GENETICALLY MODIFIED CROPS IN DEVELOPING COUNTRIES: BACK TO THE FUTURE

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Abstract

World agriculture faces enormous challenges in the coming decades. To feed the world adequately in 2050, agricultural production in developing economies will need to nearly double. Incremental production will mainly come from increases in yields or cropping intensities. This paper focuses on the potential of genetically modified (GM) crops to contribute to agricultural productivity growth and poverty reduction in developing economies. Based on a comprehensive literature review, we aim to shed light on whether GM crops benefit farmers and are able to address their current and future needs. The first part reviews farm-level impacts of GM crops in developing economies. The second part discusses the GM crop research pipeline. GM crop markets are expected to grow in the future, but not to change dramatically. We conclude that GM crops benefited farmers, including resource-poor farmers, in developing economies, but benefits are location and individual-specific. Addressing such complexities will be required to unlock technology potentials.

Keywords

Farm-level impacts of genetically modified crops, global overview, research pipeline

1 Introduction

World agriculture faces enormous challenges in the coming decades: to provide higher quality diets and other products for growing and increasingly affluent populations, to do so in ways that are environmentally sustainable, and to ensure growth opportunities for the three billion people who will continue to rely on agriculture for their livelihoods. Feeding the world adequately in 2050 requires a 70 percent increase in global agricultural outputs, and a near doubling in developing countries (Bruinsma, 2009). While this implies a lower rate of productivity growth than in the past four decades, the incremental production requirements are still considerable and need to come predominantly from increases in yields or cropping intensities because land expansions are not feasible or desirable in many countries (Bruinsma, 2009).

Natural resource degradation and climate change will put additional pressures on agriculture. Scientists predict a rise in global temperatures that will make climatic conditions hotter and drier in many parts of the world along with an increase in the frequency of extreme weather events, like droughts and floods. This will modify cropping cycles, and input requirements. Agricultural outputs could decrease significantly, if adaptation measures are not implemented at farm and regional level. Lower-latitude regions of sub-Saharan Africa, Asia and Latin America will be most adversely affected by climate change (IPCC, 2007; Binswanger-Mkhize 2009).

Agricultural output gains are required not only to meet these growing demand-and supply-side challenges, but also to support the livelihoods of over 70 percent of the world's poor, who continue to live in rural areas (De Janvry, 2009). Increases in agricultural productivity reduce poverty and promote broader economic growth through three main channels: raising farm incomes; creating linkages to the wider rural economy through higher demand for supplementary inputs, labor, and non-tradable goods and services; and boosting the purchasing power of poor urban consumers through lower food prices. Using agriculture for development also reduces the expanding rural-urban divide in many developing economies (FAO, 2004; World Bank, 2007).

Not all productivity-enhancing measures are equally supportive of poverty reduction, however. Biological technology, such as improved seeds, are often more poverty-reducing than mechanical technology because it is more scale-neutral (Evenson and Gollin, 2003). Nonetheless, productivity enhancements in sustainable, poverty-reducing way not only require the use of modern plant breeding but also improved input-uses, an effective dissemination of modern technologies, and well-functioning markets (FAO, 2009). In order to realize the largest gains in productivity and reductions in poverty, technologies should be locally adapted and accessible to all farmers, including resource-poor smallholders.

This paper focuses on the potential of genetic engineering to contribute to agricultural productivity growth in developing economies. The area under genetically modified (GM) crops rose from 1.6 million hectares in 1996 to 134 million hectares in 2009. Today approximately 14 million farmers in 16 developing and 9 developed countries cultivate GM crops (James, 2009). Four crops (soybean, maize, cotton and canola) and two traits (insect-resistance and herbicide-tolerance) dominate the GM crop market, and the development and dissemination of GM crops triggered an intense public debate. On the one hand it is argued that the technology has potential to contribute to yield stabilization and productivity increases, due to a stronger resistance to biotic and abiotic stresses (Borlaug, 2000). For example, Brookes and Barefoot (2009), in an overview of the global impact of biotech crops from 1996 to 2007, found that GM crops significantly increased farm outputs. Qaim and Matuschke (2005) and Raney (2006), in comprehensive literature reviews, showed that smallholder farmers in developing countries can share these benefits. Nonetheless, the authors concluded that farm-level impacts can be highly variable over time and space and depend critically on institutional arrangements and regulations, rural infrastructures, and functioning input and output markets (Raney, 2006). On the other hand, it is argued that GM crops carry potential health and environmental risks, which may be irreversible. Others observe that available GM technologies fail to address the needs of marginalized farmers and the challenges posed by climate change, because they are dominated by private sector companies and geared towards commercial farmers in favorable areas (Friends of the Earth, 2007). Indeed, no GM staple food crops or drought and salt-tolerant crops are currently commercialized.

In this paper we aim to shed light on whether GM crops benefit developing country farmers and are able to address their current and future needs. The first part of the paper reviews farm-level impacts of GM crops in developing economies. The second part gives an overview on GM crops that are currently in the research or regulatory pipeline. The paper is based on a comprehensive literature review. Its focus is on more recent publications, i.e. those that appeared after 2004, for two reasons: First, while early impact studies were often limited in that they used only field trial data, data from individual growing seasons, or small data sets; recent studies draw a more complex picture of farm-level impacts of GM crops. Second, earlier literature is already summarized in other publications. For example, the publication on the "State of Food and Agriculture 2003-2004" dealt extensively with the impact of agricultural biotechnology in developing countries (FAO, 2004)

The paper proceeds as follows: Section 2 looks at farm-impacts of GM crops in Asia, Africa, and Latin America. Section 3 outlines which crops are currently in the biotechnology research pipelines, and Section 4 concludes.

2 Farm-level Impacts of GM Crops in Developing Countries

2.1 Asia

With a total of 12.6 million hectares, Asia is the continent with the third largest area under GM crops; following North America and Latin America. India and China dominate the region with 8.4 million and 3.7 million GM hectares, respectively; farmers in the Philippines cultivated 0.5 million hectares of GM crops in 2009 (James, 2009). Herring (2009) reported plantings of unapproved GM crops for Pakistan, Viet Nam and Thailand. GM cotton is the main biotech crop in Asia, covering 60-65 percent of the total cotton area in India and China. GM cotton varieties in Asia generally contain a gene from the soil bacterium *Bacillus thuringiensis* (*Bt*), which makes the cotton plant resistant to Lepidoptera, like the cotton bollworm complex. In the following we discuss farm-level impacts of *Bt* cotton in India and China.

