Transferring Biotechnology to the Developing World: Bt Cotton Has Led the Way

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Abbreviations: Bt: Bacillus thuriengensis; GM: genetically-modified; RR: Round-up Ready; HT: herbicide-tolerant

ABSTRACT

The many issues involved in the transfer of biotechnology to the developing world is reviewed. In particular, the role that Bt cotton has played as the first transgenic crop introduced into many countries is highlighted. Although benefits can vary regionally and from year-to-year, overall, every country that has adopted Bt cotton has seen that it has benefited both large- and small-scale farmers in terms of reduced use of pesticides and yield increases. Some of these success stories are briefly described along with a discussion of some of the lessons learned from experiences in countries like India, China, Argentina, and South Africa. The article also analyzes what opportunities and challenges lie ahead for development of new traits in a variety of crops important to the developing world.

KEYWORDS: cotton; Bt; developing world; sub-Saharan Africa; GM crops; biotechnology

Most of my career was spent in Academia, where my research involved in one way or another use of the cotton fiber as a model, focusing in particular on the structure and biosynthesis of the fiber cell wall. Examples of this work include early studies on changes in cell wall composition during development (Meinert and Delmer, 1977), modeling metabolic flow from supplied carbon sources into cellulose (Carpita and Delmer, 1981), providing evidence for a role for sucrose synthase in providing carbon for synthesis of cellulose (Amor et al., 1995), the first identification of genes that encode cellulose synthases in plants (Pear et al., 1996), and evidence for a role for sterylglucosides as primers for cellulose synthesis (Peng et al., 2002). Late in my career, I made the decision work with The Rockefeller Foundation to help identify ways in which upstream science might be harnessed for downstream applications for agriculture in the developing world (Delmer, 2005). This work, largely involving development of a portfolio of grants to support projects in biotechnology for sub-Saharan Africa, really had nothing to do with cotton. Now, with the invitation to write this article, these two distinct worlds have collided, and I am faced with the challenge of concentrating on the role that cotton has played in the application of biotechnology in the developing world. I do this with some trepidation since almost anything one writes briefly about biotechnology in the developing world is bound to contain oversimplifications. Nevertheless, I shall try to assess the current situation and will also point out some lessons learned in some of these countries, with the hope that these may also be relevant for future technology transfer in support of agriculture for small-scale poor farmers throughout the developing world.

The recent surveys by Brooks and Barfoot (2005) and James (2006) certainly point out how the development of genetically-modified (GM) crops has transformed global agriculture. From the time of the first introduction of a GM crop in 1996 to today, current plantings of the four major GM crops (soybeans, maize, cotton and canola) have now risen globally to more than 100 million hectares, and farm incomes are estimated to have benefited from this in the past ten years by over $24 billion in revenues. For the developing world, insect-resistant (Bt) cotton has certainly paved the way, representing the first GM crop introduced into key countries like China, India, and South Africa. While soybeans has been the predominant GM crop in Latin America, Bt cotton is also now grown in countries like Mexico, Columbia, Argentina and Brazil. While the benefits vary considerably from country to country and within different regions of individual countries, in all cases one finds that overall, not only large-scale, but also small-scale, farmers have benefited. As a generalization, for countries like South Africa where access and cost considerations prevent poor farmers from using optimal amounts of pesticides, the benefits have been seen largely in increased yields that can sometimes exceed 50% (Morse et al., 2004). In countries like China where pesticide use has traditionally been high, the benefits are seen more in terms of reduced use of pesticides---the latter also contributing to reduced impacts on the environment and enhanced health benefits to farmers (Huang et al., 2002, 2003 and 2005; Pray et al., 2002).

