthermore, a concern raised among seed producers, ginners and Burkinabe farmers over cotton fiber length led to some uncertainties. Specifically, some ginners

Figure 3.5: *Cotton lint in Burkina Faso (source: Bruno Tinland, personal collection).*

reported declines in both fiber length and ginning ratios (percentage of fiber per unit weight of cotton delivered to the gin) in Bt cotton compared to some historical conventional cotton varieties. This decline in staple length has undermined the reputation of Burkinabe high quality cotton, and cut into its value on the international market (Figure 3.5).

When coupled with the decline in overall lint due to the lower ginning ratio, the inferior quality characteristics of the Bt cultivars have compromised the economic position of Burkinabe cotton companies (Dowd-Uribe and Schnurr, 2016). As a consequence, Burkina Faso has put a temporary halt on Bt cotton in 2016 to address the short fiber length issue. Some options are potentially promising and, if confirmed, might be available commercially by 2018 (James, 2015). The Inter-Professional Cotton Association of Burkina (AICB) and the government reaffirmed their commitment to biotechnology and gave an assurance that the concern was not with the technology Bollgard II®, but with the short fiber length resulting from insufficient backcrosses realized to introgress the Bt gene into local varieties*. Breeders and other stakeholders are currently working towards addressing this technical issue within the shortest time possible to restore the Bt cotton program in the country.

A significant lesson learned from Burkina Faso's case is the important role that technology developers and breeders must play in incorporating traits and qualities well-adapted to local conditions in order to meet farmer and market needs. The failed breeding program in Burkina Faso may also call into question the potential for combining GM technology and local cotton cultivars, and for investing in such long research and development efforts to produce new technologies that offer desired performance across multiple criteria (Dowd-Uribe and Schnurr, 2016).

** http://www.biotechburkina.org/aicb-restates-support-to-gm-technology-but-acknowledges-that-farmers-will-feel-heat-of-temporary-bt-cotton-suspension/*

4 Lessons learned from experiences in early-adopting Bt cotton countries worldwide

Many articles have underlined the success of Bt cotton at reducing insecticide use, boosting yields, and increasing profits for millions of smallholder producers. Examples of this success originate in the two largest Bt cotton growing areas of India and China, and in Africa, with South Africa and Burkina Faso (Krishna and Qaim, 2012; Pray *et al.*, 2002; Morse *et al.*, 2004; Pertry *et al.*, 2016; Vitale *et al.*, 2016). In these countries, the cotton sector is largely dominated by smallholder farmers, who benefit from Bt technology adoption in the form of higher incomes and low exposure to health hazards associated with insecticide sprays. Other studies, however, questioned this unmitigated success. They demonstrated that though in many cases smallholder producers in the global south benefit from Bt cotton adoption, outcomes can be variable and success depends on a mix of institutional, socio-economic, and agro-ecological factors (Glover, 2010; Dowd-Uribe, 2014).

Source: *Bruno Tinland, personal collection*

Comparing the results (yields, income) of those farmers who use the Bt technology and those who don't is not straightforward. Agricultural seasons are characterized by great variability (in rainfall, insect populations, etc.). Thus, the results from any one year may not be representative. In addition, the farmers who are the first to adopt a new technology may have other practices or resources that set them apart from their neighbors, making a side-by-side comparison problematic. Moreover, the adoption of a new technology may be so rapid that there are few farmers left to serve as a control group. Another factor can even be that farmers cultivating conventional crops might benefit from their neighbors cultivating GM crops, as this might create a lower insect pressure in the region. Finally, a technology such as Bt insect-resistance is not so much yield-enhancing as yield-protecting. Its efficacy will depend on the level of pest attack and the use of other pest control practices (Liu *et al.*, 2015). All of these factors can be addressed to some extent by careful survey and statistical methods. Nevertheless, one must be aware that this type of impact assessment is an imperfect process and assumptions should be taken with care.

Changes in yield and insecticide use

The majority of the aforementioned articles indicate gains from the use of Bt cotton in terms of reduction in insecticide use and/or yield increase and/or lower production costs. The global farmer income gains from the use of Bt cotton during the 20-year period from 1996 to 2015 have been estimated at USD 52 billion (ISAAA, 2016). These gains mainly resulted from increased yields thanks to reduced crop damage, especially in developing countries, but also from decreased input costs, mostly in developed countries (Pertry *et al.*, 2016). Since 1996, the use of insecticide and herbicide on the global GM crop area has fallen by 618.7 million kg of active ingredient (an 8.1% reduction) - most of it due to lower insecticide use - relative to the amount expected if this crop area had been planted with conventional crops (Brookes and Barfoot, 2017). The environmental impact associated with insecticide and herbicide use on these crops was reduced by 18.6% (as measured by the Environmental Impact Quotient) (Brookes and Barfoot, 2017) (Figure 4.1).

Figure 4.1: *(A) Bt cotton that displays no damage from insect attacks (source: Karim Maredia, personal collection); (B) workers spraying conventional cotton fields in Zimbabwe.*

In Burkina Faso, the large-scale adoption of Bt cotton has resulted both in a positive economic and environmental impacts when compared to conventional farming practices. By 2014, the adoption of Bt cotton was approaching 80%, the level considered by many in the production literature as the long-term upper limit of new technology adoption (Figure 4.2). Using data from six years of farm surveys (2009-2014), Bt cotton was shown to have significantly and consistently outperformed conventional cotton yields in each of the six years of commercial production (Figure 4.3). Bt cotton cultivation required approximately two-thirds less insecticide than conventional cotton and reduced farm labor allocated to spraying (Vitale *et al.*, 2016). A reduction in insecticide use resulted from the reduced annual numbers of sprays from 6 to 2. Two sprays are recommended to control sensitive insects still damaging the crop (Pertry *et al.*, 2016) (Figure 4.4).

Figure 4.2: *Hectarage (bars) and adoption rate of Bt cotton in Burkina Faso (in %: orange line) (source: adapted from Pertry* et al.*, 2016).*

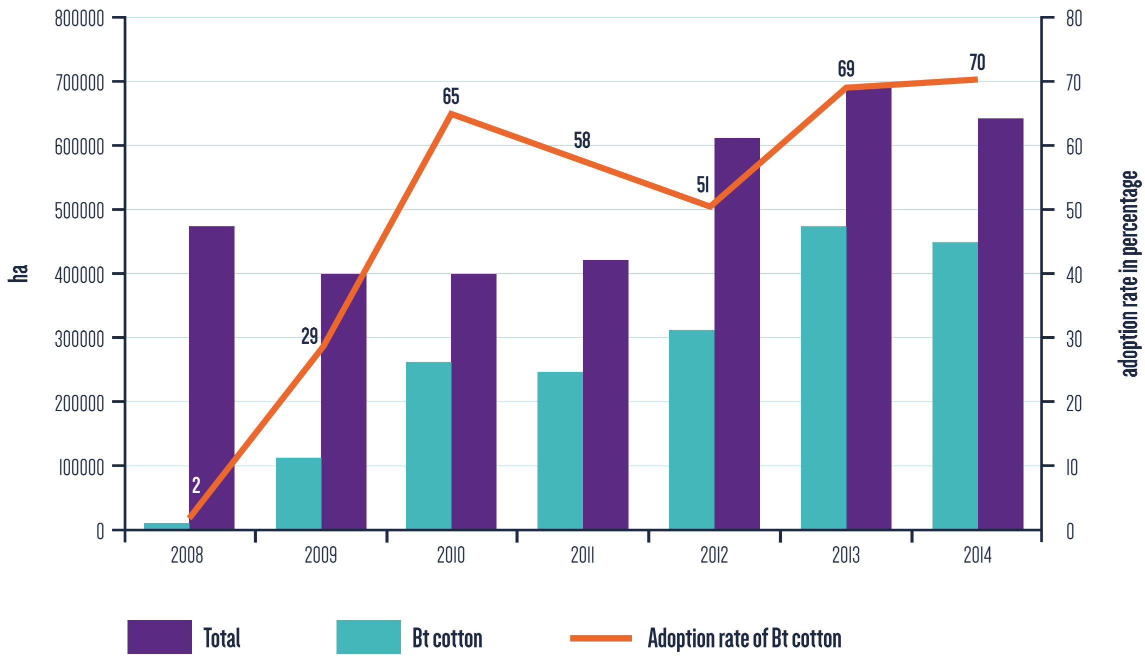
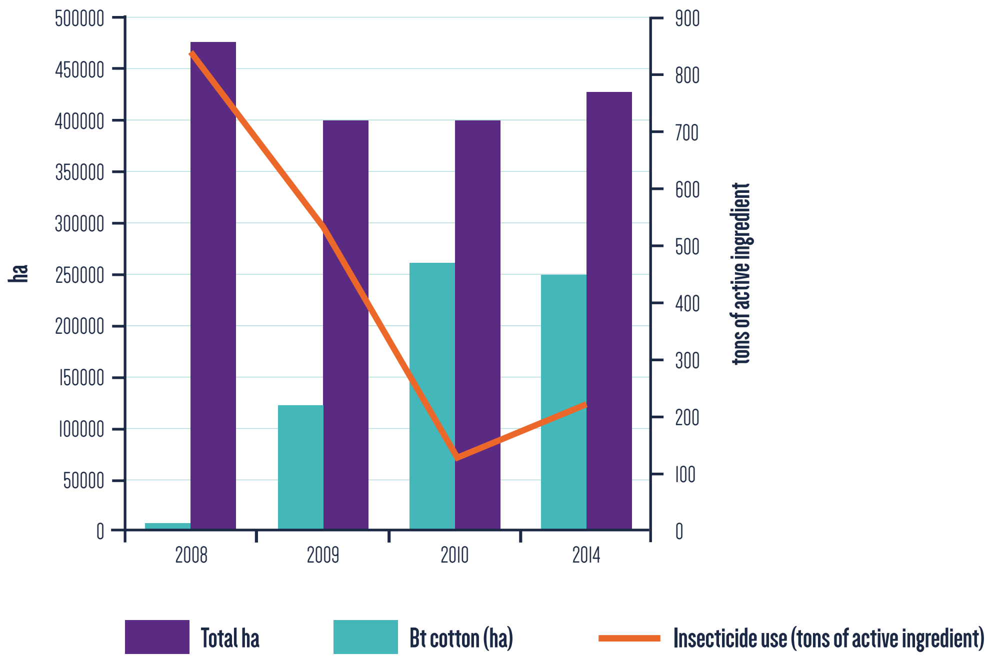