In India cotton is a major cash crop. *Bt* cotton was released in India in 2002 by Mahyco, a private sector company, in cooperation with Monsanto. Most cotton varieties in India are hybrids, and the *Bt* gene was also incorporated into cotton hybrids. To ensure the best crop performance, hybrids can not be farm-saved and must be bought fresh every season. This provides incentives to private companies to engage in R&D, because it allows them to recoup their corresponding investments. The technology premium that Mahyco initially charged for its product was very high compared to non-*Bt* cotton hybrids. Nonetheless, the share of *Bt* cotton in the total cotton area grew from 0.7 percent in 2002-03 to 65 percent in 2007-08 (Sadashivippa and Qaim, 2009). The number of commercialized *Bt* cotton varieties increased from 3 in 2002 to 137 in 2007 (Herring, 2009).

As a result of high prices for officially approved seeds, the sale of unapproved *Bt* seeds, which are often sold loose, is also flourishing (Crost et al., 2007; Gruère et al., 2008). About half of the *Bt* cotton area in India is estimated to be planted with unapproved seeds (Jayaraman as cited in Morse et al., 2005). In response to high seed prices, several Indian states introduced a price cap for *Bt* cotton. For the 2009-10 season, the states of Andhra Pradesh, Maharashtra and Gujarat set a maximum retail price of 750 Rupees per 450 gram seed packet. The state governments of Punjab, Haryana, and Rajasthan asked seed companies to charge no more than 925 Rupees per packet (The Hindu, 2010).[2] Sadashivappa and Qaim (2009), who analyzed seed prices using field survey data, found that prices fell from 1600 Rupees per packet in 2002-03 to about 800 Rupees in 2006-07. The authors also observed that not only prices for approved seeds, but also for unapproved seeds fell significantly. The impact of price controls on private sector research incentives and seed supply capacities remains to be seen.

A large number of studies evaluated farm-level impacts of *Bt* cotton in India. While early studies used field trial data (e.g. Qaim and Zilberman, 2003), more recent studies employed farm surveys to do impact assessments. Table 1 summarizes a number of studies published between 2004 and 2009. The table

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[2] In fact, governments of Andrah Pradesh, Maharashtra and Gujarat introduced a maximum retail price of 625 Rupees/450 gram seed packet for Monsanto’s Bollgard-I trait and 750 Rupees/450 gram seed packet for Monsanto’s Bollgard-II trait. Governments of Punjab, Haryana and Rajasthan asked seed companies not to charge more than 750 Rupees/450 gram seed packet for Bollgard-I and 925 Rupees per seed packet for Bollgard-II (The Hindu, 2010)

differentiates between average agronomic and economic effects. Studies are sorted by year of data collection, starting with the earliest data.

(Table 1 about here)

The table shows that *Bt* cotton decreased the number of insecticide applications significantly. However, farmers may still need to spray insecticides because resistance against certain types of bollworms may be less than 100 percent, particularly in the late stages of plant growth. In addition, *Bt* cotton does not confer resistance to sucking pests, which requires insecticide applications against these specific pests. Indian *Bt* cotton farmers experienced yield increases between 29 and 60 percent compared to their non-*Bt* growing counterparts. Yield differences tended to be higher for irrigated than for non-irrigated plots (Ghandi and Namboodiri, 2006). The *Bt* gene does not affect yields *per se*. *Bt* cotton rather acts as crop insurance against biotic stresses, because it reduces potential crop losses due to pest damages and thereby increases effective yields. Insecticide reductions and yield effects are naturally higher with strong pest pressures.

Turning to the average economic effects, *Bt* cotton reduced insecticide spending by 20 to 100 percent, due to lower insecticide applications. High seed costs were the main reason why total costs for *Bt* cotton producers tended to be 8 to 32 percent higher than for the producers of conventional cotton. In addition, higher cotton yields also raised the demand for harvest laborers and total labor costs. Particularly female wage laborers benefited from an increased demand for labor, because cotton picking in India is predominantly done by women (Subramanian and Qaim, 2009). Higher total costs were offset by higher outputs and lower insecticide costs, thus that total revenues were higher for *Bt* cotton than for non-*Bt* cotton farmers. Revenues were further increased because the superior fiber quality and color of *Bt* cotton fetched a higher market price (Barwale et al., 2004). Overall net income gains varied between 58 and 140 percent. Qaim et al. (2009) considered the distribution of direct and indirect benefits from *Bt* cotton by farm household poverty level. The authors found that the majority (60 percent) of cultivation benefits accrued to extremely poor and moderately poor households.

Despite the overall positive agronomic and economic effects, there is controversy over *Bt* cotton cultivation. Arguments are raised over the methodologies these studies apply (e.g. Glover, 2008): There may be selection bias, e.g. farmers who are more specialized, better educated or equipped are the first to adopt a new technology. Not accounting for selection bias may therefore lead to an overestimation of the impact of the technology itself. Crost et al. (2007) and Morse et al. (2007) used fixed-effects models and plot comparisons, respectively, to control for individual specific characteristics. Crost et al. (2007) stated that more efficient farmers tend to be early adopters. Morse et al. (2007, p. 498) found that "the overall effect is that when comparing Bt plots of adopters and non-Bt plots of non-adopters, roughly half of the observed increase is due to a 'farmer effect' and half to the Bt trait". Both studies concluded that accounting for potential farmer self-selection biases is essential when considering farm-level impacts. Other methodological criticisms are potential measurement and estimation biases (see Smale et al. 2009 for a discussion), which may arise from small sample sizes or when farmers are asked to recall data. Estimation biases could result from partial farm budgeting, when inherent costs (e.g. land and family labor) are not accounted for.

Another argument is that *Bt* cotton impacts are variable across regions and time. For example, it is often claimed that yield increases are not positive for all farmers (Friends of the Earth, 2007). This argument of impact variability is true and has been documented; starting from the earliest ex-post adoption studies (FAO, 2004). For example, Qaim et al. (2005), in their analysis of Bt cotton performance in four major Indian cotton states, found that in all states insecticide applications decreased significantly. Yet, in only three states (Maharashtra, Karnataka and Tamil Nadu) net income gains were positive and significant. *Bt* cotton farmers in the fourth state - Andrah Pradesh - experienced net income losses compared to their non-*Bt* growing counterparts. Morse et al. (2005a) and Bennett et al. (2006a) also reported district-level variations in net income gains for the Indian state of Maharashtra. Differences in crop performance can be explained by a wide range of factors, e.g. agronomic conditions, pest loads, availability of alternative pest control measures (FAO, 2004). In addition, the *Bt* gene may be incorporated into varieties that are not sufficiently adapted to local growing conditions (Qaim et al., 2005).