Cotton Represents a Good Entry Point for Introduction of GM Technologies. The debate over the dangers of GM crops has certainly impacted their introduction into many countries in both the developed and developing world (Kent, 2004; Delmer, 2005; Miller and Conko, 2005). The first round of debates centered on fears of food safety, fears that have largely been debunked for the current generation of GM crops since there is no solid evidence for any health effects on humans or animals from any of the current crops. Since the major product of cotton is the lint, this crop has not been subject to such intense debate. Furthermore, the Bt and herbicide tolerant Roundup Ready (RR) genes have undergone extensive safety studies with a clean record, performance of these crops in the developed world has been a clear success story, and protocols for confined field trials are well-developed. Cotton is also a huge cash crop world-wide, in particular for small-scale farmers in China, India, and sub-Saharan Africa. The pests, in particular the bollworm that the initial Bt gene (Cry1Ac) targets, are widespread in the world and are the cause of serious yield reductions unless controlled. And, although one might argue that mistakes have been made in the process of introduction of Bt cotton around the world by the major player Monsanto and its international partner Delta and Pine Land, by and large, field trials have demonstrated the clear benefits of this crop in virtually every country where it has been tested. Although benefits can vary widely among locations and habits of the local farmers, for a gross average, globally Bt cotton adopters are using 33-77% less pesticide with yield increases averaging from 9—34% (Qaim and Matuschka, 2005). For all these reasons, Bt cotton represents an easy first choice for a country wishing to explore the benefits of transgenic crops.

Lessons from India. India is unique in that most of the quality cotton is hybrid, something made possible by the relatively low labor costs for seed production. Bt cotton was first introduced in 2002 with 3 hybrids carrying the Monsanto Cry1Ac gene and marketed through Mahyco Seeds. The majority of farmers are small-holders, and benefits in terms of reduction in pesticide use have been considerable. To cite one such study, Bt adopters used 72-83% less pesticide that targets bollworms, although the same amount is still used for sucking insects. Although this savings was mostly offset by the higher cost of the transgenic seed, the real benefit came from yields that were enhanced between 45—63% (Bennett et al., 2004). One interesting lesson from India has been the demonstration of the importance of locally-adapted germplasm. For example, in 2002/3, analyses (Qaim, 2005; Qaim et al. , 2007b) report that significant benefits accrued to farmers in three states, but in the fourth state, Andra Pradesh, any gains derived from the Bt gene were counteracted by the negative effects of the germplasm used., in particular in inability to cope with a drought that year. India has been one of many countries where regulatory processes have slowed the release of new varieties that are more adapted to local conditions. However, by 2006, up to four independent events in more than 60 hybrids have been released throughout India, and recent surveys now show very positive results for Bt in Andra Pradesh (Agroeconomic Research Centre, 2007). India has been one of several countries where seed piracy has been a serious issue (Jayaraman, 2004), something that will be discussed more in the Lessons from Latin America section below. In sum, although one still reads stories of localized failure of Bt cotton, overall, one cannot dispute the overall success of this crop in India. The farmers actions speak for themselves—last year India surpassed the U.S. to become the second largest producer of cotton after China, and sales of Bt cotton showed the largest proportional increase up now to 3.8 million hectares (James, 2006).

Lessons from China. The high rates of adoption of Bt cotton in China attest to its success in providing real benefits to small-holder adopters. As mentioned previously, pesticide use has traditionally been relatively high, and the biggest benefit of Bt cotton has come, not from yield gains, but from reduced pesticide use somewhere in the range of 60% (Huang et al., 2002). Overuse of dangerous pesticides and lack of protective gear have resulted in a high incidence of poisonings, and another obvious benefit has been to the health of Bt adopters (Hossain et al., 2004). China can offer an interesting lesson regarding the complexities of resistance management in the developing world. China does not mandate use of non-Bt cotton as a refuge, and the expectation has been that serious resistance to Bt would have developed by now, but there is no strong evidence for this as of this writing. The major reason for this has been attributed to the large number of alternate crops affected by the same pests that can serve as natural refugia (Wu and Guo, 2005). Assuming this interpretation is correct, it does offer hope that resistance management need not always follow the rules of developed countries provided one can demonstrate sufficient levels of natural refugia. This is certainly a critical issue for many countries in sub-Saharan Africa where the ability to mandate and enforce rules regarding refugia seems highly problematic. Another welcome development is the creation of new events like Bollgard II that have two Bt genes (Cry1Ac with Cry2Ab) with distinct modes of action making development of resistance much more unlikely (Bates et al., 2005). This line has been performing extremely well in India since its release by Monsanto/Mahyco Seeds in 2006 but it is not clear whether an agreement may be reached to market it in China.