Figure 4.3: *Comparison of Bt cotton (BGII: Bollgard II) versus conventional cotton (CV) yields in Burkina Faso (source: adapted from Vitale* et al.*, 2016 and reproduced with permission).*

Figure 4.4: *Use of insecticides (orange line) in Burkina Faso since the introduction of Bt cotton (source: adapted from Pertry* et al.*, 2016).*



If we look at China and Australia, which contain some of the world's largest Bt cotton growing areas, the adoption of Bt cotton has also resulted in markedly lower insecticide use, but only modest yield increases (Qaim and de Janvry, 2005; Pemsl, 2006). While Chinese cotton yields were already among the world's highest, it is also important to note that the significant instance of insecticide reduction due to Bt cotton responded in fact to a situation where farmers' excessive use of insecticides had created a treadmill of growing insect-resistance and ever-increasing dependence on chemicals. Although the quantities of insecticide used on Bt cotton are now much lower in China, they are still among the highest in the world and include substantial insecticide use for bollworm late in the season (Qiao, 2015).

In countries such as South Africa where both large and smallholder farmers have access to Bt cotton, there are differences in resources and management practices between the two groups which may lead to different impacts. Large-scale cotton farmers reported insecticide and application cost savings and peace of mind about bollworms as the major benefits of Bt cotton. Smallholder farmers indicated financial savings on insecticides and yield increases as the major benefit and reason for adoption of Bt cotton (Gouse *et al.*, 2003). It was also shown that South African smallholders generally underuse insecticide and that, in this case, the Bt technology is more yield-increasing than insecticide-reducing. If farmers do not have the knowledge or resources to apply effective insecticides, the adoption of Bt cotton sometimes has as much (or more) of an impact on yields as it has on insecticide use (Shankar and Thirtle, 2005). In those regions of the world where chemical insect control alternatives are inadequate or not available, the yield impact of a crop like Bt cotton will be highest (Qaim and Zilberman, 2003).

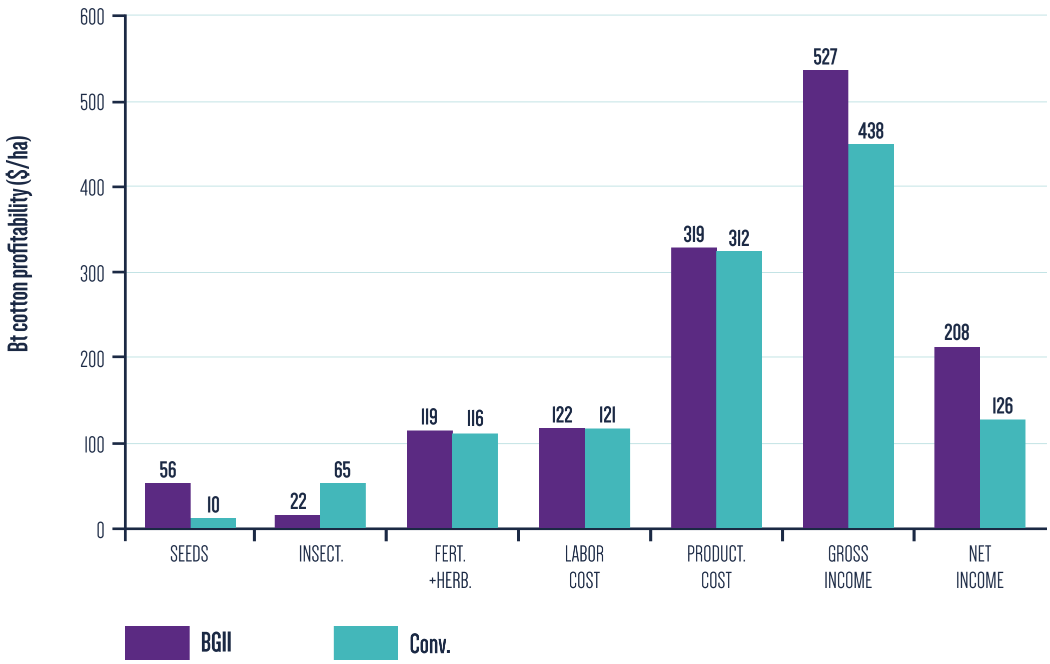
In Burkina Faso, farm size was not found to be a deterrent to Bt cotton adoption. A study based on six years of farm survey data showed that, on a relative basis, farms of all sizes benefitted equally from growing Bt cotton, though larger farms were found to be more productive and generated larger absolute benefits from Bt cotton (Vitale *et al.*, 2016).

Technology costs need to be considered and their impacts can be variable

The benefits of yield gains and reductions in insecticide use are welcome, although the net economic impact depends to a great extent on the technology cost. In cases where this is high, the financial gains are sometimes less than expected.

Owners of a technology want to earn as much as possible from their innovations in order to recover their investments and allow further research and expansion. The normal price for the seed is levied with a 'technology fee' as a separate transaction that in effect licenses the gene to each farmer (Charles, 2001). Consequently, in South Africa, for instance, Bt seeds are about three times as expensive as non-Bt seeds. A Bt cotton grower in Burkina Faso experiences on average a production cost quasi equivalent to a conventional cotton grower (319 USD/ha to 312 USD/ha, respectively) (Pertry *et al.*, 2016). This was calculated over a period of five years (2009-2013) by considering 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. This insignificant difference in production costs is due to the fact that even though Bt cotton farmers have a relevant gain in fewer insecticide treatments, they incur higher seed costs. 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 (Pertry *et al.*, 2016) (Figure 4.5).

Figure 4.5: *Bt cotton profitability ($/ha) average over 2009-2013. BGII: Bollgard II (Bt cotton); Conv.: conventional cotton; Insect.: insecticides; Fert.: fertilizers; Product.: production (source: adapted from Pertry* et al.*, 2016).*



Similarly, a study in four Indian states showed that although Bt cotton led to a significant decrease in insecticide expenditure, the high cost of the Bt seeds eliminated this saving. The majority of farmers experienced an increase in net revenues only because of higher yields from the Bt cotton (Qaim *et al.*, 2006). Many Indian cotton farmers are used to paying relatively high prices for cottonseed because of the prevalence of hybrid seeds in the market. Since hybrids are often more vigorous than either of their parental cultivars and can increase cotton yield, the amount of hybrid seed needed to plant a hectare is much less than with non-hybrid seed. Thus, the impact on costs of production is not nearly as great as the seed price comparison would indicate. In China, there is a great diversity of Bt technology and cotton seed sources (public and private, legal and illegal) making it particularly difficult to determine seed price. In 2006, for instance, although the official price for seed containing the Bt gene was approximately USD 10/kg, Bt cotton seed was available for as little as USD 2/kg (Pemsl, 2006).

Cotton is a demanding crop in terms of crop husbandry and pest management

Crop production is highly dependent on the weather and the contribution of any technology is also influenced by climatic conditions. Farmers have always had to cope with this kind of variability, but because Bt cotton cultivation requires an investment in seeds and inputs before the season begins without knowing how rainfall or pest populations will affect production and crop management, it can represent a serious risk for farmers. Such risks are more difficult to bear for resource-poor farmers. The higher the seed price, the riskier the decision for a resource-poor farmer to grow Bt cotton. In high-income countries, farmers commonly use insurance schemes to protect themselves from risks and shocks. Unfortunately, access to these types of formal financial risk management products is essentially nonexistent in most rural areas of developing countries (Jensen and Barrett, 2017).

In addition, like any other agricultural technology, Bt cotton cultivation must be integrated within existing farming systems and may require adjustments in crop management. Relevant examples described below are the implications of variable pest pressure on the added value of Bt cotton, the consequences of reduced insecticide use on non-target pests and the need for further research on the performance of Bt cotton under marginal growing conditions.