Another reason for observed yield variability may be the large number of unapproved seeds cultivated by farmers. Morse et al. (2005) compared the performance of official *Bt* cotton hybrids in Gujarat with unapproved *Bt* cotton hybrids, farm-saved unapproved *Bt* cotton hybrids, and non-*Bt* cotton. Remarkably, sample farmers referred to all three *Bt* types as GM crops, even though the farm-saved hybrids may no longer exhibit the hybrid vigor. In their analysis of farm-level impacts of these different seed types, Morse et al. (2005) demonstrated that yield increases in comparison to the non-*Bt* variety were zero percent, 14 percent, and 20 to 37 percent for the farm-saved, unapproved and official *Bt* cotton varieties, respectively. The use of insecticides was lower on all *Bt* cotton varieties. Looking at the average economic effects, the authors found that net incomes were the highest for farmers growing official seeds, followed by unapproved seeds, farm-saved seeds, and non-*Bt* seeds. The performance of different types of *Bt* seeds, which farmers recognized as being the same, may add to the perception of a large variability in the performance of GM crops. Lower prices of official *Bt* seeds, better information transfer, and a higher number of official *Bt* varieties could decrease the profitability of marketing unapproved seeds.

Finally, there is a lot of controversy on whether *Bt* cotton increased the number of farmer suicides in India (Friends of the Earth, 2007). Gruère et al. (2008), in a comprehensive review of available evidence, attempted to establish the link between farmer suicides and *Bt* cotton cultivation in India. The authors found that official statistics on farmer suicides in India vary widely. Using data from the National Crime Records Bureau, Gruère et al. (2008) stated that the number of farmer suicides increased from 13,622 in 1997 to 17,006 in 2006. Over the period 2002-2006, i.e. after the introduction of *Bt* cotton in India, the number of farmer suicides decreased - although regional differences prevailed. The study concluded that there was no observed causality between *Bt* cotton adoption and farmer suicides. These nation-wide findings were found to be valid for the state of Maharashtra, but the case of Andra Pradesh was less conclusive. As reported in the study by Qaim et al (2005), farmers in Andrah Pradesh did not experience an increase in net incomes with *Bt* cotton adoption. In their final conclusion, Gruère et al. (2008) stated that *Bt* cotton was not a sufficient explanation for farmer suicides in India and that root causes of suicides, e.g. insufficient formal credit markets, needed to be addressed.

<u>China’s</u> experiences with *Bt* cotton are slightly different from India’s, which is mainly related to China’s institutional framework. *Bt* cotton was commercialized in 1997 by the private and public sector, but public varieties dominate the *Bt* cotton market (James, 2002). About 60 percent of the total Chinese cotton area was planted with *Bt* cotton in 2005, with higher shares (close to 100 percent) in provinces with large pest

pressures. Up to 300 *Bt* varieties were marketed in 2005 (Xu et al., 2009). Unlike in India, Chinese cotton farmers can save their *Bt* seeds, because the public sector *Bt* cotton varieties are open-pollinated varieties. Xu et al. (2009) estimated that 24 percent of all *Bt* cotton seeds are farm-saved, 20 percent from non-commercial channels, and 56 percent from a seed dealer. The large number of approved and unapproved varieties led the Chinese government to introduce a subsidy on approved seeds in order to stimulate their uptake. The consequences of the subsidy remain to be seen.

To our knowledge there are no recent peer-reviewed publications that evaluate farm-level impacts of *Bt* cotton in China. A team of Chinese and American researchers carried out early impact evaluations using farm survey data that comprised the years 1999 to 2001. The results from these studies are summarized in Smale et al. (2009). Here we pick one exemplary study to illustrate general research results: Pray et al. (2002) studied the impact of *Bt* cotton in China using a dataset, which comprised three years and four provinces. In 1999, 283 farmers from one province were randomly selected. In 2000, the sample was increased to 400 farmers from two provinces; and in 2001, 366 farmers in four provinces were interviewed. The study results revealed that insecticide reductions on *Bt* plots were on average 238 percent compared to non-*Bt* plots, over the three year period. Lower insecticide applications were reported to have positive impacts on farmers' health by reducing the number of insecticide-related poisonings. Yields increased on average by 23 percent, with large seasonal fluctuations. Compared to their Indian colleagues, Chinese farmers experienced higher insecticide reductions and lower yield effects, because they had initially applied large quantities of pesticides to achieve higher cotton yields. Despite significant reductions in insecticides, compared to non-Bt plots, Pray et al. (2002) observed that the amount of insecticides applied on *Bt* plots increased from 1999 to 2001. Looking at the economic effects, the study found that seed costs were on average 170 percent higher over the three year period. Total costs were reported to be on average 21 percent lower. Net incomes of *Bt* cotton farmers were positive in all seasons, while they were negative for their non-*Bt* counterparts. Pray and Huang (2003) considered the distribution of benefits from Bt cotton cultivation. They found that smaller farmers experienced higher gains than their large-scale colleagues.

More recent studies focused on the increased insecticide use by *Bt* cotton farmers. Higher insecticide costs lower net income gains and thereby erode the profitability of *Bt* cotton cultivation. For example, Wang et al. (2006), using a household survey of 481 farmers collected in 2004 in five provinces, found that total insecticide costs for *Bt* and non-*Bt* farmers were almost equal in 2004. The authors showed that *Bt* farmers sprayed more against secondary pests, which had emerged with the adoption of *Bt* cotton. Wang et al. (2006) demonstrated that expenditures to control secondary pests had nearly offset the savings in pesticides that control for cotton bollworms. The authors concluded that farmers need to be better informed of risks associated with secondary pest in order to keep them in check. Pemsl et al. (2007), using 2002 data from 150 small-scale farmers in the Shandong province, also observed that *Bt* cotton farmers sprayed a large number of other chemical insecticides. They concluded that Integrated Pest Management techniques could help to increase the profitability of cotton production even in the case of high *Bt* cotton adoption rates. As in the study by Wang et al. (2006), the authors also emphasized the necessity to train farmers better in pest management techniques. Finally, Xu et al. (2009), using data on 31 *Bt* cotton varieties provided by the Yangtze River Valley Varietal experimental network, demonstrated that there is a large variance in bollworm protection levels among the varieties tested. This was related to the genetic background of the varieties. The study also found that due to the variability farmers tend to spray more and earlier than actually required. Xu et al. (2009), similarly to the studies above, related this to an insufficient amount of training that cotton farmers, and *Bt* cotton farmers in particular, received.