Lessons from Latin America. Compared to India and China, the amount of land devoted to cotton production in the countries of Latin America is very small, and there are correspondingly only small land areas devoted to transgenic cotton. There is an interesting lesson to be learned, however, from the experience of a country like Argentina. As for all other adopting countries to date, Bt cotton has reduced pesticide use considerably (Qaim and deJanvry, 2005). However, the low adoption rates have been mostly attributed to the very high technology fee charged for the Bt seed (Qaim and deJanvry, 2003), and a similar situation apparently prevails in Mexico as well (Traxler et al., 2003; 2007). If there is one issue for which there still seems to be no clear “right answer”, it has to be how technology fees are set for transgenic seeds in the developing world. There is certainly a temptation where IP enforcement laws are strong to over-charge the farmers. The issue has been widely debated in India as well (Qaim, 2003), although some of the criticism of the relatively higher prices there compared to countries like China do not take into account that all Bt cotton seed in India is hybrid and the seeding rates are much lower in India. China has weak protection laws, seed prices are relatively low, and farmers often save seed but this is offset somewhat by a higher seeding rate. The sale of illegal seed has been a serious problem in many of these countries. While such piracy may be seen to benefit poor farmers in short term, in the long term it almost always leads to loss of seed quality and the retreat of critical private sector suppliers. One interesting solution in South Africa has been a two-tiered pricing scheme for large-scale and small-scale farmers(Qaim et al. 2007a).   For a large company like Monsanto, the two-tiered system can be quite attractive as it is good publicity, helps build future markets, and does positive good for the poor; one challenge is how to respond to the complaints of major clients world-wide who pay much higher technology fees. One positive development is that, as a country like China begins to develop more and more of its own products, one sees a heightened respect for intellectual property law; similarly, as poor farmers realize the value of high quality seed and the pitfalls of purchasing illegal seed, the attractions of purchasing legal seed clearly become greater. Finally, one cannot neglect to mention the case of Brazil, where extensive delays in deregulating RR soybean that was much desired by its farmers, led to extensive piracy of ill-adapted seed from Argentina..

Lessons from sub-Saharan Africa. South Africa is the only country in sub-Saharan Africa where transgenic crops are grown. Bt cotton led the way, and today 93% of all cotton grown is transgenic with the rest representing the required refugia of non-Bt cotton. More recently, Bt maize and RR soybean have also been adopted. There has been a dramatic shift from Bt alone in cotton to the use now of Bt stacked with the RR trait (M. Gouse, personal communication).   Studies have clearly shown that both large- and small-scale farmers can benefit from Bt cotton, both in terms of reduced pesticide use and increased yields--the latter being more important for poor farmers (Ismael et al., 2002; Thirtle et al, 2003; Gouse et al., 2004; Morse et al., 2004). Until recently, South Africa was something of a poster child for how transgenic crops can benefit the poor.

Then something quite unexpected happened in the Makhatini Flats where the majority of poor farmers grow cotton. Traditionally, these farmers obtained credit to buy seed from the one local gin and paid this back when they sold their crop back to the gin. Then, in 2001/2, a second gin opened, an event that tempted the farmers to obtain their credit from the first gin but sell their crop to the second. Needless to say, this was an unsustainable situation and has resulted in no credit now being offered to the farmers. When coupled with lowered global prices for cotton and the strengthening of the SA Rand, the success story has been tarnished somewhat for this critical country in sub-Saharan Africa (Gouse et al., 2005).