Bt cotton benefits depend on pest abundance

Because Bt cotton is only effective against some pests, and efficacy against a pest may range from modest to high, it follows that the performance and value of Bt cotton will depend on the abundance of pests. For any pests, infestation levels vary annually and are subject to weather variability, which can then affect the performance of the technology. In some of the cases reported in the literature (Qaim *et al.*, 2006), the year of a particular survey was unusually dry, pest infestations and cotton yields were low, and the advantages offered by Bt cotton were relatively modest. In other cases, rainfall was at or above normal, yields (and insect populations) were high, and Bt cotton showed a more marked advantage. High rainfall not only increases insect pressure but also renders insecticides less effective by washing them from plants, giving Bt cotton an extra advantage over conventional cotton (Qaim *et al.*, 2006).

Consequences of reduced insecticide use for non-target pests

Reduced insecticide use on Bt cotton that targets pests such as bollworms may at times lead to the resurgence of secondary insects earlier controlled by these insecticides. For example, significant reduction in the use of synthetic insecticides in Bt cotton favored outbreaks of mirids and leafhoppers in China (Wu *et al.*, 2002; Men *et al.*, 2005). Before the introduction of Bt cotton, these had been relatively minor pests that had been controlled by the same synthetic insecticides sprayed to control cotton bollworm. Similarly, an increase in leafhoppers on Bt cotton was observed in South Africa, possibly as a result of reduced insecticidal sprays for bollworms (Kirsten and Gouse, 2003). Conversely, reduced insecticide use in Bt cotton can have positive consequences for the control of pests whose natural predators were formerly impacted by these insecticides.

Based on data from 1990 to 2010 gathered at 36 sites in six major cotton-growing provinces of northern China, a marked increase was shown in abundance of three types of generalist arthropod predators (ladybirds, lacewings and spiders) associated with widespread adoption of Bt cotton and reduced insecticide sprays in this crop (Lu *et al.*, 2012). Another positive spill-over effect of reduced insecticide use is that widespread use of Bt technology may suppress bollworm infestation levels regionally, such that non-Bt cotton growers may also be able to reduce their insecticide applications (Krishna and Qaim, 2012).

Performance under marginal growing conditions

When a new technology such as Bt cotton is introduced in developing countries, one of the primary concerns is its performance under the marginal conditions and limited resources of smallholder farmers. For example, the causes of the cotton yield stagnation observed in West Africa during the period of 1990 – 2005 can be explained by several factors, such as agronomic constraints from pest damage, poor soil fertility management, lack of varietal development and climate change. However, yields can also be negatively impacted by the expansion of cotton production into marginal lands where yields are inherently lower (Vitale *et al.*, 2011). Beginning in the mid-1980s, when the downward trend in yields first became evident in West Africa, the national cotton companies responded by pushing back the agricultural frontier, expanding into marginal production areas. While the land expansion strategy increased production in the short-run, average yields continued to stagnate and even fall into the 1990s and 2000s (Vitale *et al.*, 2011).

Moreover, there is much controversy centering around the performance of Bt cotton in some regions of India. The problems reported with the performance of Bt cotton seemed to result from specific environmental conditions, patterns of insecticide use, lack of affordable credit and the absence of social security. In addition, the expansion of the cotton area into regions less suitable for cotton may also have played a role (VIB Fact Series, 2013).

Figure 4.6: *Semi-desert region in South Africa.*

Marginal lands often have poor soil (e.g. low-fertility soil, high soil salinity) and are arid (low water availability) (Figure 4.6). They are typically characterized by low productivity and reduced economic return. The crop harvest is doomed to fail in these areas regardless of whether the crop is Bt cotton or conventional cotton. Yet, there is increasing global interest using marginal land for bioenergy biomass production as well as for non-food crops such as cotton in the face of limited arable land resources. The debate on marginal land use is also a serious topic in Africa associated with the trilemma of land use planning: food security, bioenergy, and environmental concerns (e.g. soil erosion, biodiversity loss) (Wendimu, 2016). The productivity of marginal lands can be improved either through technological improvement or through the use of new cultivars adapted e.g. to drought and salinity (Fita *et al.*, 2015).

Sustainability of the technology - how to manage the evolution of insect resistance to Bt cotton

The remarkable ability of insects to adapt to insecticides supports the conclusion that the development of resistance by pests is the main threat to the continued success of Bt cotton (Tabashnik *et al.*, 2013). Insects may also develop resistance to Bt toxins. Resistance to a toxin is defined as a genetically based decrease in the frequency of individuals susceptible to the toxin in a population that has been previously exposed to the toxin (Tabashnik, 1994). The potential for this type of resistance with the increasing cultivation of Bt crops is one of the most hotly debated topics in agricultural biotechnology. Even when appropriate Bt crops and crop management practices have been identified for local growing conditions, resistance management strategies are needed to ensure that Bt crops are controlled in such a way

Figure 4.7: *Seed packages containing various cotton seed mixes for sale in China (source: Peng Wan, personal collection).*

that the development of resistance to the toxin is kept to a minimum to enhance the sustainability of the technology (Tabashnik *et al.*, 2013).

In order to delay the emergence of insect resistance to Bt toxins in cotton, various refuge policies have been put into place. They require the planting of conventional (non-GM) cotton in or near Bt cotton fields, or the planting of other suitable crops to promote the survival of susceptible insects. Susceptible insects will mate with the rare resistant individuals surviving on Bt cotton (Carrière *et al.*, 2005). The use of plants producing two distinct toxins may also delay insect resistance. This is called the pyramid strategy. The most widespread current example is Bollgard II®, which produces Cry1Ac and Cry2Ab genes.

Refuge management is complex. However, another potential concern is the use of seed mixtures. In many countries, farmers save seed to plant the next season. Cross-pollination with other non-GM cotton varieties may cause an overall decline in seed quality and Bt technology efficiency (Heuberger *et al.*, 2008). Even when farmers purchase seed every year, it may not be purely GM or non-GM if the seed company's management of its production plots has been inadequate (Figure 4.7). An additional source of concern is the fact that when farmers are provided with non-GM seed to plant as a separate refuge, they may use it to fill gaps, thus unwittingly planting an internal refuge when an external one is required. Alternative refuge schemes such as a 'bag-in-a-bag' (whereby the GM seed is mixed with an appropriate percentage of non-GM seed before sale) have been proposed. However, this type of refuge has been shown to increase resistance to Bt cotton (Brévault *et al.*, 2015).

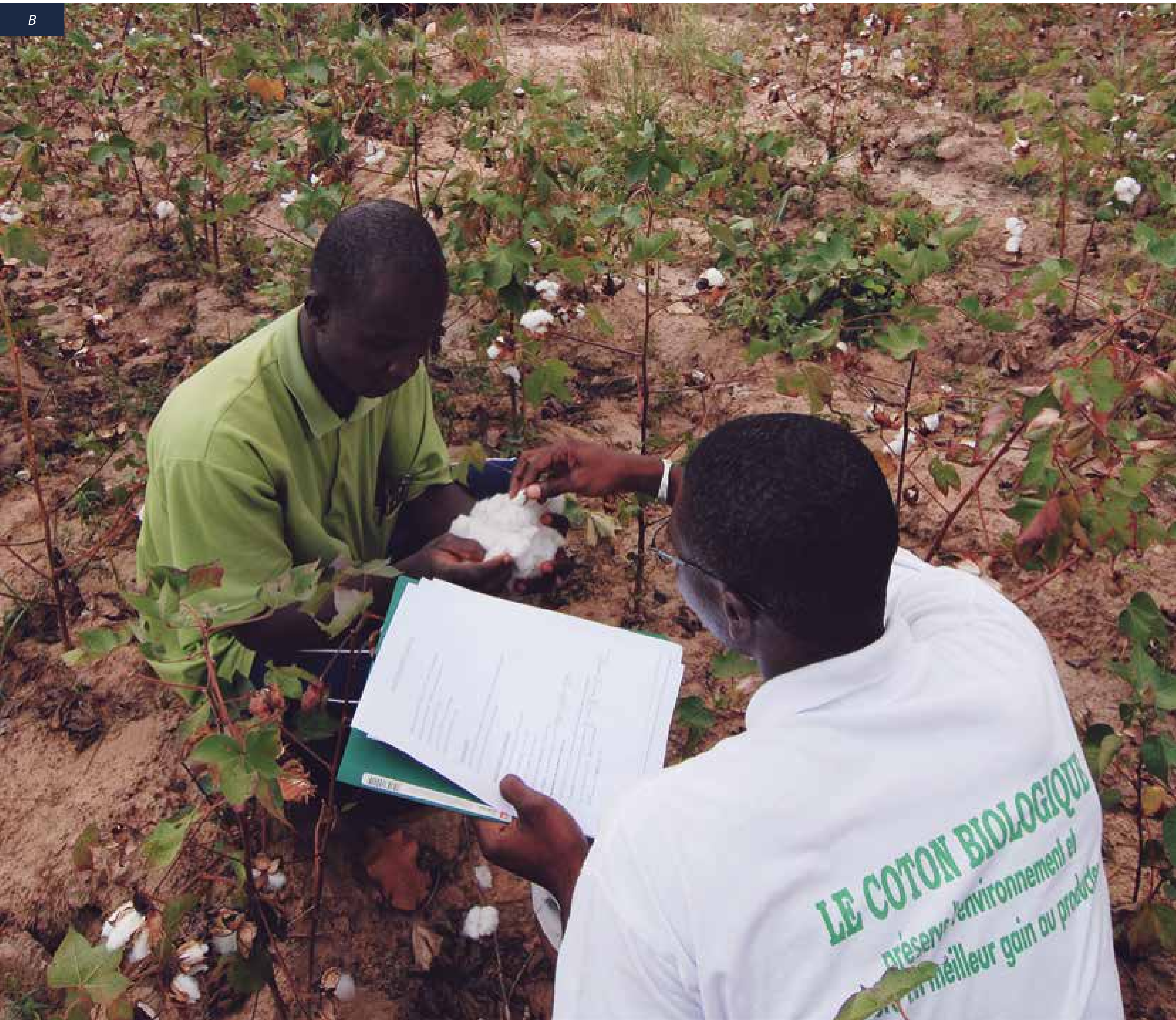
Beyond the best strategies to avoid insect resistance, there are concerns about the feasibility of implementing any mandatory management strategies in African agricultural systems. Because much of African agriculture is in the hands of smallholder farmers, the education and communication requirements of any risk management strategy are significant. In many countries, the owner or licensee of the technology is also responsible for ensuring that the refuge policy is enforced. This is most often done via signed agreements with seed distributors and farmers that obligate them to plant a refuge. This is also done by conducting on-farm inspections. In countries where such measures are difficult to enforce, the monitoring (and compliance) is less in evidence. India has dealt with the refuge challenge by requiring that the seed company provides the farmer with the requisite amount of non-GM seed when purchasing Bt cotton. However, there are few resources for monitoring compliance. In Argentina where much of the Bt cotton planted is farmer-saved (or obtained through an informal sector), refuge requirements are impossible to enforce in such circumstances (Qaim and de Janvry, 2003).