2.2 Africa

Three African countries commercialized GM crops to date. The country with the largest GM crop area in Africa is South Africa where 2.1 million hectares of GM maize, soybean, and cotton are grown. Egyptian farmers cultivate GM maize, which was commercialized in 2008, on approximately 1,000 hectares. Burkina Faso commercialized *Bt* cotton in 2008, and to date 115,000 hectares are planted with GM cotton (James, 2009). In the following, we focus on the South African experience with *Bt* maize and *Bt* cotton, because farm-level impact assessments from other countries are not yet available.

Maize is a major crop in South Africa, and the majority of South African maize farmers are commercial farmers. *Bt* maize provides protection against stalkborers, which can cause significant yield losses (Gouse et al., 2006). There are two types of Bt maize being grown in South Africa: *Bt* yellow maize is predominantly used as a feed crop and was commercialized by Monsanto in 1998. *Bt* white maize is a staple food crop and was released in 2001 by Monsanto. In 2006-07, *Bt* yellow maize covered 35 percent of the total South African yellow maize area. The share of *Bt* white maize in total white maize area increased from eight percent in 2004-05 to 44 percent in 2006-07 (Gouse et al., 2009).

Few studies considered farm-level impacts of *Bt* maize in South Africa. A survey of 33 large-scale commercial farmers of *Bt* yellow maize in 1999-00 and 2000-01 found that the average yield advantage of *Bt* yellow maize over conventional maize was about 11 percent (Gouse et al., 2005). The study also showed that *Bt* yellow maize reduced insecticide costs by 163 percent and 171 percent for irrigated and dryland maize, respectively. The income advantage of *Bt* yellow maize over non-*Bt* yellow maize was shown to be positive; it was higher in irrigated areas (117 USD/hectare) and lower in dryland areas (35.5 USD/hectare). Gouse et al. (2006) analyzed the adoption of *Bt* white maize by smallholder farmers by conducting a survey comprising three seasons. In 2001-02, which was the first year of *Bt* white maize commercialization, 368 smallholder farmers in four provinces of South Africa were interviewed. In 2002-03 the authors interviewed 104 farmers in one province (KwaZulu Natal); and in 2003-04, 196 farmers were interviewed in KwaZulu Natal. All three seasons were characterized by pest infestation levels below average. In 2001-02 about 3000 farmers, who attended a workshop, received *Bt* white maize seeds for free. In subsequent years farmers had to buy *Bt* seeds in the market, but seed shortages were reported. Gouse et al. (2006) found that in the first season yield differences between *Bt* white maize and non-*Bt* white maize were 32 percent. In the second season yield differences were 16 percent, and the authors remarked that in this particular season the sample size was smaller and data variation larger. In the third year, no significant yield differences were reported and *Bt* maize cultivation did not give an advantage to its adopters (Gouse et al., 2006). This was related to the low pest infestation levels. Survey farmers perceived *Bt* white maize to be of better quality and taste than non-*Bt* varieties. No average economic effects were reported by the study.

Cotton is produced on about 6,000 hectares in South Africa, of which 70 percent are irrigated. Cotton production is dominated by large-scale farmers. The Delta Pineland company, with genetic material from

Monsanto, commercialized *Bt* cotton in 1998. Farm-level impact studies focused on the Makhatini Flats region in the KwaZulu Natal province (e.g. Morse et al. 2006; Bennett et al., 2004a). Overall this region contributes six percent of the South African cotton production. Cotton producers in the area are mainly smallholders, and the number of women farmers is high. A private cotton company, Vunisa Cotton, introduced *Bt* cotton in the Makhatini Flats and provided inputs, credit, and extension to farmers. It also bought cotton outputs to recoup credit expenses (Morse et al., 2006). Adoption of *Bt* cotton in the Makhatini Flats was rapid: 92 percent of all cotton farmers in the area were adopters in 2002 (Bennett et al., 2004). Witt et al. (2006) describe this rapid uptake as supply rather than demand driven, because of the inputs and credit provided by Vunisa cotton.

To analyze farm-level impacts of *Bt* cotton in the Makhatini Flats, Bennett et al.(2004) and Morse et al. (2006) used data from a farm survey and Vunisa Cotton that comprised three seasons (1998-99 to 2000-01). Data for the first season included 1283 farm observations, for the second season 441 observations, and for the third season 499 observations. With respect to the agronomic effects, both studie found that insecticide amounts were reduced on average by 115 percent. These reductions were higher for smallholders than for farmers with large holdings (Bennett et al., 2006). Lower insecticide applications also had a positive impact on labor time and on water required for insecticide sprayings. Bennett et al. (2003, p. 126) estimated that “for every hectare of *Bt* cotton, farmers save two days of work (one day for spraying and one day for collecting water)”. This benefits particularly women and children who mainly apply insecticides and fetch water. Lower incidences of insecticide-related poisonings were also reported. Furthermore, the authors found that over the three year period, average yield advantages of *Bt* over non-*Bt* cotton varieties were 68 percent. Seed prices were on average 88 percent higher for *Bt* cotton. Net incomes for the season 1998-99 and 2000-01 were on average 159 percent higher. The second season, 1999-00, was a year with particular high pest pressures, and net incomes for non-*Bt* cotton plots were negative, while they were positive for Bt-plots (Morse et al. 2006). Looking at the distribution of benefits, Gouse et al. (2004) found that small-scale dryland farmers received benefits that were similar or larger compared to large-scale dryland and large-scale farmers with irrigated landholdings.

From 2003 onwards – just after three seasons of *Bt* commercialization – the production of *Bt* cotton fell drastically (Gouse et al., 2005). This was due to changes in the institutional environment: Vunisa Cotton, which initially promoted *Bt* cotton, did longer provide input credits and withdrew altogether from the Makhatini Flats (Witt et al., 2006). Consequently, the production of Bt cotton decreased and further adoption slowed down. Unfortunately, we were unable to trace information on how many farmers dis-adopted *Bt* cotton upon withdrawal of resources. Water availability is constrained in the Makhatini Flats, and dryland farmers have few alternatives to cotton cultivation (Witt et al., 2006). Improving cotton markets and cotton production is therefore paramount. The *Bt* cotton experience clearly illustrates the importance of good governance and an efficient institutional framework to unlock existing technology potentials (Gouse et al., 2005; Witt et al., 2006). A supportive institutional framework and a well-functioning infrastructure, e.g. input, credit, and output markets, can enable the uptake of modern technologies and boost the speed of innovation. On the other hand, weak rural institutions may hamper the adoption of any innovation considerably.

