Development of hybrid *Bt* cotton in China – A successful integration of transgenic technology and conventional techniques

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In China, transgenic Bt cotton is the main GM crop under large-scale commercial production. Field trials and surveys in different provinces show that Bt cotton varieties provided significant gains in net revenue to farmers as a result of reduced production costs. However, yield increase compared to the non-Bt cotton varieties with good management and pesticide applications was marginal. Hybrid (F1) Bt cotton developed after crossing a Bt line with a non-Bt line, resulted in approximately 20% yield increase over the Bt cotton variety. Hybrid Bt cotton has been widely adopted in southern China. Rapid adoption is mainly attributed to hybrid seed production in northern China and application of agronomic technique for hybrid cotton cultivation such as seedling transplanting and planting at lower population density in regions of Southern China. The experience of Bt hybrid cotton development in China could be useful to other developing countries.

DESPITE increasing evidence that transgenic *Bt* (*Bacillus thuringiensis*) cotton is contributing to yield increase, cost reduction and environmental protection[1,2], there are still doubts and concerns about the benefits and usefulness of the transgenic technology for small farmers in developing countries. Some critics argue that *Bt* cotton has little positive effect on yield, results in adverse impacts on natural enemies and can cause development of resistance to *Bt* in bollworm[3,4]. It has been suggested that genetically modified (GM) crops developed in the industrialized countries could also solve the pressing agricultural problems in developing countries such as China[5,6], South Africa[7] and India[8]. Since most of these reporters use China as an example of adopting as well as developing *Bt* cotton to support their viewpoint, it is necessary to report how and why China rapidly adopted *Bt* cotton. This paper aims to answer the following questions: Is *Bt* cotton bringing unit yield gains over non-*Bt* cotton? How and why has China developed and adopted *Bt* cotton, particularly hybrid *Bt* cotton?

History of *Bt* cotton development in China

Insect pests, particularly the bollworm (*Helicoverpa armigera*), have been a major threat to cotton production in China. Cotton growers have to struggle against these pests mainly by using pesticides. Chlorinated hydrocarbons (e.g. DDT), organophosphates, pyrethroids, or a combination of these, have been successively used in controlling cotton pests in China since 1980s. With rising pest pressure and increasing resistance to pesticides in insect pests, farmers had to use more and more pesticides in 1990s (ref. 9). As a result, China suffered a loss of approximately US$ 630 million from yield reduction and additional costs of chemicals in 1992 (ref. 10). China's pest problems led the nation's scientists to seek new alternatives to manage the pests. When the possibility of incorporating *Bt* genes for resistance to insect pests was demonstrated, research and development of transgenic cotton was immediately initiated by the Chinese authorities. By 1997, under the financial support of the government, two *Bt* cotton varieties were developed using a modified *Bt* fusion gene (*Cry lab* and *Cry lAc*) by the Chinese Academy of Agricultural Sciences (CAAS), and commercialized. Since then, more than ten cotton varieties incorporating the locally isolated *Bt* gene have been licensed for commercialization.

Although China developed *Bt* cotton with its own efforts soon after the USA, Chinese legislation did not prevent import of *Bt* cotton from USA during 1990s (ref. 11). Monsanto, in collaboration with the cottonseed company Delta and Pineland, developed *Bt* cotton varieties that were approved for commercial use in the USA in 1996. They collaborated with China Cotton Research Institute (CCRI) of CAAS for field tests of their *Bt* cotton varieties in the mid-1990s. Bollgard cotton 33B carrying *Cry lAc*, which performed well in field tests in northern China, was licensed in 1997. Since then, *Bt* cotton in China has spread rapidly. It is estimated that 1.8 million