Another concern related to the sustainability of GM crops is their potential effect on crop agrobiodiversity, which comprises the diversity of species used in agricultural production and varietal diversity within those species (Carpenter, 2011). While GM technology allows the introduction of desirable genes and traits into many existing varieties, potentially making it easier to preserve varietal diversity (Zilberman *et al.*, 2007), it is also possible that a few GM varieties might dominate a nation's cropping patterns, thereby lowering the resilience provided by wider diversity and contributing to agrobiodiversity erosion. The issue of biodiversity loss is not strictly associated with GM crops, but can also be the consequence of monoculture, regardless of whether the crop is Bt or conventional cotton. A study using data from the Indian cotton sector and comparing levels of on-farm varietal diversity between full Bt adopters, partial adopters, and non-adopters demonstrated that cotton varietal diversity - with over 96% adoption of Bt cotton by Indian farmers in 2016 (ISAAA, 2016) - is at the same level than it was before the introduction of this technology (Krishna, *et al.*, 2016).

Figure 4.8: *(A) Cotton integrated pest management training in India (source: Regional Agricultural Economic Development Centre); (B) Fairtrade cotton project in Burkina Faso.*

Any yield gains from the adoption of Bt cotton will be the result of improved pest management and will require best agronomic practice to obtain a yield gain sufficient to cover the additional input cost due to the Bt technology fee. A significant amount of work has been dedicated to crop management techniques known as 'integrated pest management' (IPM). IPM strategies for cotton require careful assessment of pest populations, reduction (or in some cases, elimination) of insecticide use, and take advantage of biological insect control products in order to maintain the insect population at levels below those causing economically unacceptable damage or loss (CropLife, 2014). State support and coordination of IPM is often essential, and appropriate incentives must be in place. There has been considerable progress in IPM methods and techniques. They are generally information-intensive, involve learning and constant adjustment, and often require coordination among farmers and the participation of various public and private institutions (Figure 4.8). As a result, they are not likely to spread rapidly among smallholder farmers without strong institutions to support the generation and management of knowledge (see Chapter 5).

B



5 The impact of agricultural policies on cotton production

The impact of an innovation such as Bt cotton should not be assessed only in terms of yields or production costs, but also with respect to the interactions with the institutions that govern farmers' access to the technology. The viability of smallholder cotton production considerably depends on the provision of adequate technology, which in turn depends on a range of institutions. These institutions include public and private research organizations, input and credit markets, regulatory and intellectual property regimes, information provision and farmer organizations. The governance of these systems of information provision is as important for GM crops as it is for conventional technology. The ability to understand and control a technology is also an important factor in determining the impact of the Bt technology on resource-poor farmers.

Source: *Bruno Tinland, personal collection*

How the introduction of Bt technology has affected the organization of the input delivery

Smallholder cotton growers need to acquire the necessary production inputs to boost their productivity, regardless of whether the crop is Bt or conventional cotton. However, they often lack access to productivity-enhancing inputs such as improved seed, fertilizers, water and information. The credit needed to finance investment in these inputs is the major constraint. As a result, smallholder farmers are unable to deliver the volume and quality of product that commercial buyers – retailers, processors and other agri-business firms – require, which in turn limits the development of markets for agricultural products. The type of credit available often plays a role in determining what inputs are available to farmers. The incentives of the credit supplier are a major factor in defining the type of technology employed by farmers. The effectiveness of input provision, and the extent to which farmers are able to understand and take advantage of the inputs that are on offer, depend to some extent on the nature of the input industries themselves.

Various strategies for input provision in cotton cultivation have been developed by African governments during colonial times. For instance, in Tanzania, cooperatives were established to provide credit, inputs and plowing services, and they also had a marketing monopoly. After independence, the cooperatives came under government control and gained a monopoly on ginning as well (Putterman, 1995). Suffering from mismanagement and lack of capital, they declined together with the country's cotton production.

In several anglophone African countries, the lack of alternative credit sources for cotton production has led to the establishment of outgrower schemes, which are systems that link networks of unorganized smallholder farmers with domestic and international buyers. Also known as contract farming, these schemes provide benefits to all players along the supply chain. Buyers can improve their control over crop supply, often at pre-agreed prices, as well as crop quality standards. Farmers can access more secure markets, often receiving technical and financial support by cultivating within outgrower schemes (TechnoServe and IFAD, 2011). Ginning companies provide inputs on loan to farmers, who are expected to deliver their harvest in return. These systems require a fine balance. Excessive competition encourages farmers to default on their loans by selling their cotton to a rival ginnery. Controlling the market by limiting the number of ginneries or providing territorial concessions can help reduce side-selling, but heavy-handed coordination or monopolies can result in lower prices paid to farmers. To be specific, side-selling is a situation in which farmers are selling to a firm other than the firm from which they received input credit. Typically, side-selling is done with the purpose of avoiding loan repayment (Tschirley *et al.*, 2009) (Figure 5.1).

The same dilemmas exist within the 'filière' system of francophone West Africa in which national parastatal cotton enterprises follow an 'administered monopoly' model, with a legal monopoly on input provision and a monopsony (a market structure in which only one buyer interacts with many would-be sellers of a particular product) on the purchase of cotton from farmers. The company provides the production inputs as well as technical advice to the farmers. After the growing season, the company buys the yield at fixed

Figure 5.1: *Cotton lint collected and waiting to be delivered to the ginning company (A) in Burkina Faso (source: Bruno Tinland, personal collection) and (B) in Malawi.*

prices from the farmers, who can pay off their input credit, and takes on transportation, ginning, and marketing (Theriault and Serra, 2014).

BT COTTON IN SOUTH AFRICA – A TECHNICAL TRIUMPH BUT AN INSTITUTIONAL FAILURE

South African smallholder farmers growing Bt cotton in the Makhathini Flats have received much attention in the literature. At first, most of the peer-reviewed reports on Bt cotton adoption were favorable and have been used to promote the technology in the rest of Africa (Ismael et al.*, 2002; Gouse* et al.*, 2003; Kirsten and Gouse, 2003; Morse* et al.*, 2004). These reports of Makhathini's success soon became emblematic of the potential that Bt cotton could offer to poor smallholder farmers throughout Africa. When South African cotton smallholders began to experience economic losses, it was explained that this was due to a combination of consecutive seasons of drought affecting Kwazulu-Natal and a change in the marketing arrangements (Gouse* et al.*, 2005).*

When Bt cotton was first introduced during the 1997-1998 season, the Makhathini smallholders were served by a single ginnery. This monopoly position induced the ginning company to invest in a credit scheme that allowed farmers to cover the input costs and the technology fee for the Bt variety. With a second ginnery licensed to operate in the same area, competition for seed cotton became the priority, and the number of loan defaulters rose dramatically. This *led to the collapse of the input credit system. Without access to credit, the technology fee for the Bt variety became unaffordable for many cotton farmers in Makhathini. By 2002-2003, the number of Bt cotton smallholders had fallen by 82%, although promotion of irrigation by the new ginning company during this growing season has seen numbers rise again with cotton lint yield increasing from less than 400 kg/ha to over 500 kg/ha (Fok* et al.*, 2007).*

The introduction of Bt cotton for smallholders in South Africa has thus been a 'technical triumph but an institutional failure' (Gouse et al., 2005). Bt cotton was planted on 17,000 ha in 2006 and 10 years later, on 9,000 ha only (ISAAA, 2016). Despite the declines in cultivated areas, adoption rates and production values, the optimism that pervaded during the early years of Bt cotton growing in South Africa remains (Schnurr, 2012). Researchers are unanimous that the environmental variability and institutional arrangements that hampered long-term success in Makhathini do not detract from Bt cotton's potential in other African environments. The lesson learned from Makhathini is that farmers can benefit from technological innovation only if the correct infrastructures and institutions are in place (Schnurr, 2012).