2.3 Latin America

Latin America is the continent with the second largest area of GM crops. Leading biotech countries in the region are Brazil (21.4 million hectares), Argentina (21.3 million hectares), and Paraguay (2.2 million hectares). Herbicide-tolerant (HT) soybeans are the predominant GM crop in Latin America. GM maize and cotton are cultivated to a lesser extent (James, 2009). Most HT soybeans contain a gene from the soil bacterium *Agrobacterium tumefaciens*, which makes the plant tolerant to the broad-spectrum herbicide Glyphosate. Monsanto markets glyphosate under the name Roundup Ready.

Compared to the area that HT soybeans occupy, it is surprising that only few studies considered their farm-level impacts in Latin America. Table 2 summarizes the results of a number of recently published studies. Qaim and Traxler (2005) evaluated the impact of HT soybeans in Argentina, which were commercialized in 1996. Since then the area under HT soybeans increased rapidly, and more than 90 percent of the Argentinean soybean area is planted with HT soybeans (Trigo and Cap, 2006). In Argentina, HT soybeans were introduced by a multinational private seed company. Farmers in Argentina can farm-save their seeds, because they are not required to sign special contracts with the seed company.

This particular institutional arrangement boosted the uptake of HT soybeans in Argentina. It is estimated that 30 percent of the Argentinean HT soybean area are planted with farm-saved seeds (Qaim and Traxler, 2005).

Qaim and Traxler (2005), in their study on HT soybean adoption, found that the overall amount of herbicides applied is higher on HT soybean plots compared to conventional soybean plots. However, the authors also showed that the composition of herbicides applied changed: HT soybean adopters tended to use herbicides that were less toxic (i.e. glyphosate), whereas conventional soybean farmers used herbicides, that were more potent. The authors detected no significant yield differences between HT soybean adopters and conventional soybean growers. With respect to the average economic effects, Qaim and Traxler (2005) established that herbicide costs were significantly reduced, because glyphosate was less expensive compared to other herbicides. As a result, net income gains for HT soybean grower amounted to approximately eight percent. This is in line with Trigo and Cap (2006) who looked at impacts of GM crops in Argentina over a ten year period and concluded that on an aggregate level no significant yield differences were observed between HT and conventional soybeans.

(Table 2 about here)

Researchers at the International Food Policy Research Institute (IFPRI) recently carried out a study on the adoption of HT soybeans in Bolivia. Bolivia approved HT soybeans in 2005. In contrast to other countries in Latin America, soybean growers in Bolivia are mainly smallholders. Preliminary results from the study of 124 randomly selected soybean farmers suggest that the yield advantage of HT over conventional soybeans was 29 percent. Seed costs were higher for HT soybeans (14 percent), while herbicide and total costs were lower. Net incomes for HT soybean farmers increased significantly by 45 percent (Paz et al., 2009).

HT soybeans also confer other – less tangible – benefits. They allow for an increased flexibility and ease in crop management, because glyphosate controls for a broad spectrum of weeds and allows for a larger time window of herbicide applications (Brookes and Barefoot, 2009). This reduces labor requirements – either reducing the need for hired labor or freeing up time of the farmers and their families. Such aspects are particularly relevant in situations of labor shortages or the high use of family-labor for crop operations. In addition to this, HT soybeans can be grown in no-tillage systems that further reduce labor requirements and machinery costs. No-till agriculture can also reduce soil erosion and lead to a higher soil productivity.

Yet, recent studies on HT soybeans in Argentina documented glyphosate resistance in weeds, e.g. in Johnsongrass (Binimelis et al., 2009). This could undermine the profitability of HT soybean cultivation, if no changes in weed management strategies are introduced. Binimelis et al. (2009) argued that a more complex weed management system should include crop diversification, crop and herbicide rotation, and integrated weed management. Other (supplementary) ways to reduce the general over-reliance on glyphosate could be to speed up the development, testing, and regulatory approval for HT crops that are tolerant to other broad-spectrum herbicides, e.g. glufosinate or Dicamba. Similar to glyphosate, the World Health Organization classified glufonisate into Toxicity class III (slightly hazardous).

The last case study presented in Table 2 is a study on *Bt* cotton adoption in Argentina by Qaim and de Janvry (2005). Monsanto commercialized *Bt* cotton already in 1998, but adoption rates are low. This is related to the high technology fee, which Monsanto applies to the *Bt* seeds. Unlike in the case of soybeans, Argentinean cotton farmers cannot farm-save their seeds as this is forbidden under the conditions under which they purchase *Bt* seeds. In line with *Bt* cotton experiences in China and India, the authors showed that *Bt* cotton significantly decreases insecticide sprays and increases yields. Moreover, differentiating by farm size, the authors stated that smallholder farmers could benefit more from cultivating *Bt* cotton than their large-scale colleagues. Qaim and de Janvry (2005) emphasized the importance of an effective institutional framework as a pre-condition for technology adoption and diffusion.

3 The Research Pipeline

FAO (2010) identified several major research areas to address the future challenges that agriculture faces: *Biotic stresses* like the current main pests, diseases, and weeds will need continued attention of researchers. In addition, new diseases, like wheat black stem rust, are projected to emerge due to increases in global trade and transportation (and imperfect phytosanitary measures). In the face of climate change, addressing also *abiotic stresses*, like drought and salinity, will become increasingly significant. Breeding for sustainable *yield increases* will be important, particularly for so-called “orphan crops”, where potential yield gaps tend to be large. Finally breeding for improving the *nutritional quality* of food crops can be an important element in tackling malnutrition in developing economies (FAO, 2010). Addressing these complex challenges will require enormous investments in research, development, and extension. In the following section, we look at GM crops that are currently in the research pipeline and check this inventory against the above described research challenges.

3.1 What is in the Research Pipeline?

The area under GM crops is expected to grow further in the future. It is projected that the number of countries approving GM crops will increase from 25 in 2008 to about 40 countries in 2015. The majority of countries adopting GM crops for the first time will be developing economies in Asia, Africa and the Near East (James, 2008). It is further estimated that, depending on the release of GM rice, the area under GM crops could increase from 125 million hectares today to 300 million hectares in 2015 (James, 2008).