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ha of *Bt* cotton was planted in China during 2002, accounting for nearly 45% of China's total cotton area (Figure 1). On the basis of personal interviews with officials in agricultural bureaus and farmers in the main *Bt* cotton growing provinces, it is estimated that 80% of the nation's total *Bt* cotton area was under Bollgard *Bt* cotton before 1999. However, presently Bollgard *Bt* cotton occupies only 55%, and the rest 45% grows China's own *Bt* cotton. This indicates a rapid increase in the proportion of locally developed *Bt* cotton in comparison to the introduced. *Bt* cotton was initially spread in the Yellow River region, mainly in Hebei and Shandong. Hybrid cotton with *Bt* gene and the corresponding techniques for seed production and cultivation were developed around 1999. Since then rapid spread of hybrid *Bt* cotton has been observed in the Yangtzer River region (mainly in Jiangsu, HuBei and Anhui) (Figure 2).

Comparison of *Bt* cotton and hybrid *Bt* cotton

To evaluate the impacts of *Bt* cotton on yield and monetary benefit to the farmers, field trials were conducted in 27 locations in 9 counties of 3 provinces (Hebei, Shandong and Jiangsu) in 2002 (ref. 12). These trials were managed by farmers using customary practices under the supervision of agronomists from Shandong Cotton Research Center (SCRC). Four adjacent 200 m^2 plots in each location were planted with four varieties respectively: (i) CCRI 12, a conventional cotton (CC) variety without *Bt* gene as control; (ii) CCRI 028, a hybrid cotton (HC) without *Bt* gene; (iii) 33B, a *Bt* cotton (*Bt*C) variety from Monsanto; (iii) SCRC 15, a popular *Bt* hybrid (HBtC)[13] cotton variety from crossing a CC line and a *Bt*C line. In addition, comprehensive information was collected from surveys on a number of households in Hebei, Shandong and Jiangsu in 2000–2001. Collected data from these households were used as complementary information to the field trials.

Previous studies conducted in USA and South Africa indicated that Bollgard cotton yielded significantly more than local CC varieties, and contributed to an additional income of US$ 54 per ha from saving in pesticides used and increased yield[14,15]. However, studies in China suggested that the current *Bt*C limited to relatively narrow genetic backgrounds, and low yield potential needed to be further improved[16].

Heterosis is a universal phenomenon in living nature. Therefore it was thought that exploitation of heterosis may be a quick way to incorporate resistance provided by *Bt* gene with other desired agronomic characters of the local cotton varieties. The dominant inheritance of *Bt* gene provides possibilities for developing worm-resistant hybrids. Though genetic background influences the expression of *Bt* gene[17], hybrids can be obtained by selection of parents and combing ability tests. Using this approach, China Cotton Research Institute (CCRI) has developed a hybrid cotton variety CCRI 29, and SCRC developed SCRC 15. Multi-location tests proved that the yield of the hybrid was about 20% higher than the *Bt*C cultivars. H*Bt*C has been widely adopted by farmers in southern China (Figure 2), where *Bt*C has been rejected due to its low yield potential[18].

Our field trials showed that mean yield per ha of *Bt*C 33B was 1.3% lower than the CC variety CCRI 12 (Table 1). Only in three *Bt*C plots, accounting for 10% of total plots, there appeared 1–9% increases in unit yield relative to their CC plots (controls). Surveys in trial fields by our agronomists indicated that the yield increase in these three *Bt*C plots was not due to its higher yield potential, but the result of the poor pest management in CC plots. Nevertheless, along with reduced pesticides application and saving of labour, approximately two times increase in average net revenue per ha were realized with *Bt*C relative to CC. It is suggested that the net revenue increase with *Bt*C primarily resulted from reduction in pesticide usage and labour, and not from yield increase. Results

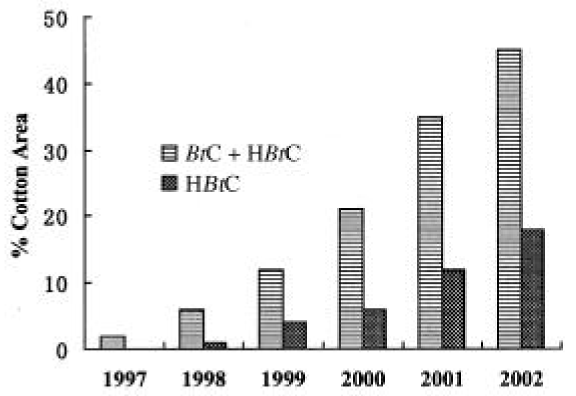

Figure 1. Adoption of *Bt* cotton (*Bt*C and H*Bt*C) in China.