Institutional structures governing cotton production in Sub-Saharan Africa

To strengthen the competitiveness of cotton production, processing, and exports in an increasingly demanding world market, governments of most cotton-producing countries in Sub-Saharan Africa began implementing sectoral reforms of their cotton industries as early as 1990s, or are considering doing so. These reforms generally involve disengaging the state and facilitating larger involvement of the private sector and farmer organizations to ensure higher competition in input and output markets. The reforms also involve improving productivity through research and development and technology dissemination, and seeking value addition through market development and processing of cotton lint and by-products (Theriault and Tschirley, 2014).

A report published by the World Bank (Tschirley *et al.*, 2009) provides an assessment of reform experience across nine of the main cotton producing countries of Sub-Saharan Africa (Benin, Burkina Faso, Cameroon, and Mali in West and Central Africa; Mozambique, Tanzania, Uganda, Zambia, and Zimbabwe in East and Southern Africa). It highlights the range of institutional structures governing cotton production in Sub-Saharan Africa and shows how these structures drive cotton sector performance. The report recognizes the tradeoffs between competition and coordination. Competition is important to ensure efficiency and the fair sharing of benefits between buyers and sellers. Yet, too much competition will make it difficult for stakeholders to engage in coordination, which is necessary to provide important services such as quality control, input credit, research and extension. A well-functioning cotton sector is one that strikes a balance between these competing needs, providing sufficient benefits to all stakeholders so that the system is able to maintain itself and grow.

Based on the structure of the market for the purchase of seed cotton and on the regulatory framework in which firms operate, the report identifies five types of cotton sectors among the nine African cotton-producing countries described above. Figure 5.2 lays out the typology based first on a distinction between market-based and regulated sectors, with the latter referring to sectors in which free competition for seed cotton purchase is not allowed. The second distinction is based on the number of buyers of seed cotton: many or few in the case of market-based systems, and one or more than one in regulated systems. These two distinctions generate four sector types: (1) national monopolies, (2) local monopolies, (3) concentrated market-based systems, and (4) competitively structured systems. A fifth category - hybrid market structures - includes the sectors that cannot be classified into one of the four main types.

In Cameroon and Mali, cotton sectors are managed by a national monopoly responsible for purchasing all cotton from farmers at fixed pan-regional prices.

Figure 5.2: *Decision tree for cotton sector typology (source: adapted from Tschirley et al., 2009; © World Bank, License: Creative Commons Attribution license CC BY 3.0 IGO).*

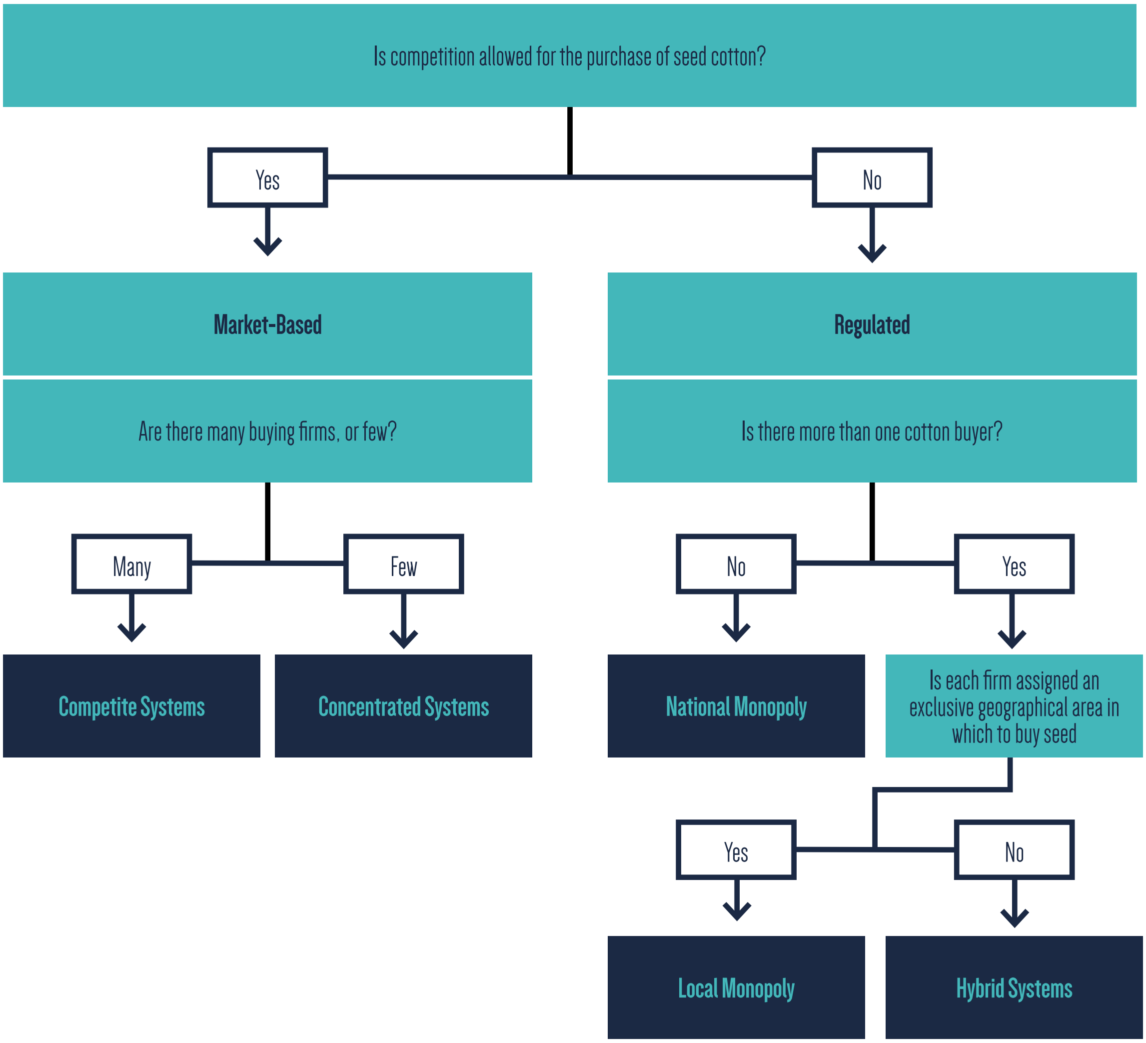


Figure 5.3: *Weighing of cotton harvested in Burkina Faso (source: Bruno Tinland, personal collection).*

National monopolies are owned and operated by public or mixed companies. Cotton sectors in Burkina Faso and Mozambique are organized into local monopolies, in which exclusive purchasing rights are given to one ginning firm within a delimited geographical zone (Figure 5.3). Concentrated market structures define cotton sectors, such as those of Zambia and Zimbabwe until at least the early 2000s, in which a very small number of firms (two in these particular examples) dominate market share but face free competition from other firms and, potentially, from each other. Unlike local monopolies, concentrated sectors have no geographical zoning that delimits firms' scopes of operations. In competitively structured sectors, such as those in Tanzania since 1994 and Uganda during the initial years of liberalization, a large number of buyers compete without restriction to purchase seed cotton from farmers, with no single set of firms dominating. Finally, hybrid structures encompass cotton sectors that are either attempting to liberalize a national monopoly (e.g. Benin) or to solve unintended consequences from the liberalization process (e.g. Uganda since shortly after liberalization) (Theriault and Tschirley, 2014).

Sector structure has a major influence on performance

Competitive, market-based systems can enhance cotton production by ensuring relatively high prices to farmers - a direct result of intense competition among companies - but poorly perform on input credit provision, extension and quality. This is because of the difficulty in coordinating across more than a few companies, whether this coordination is to prevent side-selling or to agree on discounts to be paid for poor-quality seed cotton. As a result, competitive systems tend to generate low yields and score poorly on lint quality, limiting the price advantage they actually pass to farmers. Monopolistic (national or local) and concentrated sectors can perform well on prices paid to farmers. However, such performance depends on the strategic priorities of dominant companies, on the existence of political interference (if any), and on the voices of cotton farmers in price negotiations. Since 2000, concentrated sectors (Zambia and Zimbabwe) have performed relatively poorly regarding prices to farmers, while national monopolies have paid unsustainably high (yet politically backed) prices that have been an important contributor to these sectors' fiscal crises. In the case of by-product valorization, the West and Central African sectors (especially those in Mali and Burkina Faso) receive low prices for cottonseed, an outcome related to the history of vertical integration within the sector. In any case, by-product valorization has received insufficient attention in the study of cotton sectors so far. It is an area where value could be added and redistributed to farmers through greater opening of the sector and through competition. Monopolistic and concentrated sectors do better on input credit and services to farmers - and thus on yields - as well as on quality. These structures are able to do this due to limited competition in the output market, better coordination among firms, and consequently lower risk of side-selling compared to competitive systems. Yet, they may pass little, if any, of the quality premium on to farmers, and they may tend to charge higher-than-market rates for the inputs they provide. Consequently, returns to farmers are similar in Zambia's concentrated system and Tanzania's competitively structured one (Tschirley *et al.*, 2009 and 2010).