This lesson points out another critical issue---the importance for some of these small countries of having a single-channel marketing system. Another study by Tschirley et al. (2006) also discusses the complexities of the marketing systems for cotton in sub-Saharan Africa and shows other examples, as in Zambia, where a single-channel marketing system performs very well and is unrelated to the issue of transgenic vs. conventional cotton. In some ways, this may seem counter-intuitive and may not always be the best solution, but it clearly can be one very good solution where credit is important and marketing systems are not advanced. Indeed, the single-channel marketing system in Burkina Faso in West Africa may have contributed to the decision by Monsanto to work with scientists at INERA, the national agricultural research lab, to conduct a series of comprehensive field trials of their state-of-the-art Bollgard II cotton. The trials have gone very well, showing strong control by the Bt gene of local pests. The genes have now been back-crossed into local varieties, a biosafety system has now been instituted, and release of these varieties to farmers is expected within the next few years (J. Ouedraogo, personal communication).

What about subsidies and tariffs? There is much in the news today about the potentially damaging effects that subsidies can have for poor farmers in the developing world who are trying to compete in the export markets of the world. No doubt this debate prompted a recent comprehensive study by the World Bank and the World Trade Organization (Anderson et al., 2007) that analyzed the comparative benefits removal of such subsidies (and tariffs) might have on poor farmers in various countries compared to the benefits they might gain by much more extensive adoption of transgenic Bt cotton. The results are surprising in some ways. The study found that, globally, farmers would benefit much more from widespread adoption of Bt cotton (estimated benefit at $2.3 billion) than through removal of subsidies by the developed world (estimated benefit $283 million). However, one clear winner if subsidies were to be removed would be many of the cotton-producing countries of sub-Saharan Africa. They calculate that $147 million of the global benefit of $283 million from removal of subsidies would accrue to these countries, a value that is close to the benefit these same countries would receive from their more wide-spread adoption of Bt cotton that was estimated at $187 million. But the issue is complex because many small, poor countries are net importers of cotton, and these would benefit more from the lowered prices of cotton that would prevail if subsidies were maintained.

The next generation of transgenic crops. Because a number of key countries have now seen the benefits of Bt cotton, one may predict that this experience can in some ways at least help pave the way for testing of genes and other types of transgenic crops. For cotton, there is a clear need to identify genes that might control sucking pests, and also interesting is new work demonstrating specific down regulation of gossypol production in the seed (Sunilkumar et al., 2006). Some examples for other crops of where Bt genes could have real impact for small-scale farmers include: control of stem borers in maize, sorghum, or rice; of pod borers in pigeon pea or cowpea; of fruit and shoot borers in vegetables such as eggplant. Since mycotoxin contaminations can be particularly heavy in maize and sorghum in places like sub-Saharan Africa, the demonstration that Bt maize is more resistant to such infections (Wu, 2006), suggests an additional benefit. Although the current genes in use tend to target the Lepidopteran insects, several ongoing projects still being supported by The Rockefeller Foundation are now discovering that other Bt genes do have potential for control of some important Coleopteran pests such as the weevils that affect sweetpotato (cooperative project of The International Potato Institute, Auburn University and the national lab of Uganda) as well as parasitic nematodes such as those that affect banana (Ugandan national lab and University of California, San Diego). Numerous studies have shown that the pandemic of HIV/AIDS is seriously limiting labor for agriculture in sub-Saharan Africa (FAO, 2006), so any technology that is labor-saving, such as the use of herbicide-tolerant crops (HT) combined with no-till practices, has also attracted favorable responses from small-scale farmers in Africa (M. Gouse, personal communication). Still others conclude (L. Liu, personal communication) that the trend to move from paddy rice to direct-seeding ("aerobic rice") in Asia will never really take off until genes like RR are incorporated to solve the problems of weeds that are normally controlled by early submersion of the crop. Development of crops with enhanced tolerance to drought at key stages of development should have benefits for many crops globally. Control of RNA viruses through coat-protein mediated resistance or RNAi is already possible and has had great success already for papaya (Tripathi et al., 2007), but control of the very widespread and devastating geminiviruses that affect maize, cassava and many vegetables is still more of a challenge but certainly hugely important. We need new approaches also for the control of fungi that are so devastating to many crops. For farmers who lack transport and good storage, delayed ripening for fruits and vegetables is also a very attractive target. And of course, much is now being touted about the possibilities for biofuels. Clearly, Brazil has shown much more foresight than the rest of the world for ethanol production, and there may be good promise for some other tropical countries to revive moribund sugar cane industries and/or establish new sugar crops based upon tropical sugar beet or sweet sorghum. Yet I remain cautious about creating competition with food crops, and the poor also already face the dilemma of needing to use crop residues for fuel and building materials instead of replenishing infertile soils, so adding yet another use for residues as biofuels seems ill-advised. More attractive may be the development of integrated farming systems suitable for small-scale farming regions that lack power—systems that integrate the production of biodiesel with production of crops for human and animal consumption.