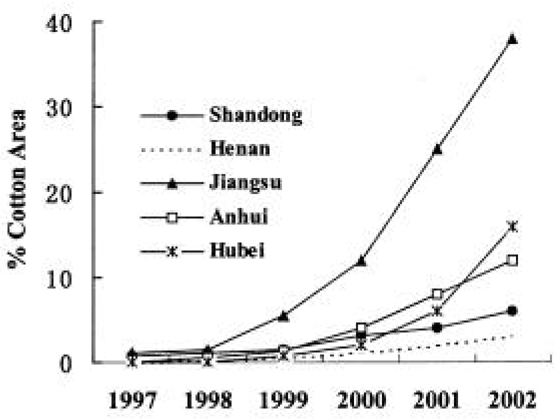

Figure 2. Spread of Hybrid *Bt* cotton (H*Bt*C) by province in China.

Table 1. Comparison of yield, costs and net revenue on conventional cotton (CC), hybrid cotton (HC), *Bt* cotton (*Bt*C) and hybrid *Bt* cotton (H*Bt*C) planted in three provinces

Cotton type	Lint yield (kg/ha)	Input value (US$/ha)	Output value (US$/ha)	Net revenue (US$/ha)
CC	1021 ± 35	1008 ± 57	1143 ± 75	125 ± 88
HC	1153 ± 84	1029 ± 65	1265 ± 92	235 ± 103
*Bt*C	1008 ± 57	722 ± 69	1107 ± 62	387 ± 117
H*Bt*C	1223 ± 85	760 ± 71	1286 ± 113	532 ± 147

Production costs mainly include fertilizer, seed, irrigation, plastic film and labour. Data (average ± sd) in the table were obtained from field trials in 2002. Figures were converted from Chinese Yuan to US$ with the official exchange rate.

Table 2. Comparison of yield, costs and net revenue on conventional cotton (CC), hybrid cotton (HC), *Bt* cotton (*Bt*C) and hybrid *Bt* cotton (H*Bt*C) in provinces sampled in 2000–2001

	2001				2002			
	Plots	Yield (kg/ha)	Costs ($/ha)	Revenue ($/ha)	Plots	Yield (kg/ha)	Costs ($/ha)	Revenue ($/ha)
Hebei								
CC	na	na	na	na	na	na	na	na
HC	na	na	na	na	na	na	na	na
*Bt*C	30	989	802	284	40	919	824	186
H*Bt*C	5	1127	982	258	10	1108	896	322
Shandong								
CC	10	1017	1089	29	na	na	na	na
HC	10	1108	1112	105	na	na	na	na
*Bt*C	80	1002	843	259	60	989	858	229
H*Bt*C	30	1119	879	352	80	1124	865	371
Jiangsu								
CC	50	1026	1098	306	40	1007	1123	–15
HC	50	1124	1121	109	20	1069	1145	31
*Bt*C	30	1018	834	285	30	1002	902	200
H*Bt*C	50	1189	858	440	80	1206	914	412
All samples								
CC	60	1021	1094	167	40	1007	1123	–15
HC	60	1116	1116	107	20	1069	1145	31
*Bt*C	90	1003	826	276	130	978	861	205
H*Bt*C	85	1145	906	350	190	1146	890	368

Counties included in the surveys are: Hejian and Xinji of Hebei Province; Linqing, Xiajin, Huimin, Chengwu and Wenshang of Shandong Province; Sheyang and Dafeng of Jiangsu Province. na, absence of samples.

from the comprehensive surveys on households (Table 2) are in agreement with those from the field trials. Therefore, our results do not support the viewpoint that current *Bt*C provides benefit from both yield increase and cost saving. In contrast, H*Bt*C in field trials supplied 6.1% and 21.3% increase in unit yield compared to HC and *Bt*C, respectively (Table 1). Yield increases were also found in household surveys (Table 2). It is evident that the increased monetary benefit with H*Bt*C was from both increased yield and cost saving on pesticides.