As a result, no single market sector type seems to have performed so well that it can be used as a reference for other countries (Theriault and Tschirley, 2014). All sectors show productivity and performance gaps. Thus, they generally lag well behind the best performers in the world. Nevertheless, sector type (market structure and associated regulatory framework) does say a great deal about the key challenges that will be most difficult for a sector to meet, and about the most promising approaches for dealing with those challenges. For example, input credit, extension, and quality will be problems in competitive systems; prices to farmers will tend to be low in concentrated sectors; and company efficiency will tend to be poor in monopolies (Tschirley *et al.*, 2009, 2010).

The implementation of reforms that are in line with local realities faced by cotton farmers is required to enhance efficiency in cotton production and revitalize Sub-Saharan African cotton sectors, while inducing economic growth and poverty alleviation (Theriault and Serra, 2014). Improvement in the credit market requires strong engagement from governments, financial institutions and farmers' associations. However, access to credit is a necessary but insufficient solution to high performance. To ensure efficient delivery of information and adoption of technological innovations as well as better agricultural practices, fostering farmer management skills via functional extension services is as important as the establishment of adequate pricing mechanisms that ensure reasonable prices and on-time payment to farmers.

Farmers' access to information on managing the Bt technology

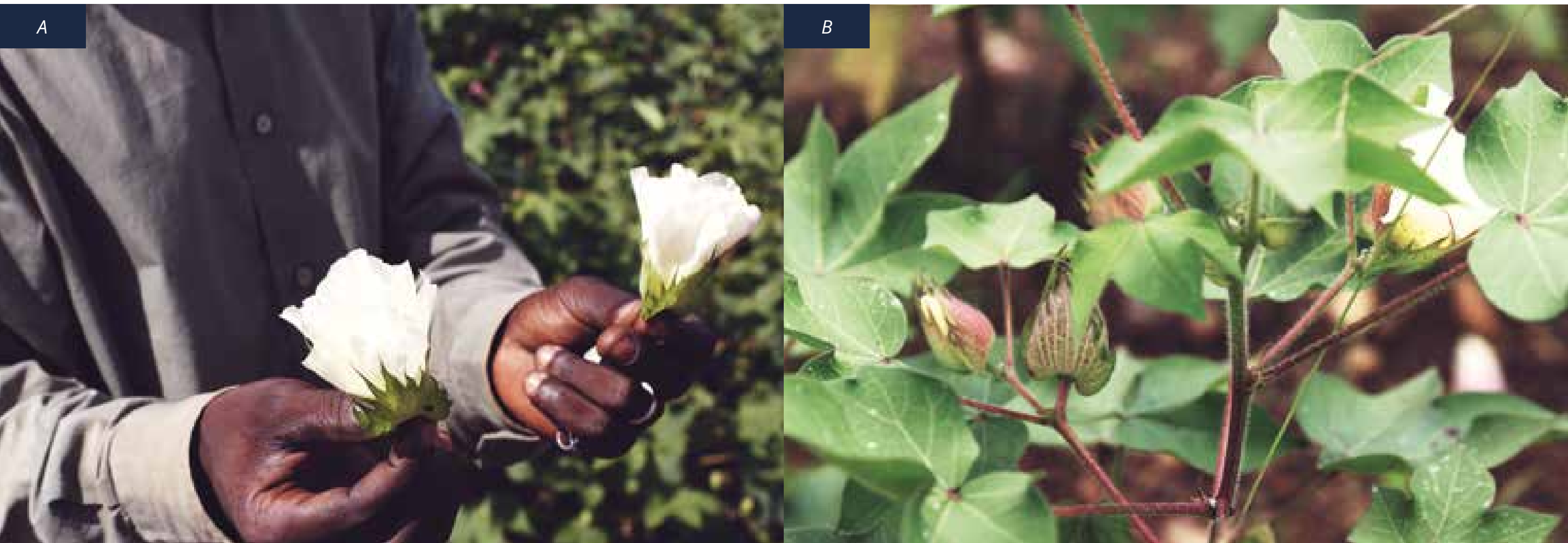
The way in which inputs are made available has implications for cotton farmers' understanding of, and control over, Bt technology. While farmers need to be able to recognize and select the most appropriate cotton variety, they also need to understand something about the nature of Bt cotton and how it can contribute to pest management strategies. Information on variety characteristics should be available from extension agents, the commercial input system or the advice of other farmers (Figure 5.4). In addition to information provided through input markets, farmers also require considerable information about crop management. The stewardship in the case of GM crops requires the technology developer to provide downstream actors with the necessary information and training for optimal use of the material. This can be done directly by the technology provider, or through contractors.

Farmers often rely on the experience of their neighbors rather than on formal information sources, and the same pattern may hold true in the case of Bt cotton. A long-term study that follows decision-making on Bt cotton in India has found that although farmers rely on information from each other in their choice of cotton varieties, the process is subject to fads and rumors rather than being the product of careful experimentation. It resulted in large shifts in the popularity of individual varieties from one season to the next (Stone, 2007). This study showed that farmers are often unable to describe the basic characteristics (such as maturity or moisture requirements) of the varieties that they have purchased.

Similarly, differences in pest control practices are not only due to differences in farmer income or national input markets. For instance, better-educated Indian farmers make fewer and more selective applications of insecticide (Qaim, 2003). In Argentina on the other hand, where many farmers under-invest in inputs, more education is correlated with higher insecticide use (Qaim and de Janvry, 2005). Farmer knowledge is certainly a crucial element in the ability to use pesticides properly or to best take advantage of an innovation such as Bt cotton. It appears that some South African smallholders believed that Bt cotton provided protection against other insects besides bollworms and may have mistakenly changed their use of insecticides accordingly (Bennett *et al.*, 2006).

We have seen that farmers are sometimes badly served by the guidance made available to them through commercial seed and pesticide markets and often have to contend with confusing or deceptive information. On the other hand, there are occasionally instances when farmers may be able to deceive the output market. The refuge management rules imposed on seed companies, which they are supposed to enforce, may be ignored by farmers either because of lack of understanding or insufficient follow-up. A study found that even many Indian seed retailers were unable to explain the rationale for the small packets of refuge seed they were obliged to sell along with the Bt cotton seed (Stone, 2004).

Figure 5.4: *(A) Cotton flowers and (B) a Burkinabe cotton plant variety (source: Bruno Tinland, personal collection).*



6 Conclusion

Throughout Sub-Saharan Africa, the cotton sector faces major challenges regarding competitiveness and sustainability, including financial crises brought on by years of declining productivity throughout the sector. These crises are associated with unfavorable external factors such as market distortions and credit default crises. An innovation such as a Bt crop is not simply a technical solution. It is an intervention with social, economic and political consequences. Bt technology can certainly contribute to the reduction of insecticide use and insect damage, increased yield and higher farmer profits, and the conservation of beneficial natural enemies. However, more attention needs to be focused on the development of local institutions for farmers to take full advantage of the technology. These local institutions include the institutions that support public and private capacity for technology generation, technology delivery through markets, extension and regulations, and farmer capacities to demand services, participate in markets and understand the technology they are using. Much broader access by smallholders to improved input packages, such as improved seed and fertilizer and to the technical advice needed to use them properly, is also largely required.

Donors and governments that invest heavily in the hope that GM crops will bring significant improvements to the livelihoods of resource-poor farmers, without first paying attention to the fundamental institutions that support broader agricultural development and technology generation (with or without GM crops), are in danger of misallocating their resources.

The contribution of Bt technology to insect control in the cotton-producing countries of Sub-Saharan Africa depends on:

1. The development of a commercial seed sector and the establishment and enforcement of the basic regulations that provide an enabling environment for that sector.
2. The support of agricultural research.
3. A well-implemented capacity-building strategy, so that the potential benefits of Bt cotton are understood and farmers appreciate that making a profit will depend, even more than it did with conventional varieties, on the implementation of best practices in integrated pest management.
4. An improved farmer access to credit for input purchase and to technical advice. The public-sector extension service does not have the manpower to deliver this and the appropriate provider is the ginning company. Yet, the conflict between cooperation and competition between ginning companies needs to be addressed in some countries.
5. The promotion of Bt cotton as a crop protection technology and not primarily as a yield-enhancing one.

7 References

Abhiyan, H.B., Abhiyan, B.S. (2012). A decade of BT cotton in Madhya Pradesh: A report.

Aronson, A. I., Beckman, W., Dunn, P. (1986). *Bacillus thuringiensis* and related insect pathogens. *Microbiology Review* 50: 1-24.

Baffes, J. (2011). Cotton Subsidies, the WTO, and the 'Cotton Problem'. *The World Economy*: 1534-1556.

Bennett, R., Morse, S., Ismael, Y. (2006). The economic impact of genetically modified cotton on South African smallholders: yield, profit and health effects. *Journal of Development Studies* 42: 662-677.

Brévault, T., Tabashnik, B. E., Carrière, Y. (2015). A seed mixture increases dominance of resistance to Bt cotton in *Helicoverpa zea. Scientific Reports* 5, 9807; DOI: 10.1038/srep09807.