In the short to medium run, new variety releases will remain focused on crops that are currently dominating the market for GM crops, i.e. maize, soybeans and cotton. Herbicide-tolerance and insect resistance will continue to be key traits incorporated into GM crops. Stacked crops, i.e. crops with one or more traits, will increasingly become available. Stein and Rodriguez-Cerezo (2009) provide a comprehensive overview of crops that are currently in the research or regulatory pipelines worldwide. Figure 1 summarizes the number of GM events to be released in the short to medium run for six different crops. GM events describe the type of gene incorporated into a plant. Commercialization dates should be read with caution, because regulatory processes as well as consumer resistance to certain crops are factors that are difficult to project and may delay commercialization dates considerably.

(Figure 1 about here)

The figure shows that the number of events in a number of crops is expected to grow. Soybean events, for example, are projected to increase from currently one event to 17 events in 2015. Herbicide tolerance will remain the main trait. Research on new GM soybeans will continue to be dominated by the large multinationals, e.g. Monsanto, Bayer Crop Science, Pioneer (Stein and Rodriguez-Cerezo, 2009).

For maize the situation looks similar: Insect-resistance will remain the dominant trait in maize, and GM events that are currently in the advanced research or regulatory pipelines are mainly developed in the laboratories of large private sector companies. It is not clear whether the genes will be incorporated into yellow or white maize (i.e. into feed or food crops). A special case is drought-tolerant maize that is expected to be commercialized in 2012 in the USA and by 2017 in sub-Saharan Africa (Edmeades, 2008). Drought-tolerant maize is considered in more detail below.

The number of cotton events becoming available on the market may more than double by 2015, and insect resistance as well as herbicide tolerance will remain the main traits in cotton. The majority of cotton gene events are developed in China and India, respectively. This follows the general trend that GM events in major crops will increasingly be developed in developing countries of Asia and Latin America for domestic crops and markets (Stein and Rodriguez-Cerezo, 2009). In line with increased R&D activities of major emerging economies, South-South cooperation in research and development is expected to increase (e.g. Dickson, 2003). There are a number of other crops at various stages of the R&D pipeline that may be released in the medium to long-run in developing economies. These crops are summarized in Table 3 below, by country.

(Table 3 about here)

The table demonstrates that even though the research pipeline is impressive, in the medium to long run the market for GM crops will expand, but it will not change dramatically. Maize, soybean, and cotton are expected to continue to dominate the global market. Insect-resistance and herbicide-tolerance will be the main traits incorporated into GM crops. Given the evidence presented in the previous section, this gives reason to assume that farmers will be able to extract higher net incomes from these crops by the means of lower input requirements and/or higher yields. Yet, the challenges that agriculture faces, as outlined above, may not be adequately addressed. Insect-resistant rice and drought-tolerant maize are research efforts that try to address some of these challenges. They are considered in detail below.

3.2 Genetically Modified Drought-tolerant Maize

Water scarcity and climate change have unfavorable effects on crop growing conditions, particularly in low latitude regions like sub-Saharan Africa. Climate change is projected to increase temperatures and the number of adverse weather events, and appropriate measures need to be taken to adapt to these impacts. Drought-tolerant crops are one potential option. Edmeades (2008, p. 4) states that "As a rough rule of thumb, it has been estimated that 25% of losses due to drought can be eliminated by genetic improvement in drought tolerance, and a further 25% by application of water-conserving agronomic practices, leaving the remaining 50% that can only be met by irrigation". Among drought-tolerant crops, research on maize, which is a major staple food crop, is the most advanced. This is particularly relevant as most of the global maize area is rainfed, and yield losses in drought years can be substantial (Edmeades, 2008; Fischer et al, 2009).

Monsanto and BASF are leaders in the research on drought-tolerant maize. In a joint press release in June 2009, the companies announced that they identified a gene that, when incorporated into maize, will make the maize plant more resistant to abiotic stresses. Field trials, carried out in the drought-prone Western Great Plains of the USA, showed that drought-tolerant maize had a yield advantage of 6 to 10 percent. Product registrations have been filed by the two companies in North America, Colombia, and the European Union. Drought-tolerant maize is expected to be released in the USA by 2012 (Monsanto and BASF, 2009).

There are currently two initiatives that aim to develop and distribute drought-tolerant maize for smallholder farmers in sub-Saharan Africa; the Water Efficient Maize for Africa (WEMA) and the Drought Tolerant Maize for Africa (DTMA) initiative. WEMA is a large-scale public-private partnership between various partners from the North and the South. The International Maize and Wheat Improvement Center (CIMMYT) contributes locally adapted high-yielding maize varieties. BASF and Monsanto provide proprietary, but royalty-free, germplasm and their top-class expertise in genetic engineering and commercial seed development. The African Technology Foundation distributes the developed seeds. National Agricultural Research Institutes and private sector companies in Kenya, Uganda, Tanzania and South Africa test, multiply, and distribute the seeds to small-scale farmers (African Agricultural

Technology Foundation, not dated). Kenya, under the lead of the Kenya Agricultural Research Institute, is expected to start the first confined field trial of drought-tolerant maize developed under the partnership scheme in 2010 (Muthaka, 2009). Drought-tolerant maize is projected to be released in sub-Saharan Africa by 2017.

The DTMA Initiative is led by CIMMYT and IIATA in partnership with 50 organizations. According to the DTMA, the goal over the next ten years is "to generate maize varieties with 100% superior drought tolerance; increase productivity under smallholder farmer conditions by 20-30%; and reach 30-40 million people in sub-Saharan Africa" (CIMMYT, not dated). The project comprises 14 countries in sub-Saharan Africa and is also concerned with improving seed marketing and seed production of maize in these countries.

While these initiatives are promising their actual impact will depend on many factors. One of these factors is whether newly developed varieties will by open-pollinated varieties or hybrids. This could have significant consequences on extension and distribution channels, seed costs, the willingness of farmers to adopt, speed of adoption, and the distribution of benefits. In addition, as stated above, drought-tolerant crops will need to be supplemented by improved water management techniques to achieve the highest possible gains (Edmeades, 2008).