Successful integration

India is the most successful nation in developing and adopting hybrid cotton[19], however, *Bt* hybrids were planted for the first time until 2002–2003 season[20]. With similar national situation such as large population and limited arable land per capita, China became a nation to successfully commercialize hybrid cotton with *Bt*. According to our previous study [21] and this trial, the current H*Bt*C, such as CCRI 29 and SCRC 15, are more vigorous in growth and development of plants. They have larger boll-setting potential, larger boll weight and higher lint percentage than *Bt*C. The H*Bt*C provided 20% increase in yield (Tables 1 and 2).

However, seed production of hybrid cotton depends on hand emasculation and pollination in China, which is time-consuming and labour-intensive[22]. Cost of hybrid seed is more than Bollgard *Bt* cotton seed. If the conventional seeding rate per ha is used in growing *Bt* hybrid, it would not be possible for farmers to bear the seed costs. To overcome this problem, based on a series of investigations and surveys, Chinese scientists have recommended two ways: (i) to produce hybrid seed in northern China with rich sunshine in cotton growing seasons and cheap labour, which is planted in southern China with rich fertile land, good rainfall and double cropping system. (ii) to reduce seeding rate by introducing techniques of sparse planting and transplanting of seedlings[23,24]. These recommendations were immediately adopted by the farmers and seed producers. They have contributed to great success in extending the cultivation of *Bt* hybrid. Presently, the Shandong Province has become the largest base for *Bt* hybrid seed production since 2000. Farmers now grow *Bt* hybrid cotton with 22,500 plant population per ha, compared to traditionally 45,000 plants per ha for growing local cotton. Seeding rate of 4.5–5 kg per ha is used now in contrast to traditionally 22.5–45 kg per ha. In low density in planting, farmers leave vegetative branches on the plants that were traditionally removed by hand[25], but get yield equivalent to that with conventional cultivation techniques. Sheyang County of the Jiangsu Province took advantage of the *Bt* hybrids with seed-saving techniques, and covered an area of 33,300 ha, accounting for 90% of its total cotton area, with an average yield of 1300 kg per ha even with a severe drought in 2002.

However, Chinese government and scientists are still not satisfied with the development in H*Bt*C, particularly with seed production by hand emasculation. To increase the efficiency in seed production, efforts have been made for selecting potent crosses using male-sterile lines as female parent. CCRI 38, a H*Bt*C variety with a double recessive male-sterile line as the female parent, was developed by CCRI and commercialized in 2000. With CCRI 38, 50% labour cost was saved for seed production relative to CCRI 29, but the productivity of the F1 plants was lower than that of CCRI 29. Much research needs to be done for raising the efficiency in hybrid seed production.

There is no evidence so far for the evolution of resistance of boll worm insect to *Bt* in Yellow River and Yangtze River region where *Bt* cotton has been planted for the past 4–7 years. As in USA and Australia, monitoring for pest resistance in China was started in late 1999 (ref. 26). To deal with such possibility, up to now *Bt* cotton is permitted to be grown only in Yellow River and Yangtze River regions, where the popular double cropping and intercropping systems provide a natural 'refuge' for the pests. Besides, research on the development of resistance continues in China.