Brookes, G., Barfoot, P. (2017). Environmental impacts of genetically modified (GM) crop use 1996-2015: Impacts on pesticide use and carbon emissions. *GM Crops and Food* 8: 117-147.

Carpenter, J. (2011). Impact of GM crops on biodiversity. *GM Crops* 2(1): 7-23.

Carrière, Y., Ellers-Kirk, C., Kumar, K., Heuberger, S., Whitlow, M., Antilla, L., Dennehy, T. J., Tabashnik, B. E. (2005). Long-term evaluation of compliance with refuge requirements for Bt cotton. *Pest Management Science* 61: 327-330.

Charles, D. (2001). *Lords of the Harvest*. Cambridge, MA: Perseus.

CropLife International (2014). Integrated Pest Management. https://croplife.org/crop-protection/stewardship/integrated-pest-management/

Dong, H., Li, W., Li, Z., Tang, W., Zhang, D. (2004). Development of hybrid Bt cotton in China: a successful integration of transgenic technology and conventional techniques. *Current Science* 86: 778-782.

Dowd-Uribe, B. (2014). Engineering yields and inequality? How institutions and agro-ecology shape Bt cotton outcomes in Burkina Faso. *Geoforum* 53: 161-171.

Dowd-Uribe, B., Schnurr, M. A. (2016). Briefing: Burkina Faso's reversal on genetically modified cotton and the implications for Africa. *African Affairs* 115(458): 161-172.

Duck, N., Evola, S. (1997). Use of transgenes to increase host plant resistance to insects: Opportunities and Challenges. In Carozzi, N., Koziel, M. (eds) *Advances in Insect Control: The Role of Transgenic Plants*, Bristol, PA: Taylor & Francis Ltd, pp. 1-20.

FAO (2012). Crop yield response to water. *FAO irrigation and drainage paper No. 66. Rome.*

FAO and ICAC (2015). Measuring Sustainability in Cotton Farming Systems: Towards a Guidance Framework. Rome, 2015.

FAOSTAT (2017). Available at http://www.fao.org/faostat/en/#data.

Fita, A., Rodríguez-Burruezo, A., Boscaiu, M., Prohens, J., Vicente, O., (2015). Breeding and domesticating crops adapted to drought and salinity: a new paradigm for increasing food production. *Frontiers in Plant Science* 6 (978): 1-14.

Fok, M., Hofs, J. L., Gouse, M., Kirsten, J. F. (2007). Contextual appraisal of GM cotton diffusion in South Africa. *Life Sciences International Journal* 1: 468-82.

Gadelha, I. C. N., Fonseca, N. B. S., Oloris, S. C. S., Melo, M. M., Soto-Blanco, B. (2014). Gossypol toxicity from cottonseed products. *The Scientific World Journal*: 11p.

Glover, D. (2010). Exploring the resilience of Bt cotton's pro-poor success story. *Development and Change* 41(6): 955-981.

Gouse, M., Kirsten, J., Jenkins, L. (2003). Bt cotton in South Africa: adoption and the impact on farm incomes amongst small-scale and large-scale farmers. *Agrekon* 42: 15-28.

Gouse, M., Kirsten, J., Shankar, B., Thirtle, C. 2005. Bt cotton in Kwazulu Natal: technological triumph but institutional failure. *AgBiotechNet* 7: 1-7.

Govereh, J., Jayne, T. (1999). Effects of cash crop production on food crop productivity in Zimbabwe: synergies or trade-offs? *MSU International Development Working Paper N°. 74*, East Lansing, MI: Michigan State University.

Heuberger, S., Ellers-Kirk, C., Yafuso, C., Gassmann, A. J., Tabashnik, B. E., Dennehy, T. J, Carrière,Y. (2008). Effects of refuge contamination by transgenes on Bt resistance in pink bollworm (Lepidoptera: Gelechiidae). *Journal of Economic Entomology* 101: 504-514.

Höfte, H., Whiteley, H.R. (1989). Insecticidal crystal proteins of *Bacillus thuringiensis. Microbiology Review* 53: 242-255.

ICAC (2017). Cotton: world statistics. *International Cotton Advisory Committee, Washington DC.*

ISAAA (2016). Global Status of Commercialized Biotech/GM Crops: 2016. *ISAAA Brief N°. 52*. ISAAA: Ithaca, NY.

Isaacman, A., Roberts, R. (1995). Cotton, colonialism, and social history in Sub-Saharan Africa. London: James Currey.

Ismael, Y., Bennet, R., Morse, S. (2002). Benefits from Bt cotton use by smallholder farmers in South Africa. *AgBioForum* 5 (1): 1-5.

James, C. (2015). Global status of commercialized Biotech/GM crops: 2015. *ISAAA Brief No 51* ISAAA: Ithaca, NY.

Jensen, N., Barrett, C. (2017). Agricultural index insurance for development. *Applied Economic Perspectives and Policy* 39(2): 199-219.

Kirsten, J., Gouse, M. (2003). The adoption and impact of agricultural biotechnology in South Africa. In Kalaitzandonakes N. (ed.) *The Economic and Environmental Impacts of Agbiotech*, New York: Kluwer Academic / Plenum Publishers, pp. 243-259.

Kooistra, K., Pyburn, R., Termorshuizen, A. (2006). The Sustainability of cotton. Consequences for man and the environment. Science Shop Wageningen University and Research Center Report N°. 223.

Kranthi, K., Naidu, S., Dhawad, C., Tatwawadi, A., Mate, K., Patil, E., Bharose, A., Behere, G. Wadaskar, R., Kranthi, S. (2005). Temporal and intra-plant variability of Cry1Ac expression in Bt-cotton and its influence on the survival of the cotton bollworm, *Helicoverpa armigera* (Hübner) (Noctuidae: Lepidoptera). *Current Science* 89(2): 291-298.

Krishna, V. V., Qaim, M. (2012). Bt cotton and sustainability of pesticide reductions in India. *Agricultural Systems* 107: 47-55.

Krishna, V., Qaim, M., Zilberman, D. (2016). Transgenic crops, production risk and agrobiodiversity. *Eur Rev Agric Econ* 43 (1): 137-164.

Liu, Y., Ge F., Liang, Y., Wu, G., Li, J. (2015). Characterization of competitive interactions in the coexistence of Bt-transgenic and conventional rice. *BMC Biotechnology* 15(27): 1-12.

Lu, Y., Wu, K., Jiang, Y., Guo, Y., Desneux, N. (2012). Widespread adoption of Bt cotton and insecticide decrease promotes biocontrol services. *Nature* 487: 362-367.

Men, X. Y., Ge, F., Edwards, C. A., Yardim, E. N. (2005). The influence of pesticide applications on *Helicoverpa armigera* Hübner and sucking pests in transgenic Bt cotton and non-transgenic cotton in China. *Crop Protection* 24: 319-24.

Meng, E. C. H., Hu, R., Shi, X., Zhang, S. (2006). Maize in China: production systems, constraints and research priorities. Mexico, D. F.: CIMMYT.

Minot, N., Daniels, L. (2005). Impact of global cotton markets on rural poverty in Benin. *Agricultural Economics* 33: 453-466.

Morse, S., Bennett, R., Ismael, Y. (2004). Why Bt cotton pays for small-scale producers in South Africa. *Nature Biotechnology* 22(4): 379-380.

Naylor, R. (1994). Herbicide use in Asian rice production. *World Development* 22: 55-70.

OECD (2006). Cotton in West Africa. *The Economic and Social Stakes*, Paris: OECD.

Oerke, E.C. (2006). Crop losses to pests. *J. Agric. Sci.* 144(1): 31-43.

Pemsl, D. (2006). Economics of Agricultural Biotechnology in Crop Protection in Developing Countries – The Case of Bt-Cotton in Shandong Province, China. *Pesticide Policy Project Publication Series* No. 11, Hannover, Germany: University of Hannover.

Pertry, I., Sanou, E.I.R., Speelman, S., Ingelbrecht, I. (2016). The success story of Bt cotton in Burkina Faso: a role model for sustainable cotton production in other cotton-growing countries? In: *Innovative farming and forestry across the emerging world, the role of genetically modified crops and trees*, De Buck S., Ingelbrecht I., Heijde M. and Van Montagu M. (eds.).

Potrykus, I., Bilang, R., Futterer, J., Sautter, C., Schrott, M. (1998). Genetic engineering of crop plants. In Altman A. (ed.) *Agricultural Biotechnology*, New York: Marcel Dekker, Inc, pp. 119-159.

Pray, C., Huang, J., Hu, R., Rozelle, S. (2002). Five years of Bt cotton in China – the benefits continue. *The Plant Journal* 31: 423-430.

Putterman, L. (1995). Economic reform and smallholder agriculture in Tanzania: a discussion of recent market liberalization, road rehabilitation, and technology dissemination efforts. World Development 23(2): 311-326.

Qaim, M. (2003). Bt cotton in India: Field trial results and economic projections. *World Development* 31: 2115-2127.

Qaim, M., de Janvry, A. (2003). Genetically modified crops, corporate pricing strategies, and farmers' adoption: the case of Bt cotton in Argentina. *Amer. J. Agr. Econ*. 85(4): 814-828.