3.3 Genetically Modified Rice

Application of biotechnology tools to rice breeding is currently carried out in a number of countries. China is the leading country in *Bt* rice development, and 20 percent of the Chinese public expenditures in agricultural biotechnology research are allocated to rice (Huang et al., 2008). *Bt* rice provides resistance to the rice stemborer and bacterial blight and is on the eve of commercialization in China. GM rice has been tested in confined field trials since 1997. Huang et al. (2008) published a study on the farm-level impacts of *Bt* rice in preproduction trials. Their data comprised three years (2002-2004) and 17 villages in two rice growing provinces. The authors surveyed 320 randomly selected farm households: 73 in 2002, 104 in 2003 and 143 in 2004. Of these, 119 households had both *Bt* and non-*Bt* rice plots. The average land holding of sampled households was one hectare. In total, data for 584 rice plots were collected. In the following, we report results for the 119 households that had *Bt* and non-*Bt* rice plots to control for potential biases related to farm household characteristics. Applying partial farm budgeting, the authors found that *Bt* rice adoption decreased pesticide sprayings by nearly four times, but yields increased by only one percent. Huang et al. (2008) also reported a six fold decrease in pesticide costs, and labor days per hectare for pesticide spraying decreased by almost nine days for *Bt* rice adopters.

Despite these positive farm trial results, a number of factors concerning the commercialization of *Bt* rice need to be considered. First of all the demand for rice in China is expected to decrease as consumers increasingly demand more protein-rich foods and meat products. In addition to this, *Bt* rice has been incorporated into varieties of lower quality hybrid rice cultivars, which may decrease the potential demand for *Bt* rice. Inserting the *Bt* gene into rice hybrids could decrease the farmers' willingness to adopt the new varieties and slow down the speed of adoption. Additionally, China is currently a net exporter of rice; in 2007 Chinese exports were valued at 28 million USD, which is relatively small compared to other major rice exporters. The impact of GM rice commercialization on international trade remains to be seen (Huang et al., 2008).

4 Summary and Concluding Remarks

This paper reviewed farm-level impacts of GM crops in developing countries and gave an overview on GM crops that are currently in the research pipeline in developing countries. We showed that GM crops can be beneficial to farmers in developing economies. Case studies from three continents proved GM crops have positive agronomic as well as economic effects: In general, farmers benefited significantly from adopting GM crops by means of reduced input requirements and/or higher yields. This led to considerable average gains in farmers' net incomes. Looking the distribution of benefits revealed that farmers, including smallholders, benefited most from the seed technology. Increases in farm incomes tended to have positive indirect effects on the rural economy.

Farm-level impacts of GM crops can vary considerably by region and season. Case studies in India, for example, showed large yield variations between and within states. Case studies from Africa pointed out that annual variation significantly influences farmers' net benefits. Like for conventional crops, GM crop performance depends on a wide range of factors, like agronomic conditions, pest loads, availability of alternative pest control measures and local adaptation of the plant variety used. Furthermore different GM seed types (i.e. approved, unapproved and farm-saved) may also have contributed to yield variability observed in many countries.

Sales of unapproved seeds were reported on most continents. This highlights that controlling the spread of GM crops is difficult, and caution in permitting field trials should be exercised. The spread of unapproved seeds also points out to the importance of functioning regulatory frameworks. Regulatory frameworks should be set-up in a way that ensures that newly released crops are safe for human and animal health and for the environment and that encourages research and development by being cost-efficient and clearly defined. To date a number of countries (particularly in Africa) do not have fully-functioning regulatory systems in place (Barry, 2009). Even in countries where regulatory systems are in place, technical and management capacity to implement regulations may be lacking (Zepeda et al., 2009). In addition, regulatory costs may be discouraging innovators. Bayer et al. (2009), in a case study on regulatory costs in commercializing *Bt* eggplant, virus-resistant tomato, and *Bt* rice in the Philippines, calculated that regulatory cost can make-up up to 50 percent of the total costs.

The case studies also illustrated the significance of institutional frameworks and functioning input and output markets. The capacity of the agricultural research system (private/public), the enforcement of intellectual property rights, properly functioning seed and credit markets were shown to have an important impact on the speed of adoption and the distribution of cultivation benefits to farmers (Raney, 2006). These enabling factors are highly relevant to unlock technology potentials and to ensure that all farmers have access to productivity-enhancing technologies. In relation to this, the case studies also emphasized the role of extension systems. In order to reap the full benefits of a technology and to use it in the best possible way, farmers need to receive better training on modern technologies. Information on refuge areas, the emergence of secondary pests, and glyphosate resistance should be provided as well as information on supplementary farm-practices such as integrated pest management or integrated water management techniques.

Current research on GM crops in developed and developing countries remains focused on commercial crops over the short to medium term. Yet, large developing countries, like India and China, are becoming larger players in the market for GM crops and South-South cooperation in research and development is also projected to increase. Many technologies that could address farmers' needs and the future challenges to agriculture effectively are also in the research pipelines and may be released over the medium to long run. Greater research efforts and large-scale investments in agricultural markets and regulatory and institutional frameworks are required to make such technologies available and accessible for farmers in developing economies.

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Table 1: Average farm-level impacts of *Bt* cotton in India, partial farm budgeting

Source	Data	Average agronomic effects		Average economic effects			
		Insecticide sprays	Yields	Seed costs	Insecticide costs	Total costs	Net income
Barwale et al. (2004)	1069 cotton farmers, six states, 2002 season, survey administered by Mahyco	-62%	+61%	n/a	n/a	n/a	n/a
Qaim et al. (2005)	341 cotton farmers, four states, panel data, 2002 – 03 season	-62%	+34%	+221%	-69%	+17%	+69%
Morse et al. (2005)	3496 farmers, Maharashtra state, 2002 – 03 and 2003 – 04 season	-59%	+51%	n/a	-112%	n/a	+58%
Bennett et al. (2004)	787 cotton farmers, Maharashtra state, 2002 – 03 and 2003 – 04 season	-69%	+54%	+224%	-111%	+8%	+62%
Kambhampti et al. (2006)	2709 cotton farmers, Maharashtra state, 2002 – 03 and 2003 – 04 season	-70%	+54%	n/a	n/a	+9%	+62%
Morse et al. (2007)	157 cotton farmers, Maharashtra state, 2002 – 03 and 2003 – 04 season	n/a	+35-86%*	n/a	n/a	+13-32%*	+62-144%*
Crost et al. (2007)	338 cotton farmers, Maharashtra state, panel data comprising the years 2002 to 2003	n/a	+11-31%*	+243%	-15%	n/a	n/a
Ghandi and Namboodiri (2006)	694 cotton farmers, four states, 2003 – 04 season	-66%	+47%	+183%	-44%	+17%	+102%
Bennett et al. (2005)	622 cotton farmers, Gujarat state, 2003 – 04 season	n/a	+29%	n/a	n/a	n/a	+132%
Sadashvippa and Qaim (2009)	341 cotton farmers, four states, panel data comprising the years 2002 – 2007	-29%	+40%	+166%	-24%	+17%	+89%