Some final thoughts. It is clear that the introduction of Bt cotton has taught us many valuable lessons about the right and wrong ways to transfer biotechnology to countries of the developing world. The key question now is how to move forward beyond this. Can the good that biotechnology can offer can be harnessed for the introduction of other types of crops that can have real value for poor, small-scale farmers around the world? Certainly we now see that the power of genomics can, and is, being put to use to create a whole new approach to breeding that can much more easily assess and bring to bear much more diversity in breeding lines and can greatly speed the process of introgression of good alleles into crops of value to all farmers. To many of us, it remains quite illogical that so many in society can accept without fear the many unidentified changes that can occur during the normal breeding process and can even find quite acceptable the idea that mutation breeding that introduces very large numbers of mutations into the genome while, at the same time, these same people reject the idea of GM crops. Yet the preciseness of the transgenic approach that moves one or only a few genes that are extremely well-characterized and documented to be safe would clearly seem to be, in the long run, the direction that modern breeding will inevitably take, particularly in cases where conventional breeding has not succeeded.

To counteract some of the negative attitudes toward the transgenic approach, obviously one goal is to promote a keener understanding of biology and genetics in the general population, and, of great immediate importance, to help ensure that every regulatory body in countries of the developing world has at least one scientist who understands the process of genetic engineering. The critical importance of having regulatory systems that are based upon sound science cannot be underestimated (Bradford et al., 2005). Also critical is to have these processes adapted to national needs and affordable. In this regard, I would give high praise to the regulatory process in The Philippines and would recommend it be examined as a potential model for other similar countries. Several recent initiatives liked the Public Research and Regulatory Initiative (www.pubresreg.org and the Specialty Crops Regulatory Initiative (http://www.biotech.ucdavis.edu/Links/BiotechIssues.cfm) have been trying to promote science-based regulation and also to ensure that public sector scientists have a voice in the development of global regulatory standards.

From my own recent experience, I might add a few other goals that I would see as key for developing world countries: 1) Development of strong local capacity to create, test, and develop products alone or with partners in advanced labs is essential; countries need to play a strong role in determining what products might be developed that have real benefit for their local agriculture, and their own scientists need to participate in that process. 2) Develop a clear understanding that there is a huge difference between contained and/or confined research trials that aim simply to test if a particular gene performs as predicted and more extensive field trials that would be performed later to test performance of a promising gene or genes in a larger number of genotypes and would also address food safety and environmental concerns prior to release to farmers. Functional genomic studies are now identifying the function of huge numbers of genes, and there is no question that a select number of these may have great value for crop improvement (Delmer, 2005). Yet, countries cannot do serious development of GM crops if they cannot do simple research trials to test these new ideas, without fuss and under well-controlled field conditions. There is only so much one can do in a laboratory or greenhouse. Transgenics must be evaluated in the field and protocols must be in hand to do this without endless applications, delays, and huge costs. Because such simple trials are an integral part of the research process, if this cannot happen, then local scientists will not be able to effectively participate in and evaluate these new technologies. 4) A need to more seriously address mechanisms of transgenic seed delivery for crops beyond cotton and maize and also to build up strong output markets; in particular, creation of competitive textile industries in sub-Saharan Africa could very much help promote the growth of cotton; 5) It would be most desirable to see the public sector succeed in ways that the private sector has already done. One has to note that all initial transfers of the Bt trait into cotton were made possible through the development of a superior product and the intense determination of one company—Monsanto. In this regard, it might be important for public sector scientists to resist wasting too much time trying to justify transgenic approaches and spend more time just getting the job done---creating new and successful varieties that can enrich the lives of the poor throughout the world.

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