Qaim, M., de Janvry, A. (2005). Bt cotton and pesticide use in Argentina: economic and environmental effects. *Environment and Development Economics* 10: 179-200.

Qaim, M., Subramanian, S., Naik, G., Zilberman, D. (2006). Adoption of Bt cotton and impact variability: insights from India. *Review of Agricultural Economics* 28: 48-58.

Qaim, M., Zilberman, D. (2003). Yield effects of genetically modified crops in developing countries. *Science* 299: 900-902.

Qiao, F. (2015). Fifteen years of Bt cotton in China: the economic impact and its dynamics. *World Development* 70: 177-185.

Sahn, D. (1990). The impact of export crop production on nutritional status in Côte d'Ivoire. *World Development* 18: 1635-1653.

Schnurr, M. A. (2012). Inventing Makhathini: creating a prototype for the dissemination of Genetically Modified crops into Africa. *Geoforum* 43(4):784–792.

Shankar, B., Thirtle, C. (2005). Pesticide productivity and transgenic cotton technology: The South African smallholder case. *Journal of Agricultural Economics* 56: 97-116.

Sidhu, M. S. (1999). Impact of intellectual property rights on the Indian seed industry. *Indian Journal of Agricultural Economics* 54: 370-379.

Skinner, D. Z., Muthukrishnan, S., Liang, G. H. (2004). Transformation: a powerful tool for crop improvement. In Liang G. H. and Skinner D. Z. (eds), *Genetically Modified Crops: Their Development, Uses, and Risks*, New York: Food Products Press, pp 1-16.

Smith, R. H., Smith, J. W., Park, S. H. (2004). Cotton transformation: successes and challenges. In Liang G. H. and Skinner D. Z. (eds) *Genetically Modified Crops: their Development, uses and risks,* New York: Food Products Press, pp. 247-257.

Stoll, S. (2002). Larding the Lean Earth. Soil and Society in Nineteenth Century America. New York: Hill and Wang.

Stone, G. (2004). Biotechnology and the political ecology of information in India. *Human Organisation* 63: 127-140.

Stone, G. (2007). Agricultural deskilling and the spread of genetically modified cotton in Warangal. *Current Anthropology* 48: 67-103.

Tabashnik, B. E. (1994). Delaying insect adaptation to transgenic plants: seed mixtures and refugia reconsidered. *Proceedings of the Royal Society London* 255: 7-12.

Tabashnik, B. E., Brévault, T., Carrière, Y., 2013. Insect resistance to Bt crops: lessons from the first billion acres. *Nature Biotechnology* 31(6): 510-521.

TechnoServe and IFAD (2011). Technical brief on outgrower schemes – Enhancing profitability. http://www.technoserve.org/resources.

Theriault, V., Serra, R. (2014). Institutional environment and technical efficiency: a stochastic frontier analysis of cotton producers in West Africa. *Journal of Agricultural Economics* 65: 383-405.

Theriault, V., Tschirley, D. L. (2014). How institutions mediate the impact of cash cropping on food crop intensification: an application to cotton in Sub-Saharan Africa. *World Development* 64: 298-310.

Thompson, W. M., Anderson, J., Ibendahl, G., Hudson, D. (2007). The impacts of GM seed technology on cotton: cost of production in Mississippi, 1996-2005. Paper presented at the Southern Agricultural Economics Association Annual Meeting, Mobile, Alabama, February 2007.

Traoré, O, Denys, S, Vitale, J, Traoré, K, Bazoumana, K (2008). Economics and marketing: testing the efficacy and economic potential of Bollgard II under Burkina Faso cropping conditions. *J Cotton Sci* 12: 87–98.

Tripp, R. (2009). Biotechnology and agricultural development. Transgenic cotton, rural institutions and resource-poor farmers. By Tripp R. (ed.) London and New York: Routledge.

Tschirley, D., Poulton, C., Gergely, N., Labaste, P., Baffes, J., Boughton, D., Estur, G. (2010). Institutional diversity and performance in African cotton sectors. *Development Policy Review* 28(3): 295-323.

Tschirley, D., Poulton, C., Labaste, P. (2009). Organization and performance of cotton sector in Africa: learning from reform experience. *World Bank,* Washington, DC.
VIB Facts Series (2013). Bt cotton in India – A success story for the environment and local welfare.
VIB Facts Series (2016). From plant to crop: the past, present and future of plant breeding.
Vitale, J., Greenplate, J. (2014). The role of biotechnology in sustainable agriculture of the twenty-first century: the commercial introduction of Bollgard II in Burkina Faso. *In Convergence of Food Security, Energy Security and Sustainable Agriculture, Biotechnology in Agriculture and Forestry,* Vol. 67, D.D. Songstad, J.L. Hatfield, and D.T. Tomes (Eds.). Berlin, Springer-Verlag, pp. 239-293.
Vitale, J., Ouattarra, M., Vognan, G. (2011). Enhancing sustainability of cotton production systems in West Africa: a summary of empirical evidence from Burkina Faso. *Sustainability* 3: 1136-1169.
Vitale, J., Vognan, G., Vitale, P. P. (2016). The Socio-economic impacts of GM cotton in Burkina Faso: does farm structure affect how benefits are distributed? *AgBioForum* 19(2): 120-135.
Wendimu, M. A. (2016). Jatropha potential on marginal land in Ethiopia: reality or myth? *Energy for Sustainable Development* 30: 14–20.
Wu, K., Li, W., Feng, H., Guo, Y. (2002). Seasonal abundance of the mirids, *Lygus lucorum* and *Adelphocoris* spp. (Hemiptera: Miridae) on Bt cotton in northern China. *Crop Protection* 21: 997-1002.
Zhang, B. H., Liu, F., Yao, C. B., Wang, K. B. (2000). Recent progress in cotton biotechnology and genetic engineering in China. *Current Science* 79: 37-44.
Zilberman, D., Ameden, H., Qaim, M. (2007). The impact of agricultural biotechnology on yields, risks, and biodiversity in low-income countries. *Journal of Development Studies* 43(1): 63-78.

IPBO (International Plant Biotechnology Outreach), which forms part of the VIB, was set up in 2000 by Prof. Em. Marc Van Montagu and Ghent University. IPBO's mission is to promote knowledge and technology transfer in the area of plant biotechnology to developing countries, with a focus on a green and sustainable agriculture and agro-industry. To accomplish this mission, IPBO focuses on communication, training in plant breeding, green biotechnology and related biosafety, and fosters networking and project development to implement cooperation between developing countries and Flanders. For more information, visit: www.ipbo.vib-ugent.be

Basic research in life sciences is **VIB**'s raison d'être. VIB is an independent research institute where some 1,500 top scientists from Belgium and abroad conduct pioneering basic research. As such, they are pushing the boundaries of what we know about molecular mechanisms and how they rule living organisms such as human beings, animals, plants and microorganisms. Based on a close partnership with five Flemish universities – Ghent University, KU Leuven, University of Antwerp, Vrije Universiteit Brussel and Hasselt University – and supported by a solid funding program, VIB unites the expertise of all its collaborators and research groups in a single institute. The VIB-UGent Center for Plant Systems Biology wants to gain insight into how plants grow and respond to the environment. Scientists study how leaves and roots are formed, which micro-organisms live on and around the plant and which substances the plant makes. This knowledge can lead to sustainable innovations in agriculture and food.

After more than twenty years of uninterrupted growth, **Ghent University** is now one of the most important institutions of higher education and research in the Low Countries. Ghent University yearly attracts over 41,000 students, with a foreign student population of over 2,200 EU and non-EU citizens. Ghent University offers a broad range of study programs in all academic and scientific fields. With a view to cooperation in research and community service, numerous research groups, centers and institutes have been founded over the years. For more information, visit: www.UGent.be.

The International Industrial Biotechnology Network (**IIBN**) was established in 2010 as a joint initiative of UNIDO, the Flemish Government (EWI) and IPBO. IIBN serves as a catalyst for advancing sustainable applications of agricultural and industrial biotechnology in developing and emerging economies in cooperation with Flanders and other international partners. IIBN is being developed along three tracks: (1) engage in advocacy to raise awareness for the development potential of agricultural biotechnology by providing science-based information and case studies; (2) establish a formal network of like-minded institutions and organizations, and (3) foster R&D cooperation and capacity building in biosciences that addresses the needs of developing and emerging economies, in cooperation with stakeholders in Flanders and beyond.

The department of Economy, Science and Innovation (**EWI Department**) of the Flemish Government prepares, monitors and evaluates policy in the economy, science and innovation policy area. The aim is to develop Flanders into one of the most advanced and prosperous regions of the world. Their driving forces are the promotion of (1) excellence in scientific research, (2) an attractive and sustainable business strategy and (3) a creative, innovative and entrepreneurial society.

The United Nations Industrial Development Organization (**UNIDO)** aims to eradicate poverty through inclusive and sustainable industrial development (ISID). UNIDO advocates that ISID is the key driver for the successful integration of the economic, social and environmental dimensions, required to fully realize sustainable development for the benefit of future generations.

IPBO
Technologiepark 3, 9052 Ghent, Belgium
Tel: + 32 9 264 87 27 - ipbo@vib-ugent.be - www.ipbo.vib-ugent.be

R.E. Silvia Travella (IPBO/VIB) D/2017/12.267/7