Upper and lower range, when accounting for self-selection biases (see discussion in text)

Table 2: Farm-level impacts of GM crops in Latin America, partial farm budgeting

Source	Crop/Country	Data	Average agronomic effects			Average economic effects		
			Herbicide applications	Yield	Seed cost	Herbicide cost	Total cost	Net income
Qaim and Traxler (2005)	Soybeans/Argentina	59 soybean farmers, three provinces, 2001, 3 year average, plot comparisons	+107%	+0.3%	+21%	-76%	-11%	+8%
			Number of insecticide sprays	Yield	Seed cost	Insecticide cost	Total cost	Net income
Qaim and de Janvry (2005)	Cotton/Argentina	299 cotton farmers, two provinces, 1999 and 2000 season, plot comparisons	-52%	+61%	n/a	n/a	n/a	n/a

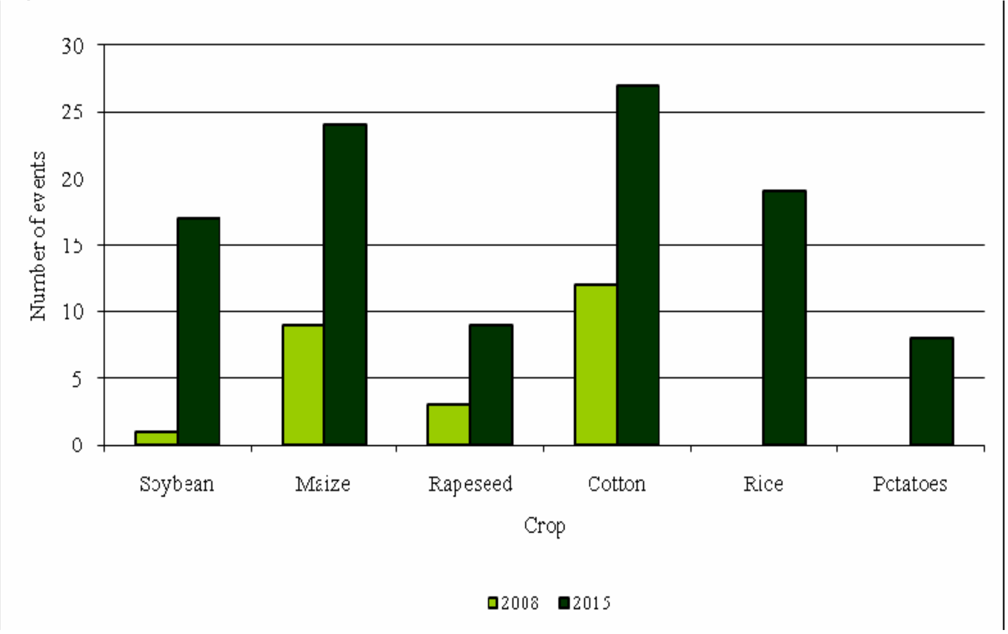
Table 3: Research pipeline, selected crops, by country

Country	Crop	Trait	Status
Argentina	Safflower	Modified product quality	Field trials
	Tomato	Modified product quality/virus/insect/ fungal resistance	Field trials
	Wheat	Herbicide tolerance/fungal resistance	Field trial
Brazil	Rice	Herbicide tolerance	Field trials
	Beans	Herbicide tolerance/fungal resistance	Field trials
	Sugarcane	Insect resistant/Herbicide tolerance/Crop composition	Field trials
Chile	Tomato	Modified product quality/virus/insect/ fungal resistance	Field trials
China	Papaya	Virus resistance	Recommendation for commercialization
	Soybean	Herbicide tolerance	Field trials
	Tomato	Modified product quality/virus/insect/ fungal resistance	Field trials
	Wheat	Herbicide tolerance/fungal resistance	Field trial
Egypt	Potato	Potato Tuber Moth resistance	Field trials
	Tomato	Modified product quality/virus/insect/ fungal resistance	Field trials
Guatemala	Tomato	Modified product quality/virus/insect/ fungal resistance	Field trials
India	Eggplant	Shoot and fruit borer resistance	Field trials
	Tomato	Disease resistance	Field trials
	Cabbage/Cauliflower	Herbicide/Insect resistance	Field trials
	Okra	Insect resistance	Field trials
	Groundnut	Aflatoxin-resistance	Field trials
	Mustard	Herbicide resistance	Field trials
	Rice	Herbicide tolerance	Field trials

Indonesia	Potato	Late blight-resistance	Isolated field test (IFT) of transgenic potato selected lines for one season
	Tomato	Multiple virus resistance	Field trials
	Rice	Herbicide tolerance	Field trials
	Cassava	Virus resistance	Field trials
Kenya	Sweet potato	Insect and virus resistance	Field trials
	Maize	Insect resistance	Field trials
	Cassava	Cassava mosaic virus resistance	Field trials
Mexico	Rice	Herbicide tolerance	Approved
	Tomato	Modified product quality/virus/insect/ fungal resistance	Approved
Philippines	Papaya	Papaya ring spot virus resistance	Proposals for confined trials 1 and 2 approved and completed
	Eggplant	Fruit and Stemborer resistance	Field trials
	Tomato	Multiple virus resistance	Greenhouse and laboratory studies completed
	Rice	Herbicide tolerance	Field trials
South Africa	Potato	Potato Tuber Moth resistance	Field trials
	Sorghum	Food composition	Greenhouse trials
Tanzania and Mali	Cotton	Bollworm resistance	Field trials
Thailand	Tomato	Modified product quality/virus/insect/ fungal resistance	Field trials
Uganda	Banana	Pest (e.g. Black Sigatoka) and disease (Banana weevils resistance)	Field trials
West Africa	Cowpea	Pod borer resistance	Establishment of the network for genetic improvement for cowpea in Africa

Source: Norton and Hautea (2009), Eicher et al. (2006), GMO Compass, Barry (2009)

Figure 1: Projected increase in GM events, 2008-2015



Source: Stein and Rodriguez-Cerezo (2009)