Summary and conclusion

China with a population of over 1.2 billion gives top priority for developing GM crops by introducing advanced technology from abroad, as well as through its own research program. Although *Bt* transgenic cotton was developed in China through local efforts soon after the USA, the introduction from USA was permitted as early as in 1997. *Bt*C brings incremental benefits by decreasing pesticide usage, reducing environmental pollution and saving labour, thus significantly increasing the net revenue of farmers in northern China. However, *Bt*C does not bring unit yield gains relative to non-*Bt* cotton that is well managed by pesticides. The increased revenue results from cost savings, which differs from previous reports that monetary benefits were from both increased yield and saving on pesticides. This is also one of the reasons why *Bt*C was introduced slowly in southern China before 1999. In response to the low yield potential of *Bt*C, the Chinese authorities and scientists quickly developed and commercialized H*Bt*C by integrating *Bt* transgenic technology, utilization of heterosis and agronomic techniques with 'Chinese characteristics' for seed production and planting. As a result, H*Bt*C has been widely adopted in southern China. China's experience in adopting *Bt* cotton may be useful to other developing countries.

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12. Field trials were conducted in Hejian and Jixian county of Hebei province, Xiajin, Linqing, Huimin, Chengwu, Juye county of Shandong Province, and Sheyang and Dafeng County of Jiangsu Province in 2002. Three locations in each county were selected for testing 4 types of cotton varieties. Seeds of each variety were provided by SCRC at market price, with each variety as a treatment. Data were analysed with Microsoft Excel 2000, Microsoft Corporation, USA.

13. Customarily there are 4 types of cotton varieties in China. Cotton variety without *Bt* is called conventional cotton (CC), like CCRI 12; Hybrid cotton variety without *Bt* called hybrid cotton (HC); Conventional cotton variety with *Bt* called *Bt* cotton (*Bt*C); Hybrid cotton variety with *Bt* called hybrid *Bt* cotton (*Bt*C). Normally, *Bt* cottons consist of conventional *Bt*C and H*Bt*C. Main material varieties either tested or surveyed in the paper were: CCRI-12, Simian 3 or Simian 4 (CC); CCRI-028 or Suza-2 (HC); 33B, GK 12, GK 19, SGK 321, CCRI 41 or SCRC 16 (*Bt*C); CCRI 29, CCRI 38 or SCRC 15 (H*Bt*C).
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18. There are three major cotton-growing regions in China, including Yellow River region in northern China (35% of the total area), Yangtze River Region in Southern China (30% of the total area), and Northwest region (25% of the total area). Yangtze River Region is richer in economy and holds higher unit yield in cotton than Yellow River Region. With expensive labour and long frost-free duration for cotton growth, farmers in southern China prefer to grow cotton varieties with high yield potential, large boll size and vigorous growth. 33B and other *Bt*C varieties do not accord with such properties, thus were rejected there.
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22. Hybrid seed is basically produced by hand-emasculation and hand-pollination at present in China. Flowers of female parent plants are emasculated in the afternoon one day pre-anthesis, and pollinated the next morning with pollens from the male parent plants. This process needs 30–60 labourers per ha and lasts for 40–45 days. Generally, hybrid seed yield per ha is 1500–1800 kg. The price of *Bt* hybrid seed per kg is usually 1–2 times higher than that of 33B, but the seeding rate per ha is 2–3 times lower with seed-saving technique.
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24. Transplanting of seedling, one of the techniques of intensive farming, has been widely used for cotton growing in China. Nutritive pot, made of soil and organic fertilizer, usually 5–6 cm in diameter and 12–15 cm high each, is prepared before planting. Each pot is planted with one seed only for raising cotton seedling. After the seedlings reach 2–3 true leaves stage, nutritive pots with seedlings are transplanted to the cotton fields. It is an effective seed-saving technique.
25. With a large labour power and poor mechanization, China has been attaching importance to intensive farming in cotton. Removal of vegetative branches by hand to save nutrition and avoid being overshadowed in cotton fields, is one of the most popular techniques. This operation is time and labour consuming. Since H*Bt*C was applied, removal of vegetative branches has been saved, as this cotton holds high productivity per single plant and fits for sparse planting.
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