1. Introduction

Global population reached 6 billion on 12 October 1999, will reach 8 billion in 2025, 9 billion by 2050, and will probably stabilize at between 9 and 10 billion during the latter half of the next century. Thus, in the next 50 years population will increase by 50% from 6 to 9 billion. The magnitude of the challenge of feeding tomorrow's world is difficult to conceive and the enormity of the task is probably best captured by the statement: "In the next 50 years mankind will consume twice as much food as mankind has consumed since the beginning of agriculture 10,000 years ago." There is a widely held view in the international scientific and development community that conventional crop improvement alone will not allow us to meet the global food demands of 2025. What is being advocated is a global strategy that integrates both conventional crop improvement and biotechnology, specifically including transgenic crops, to allow society to harness and optimize the contribution of technology to global food security. The adoption of such a strategy will capitalize on the full potential that both conventional crop improvement and transgenic crops offer. It also provides a unique opportunity to optimize the use of technology as one of several essential inputs in a multiple-thrust strategy, that includes improved food distribution and population control to ensure global food security; no approach dependent on a single thrust will succeed; a strategy with multiple thrusts that addresses all major issues is required. There is cautious optimism in the international scientific and development community that by integrating conventional and biotechnology applications, a significant contribution can be made by technology towards the alleviation of poverty and malnutrition, which afflicts 1.3 billion people and 840 million people, respectively, today, and that global food demands of 2025 and beyond can be met.

China was the first country to commercialize transgenic crops in the early 1990s. The first approval for commercial sale of a genetically modified product for food use in an industrialized country was in the United States in 1994 when Calgene marketed its Flavr-Savr™ delayed ripening tomato. In the interim, the number of countries growing transgenic crops has increased from 1 (China) in 1992, to 6 in 1996, to 9 in 1998. Global acreage of transgenic crops increased from 1.7 million ha in 1996 and within 2 years reached 27.8 million ha in 1998. Transgenic crops were planted commercially in 1998 in industrial countries of the United States, Canada, and Australia, the developing countries of Argentina, China, Mexico, and South Africa, with limited small introductory areas planted in Spain and France, as countries of the European Union continued to debate the adoption of transgenic crops, and products derived from them.

The adoption rates for transgenic crops globally are unprecedented and are the highest for any new technologies by agricultural industry standards. High adoption rates reflect grower satisfaction with transgenic crops that offer significant and multiple benefits which collectively contribute to a more sustainable agriculture and higher net returns per hectare. The first generation of transgenic crops has already demonstrated that incorporation of input traits has conferred beneficial control of biotic stresses that was not possible with conventional technology, for example, effective and targeted control of specific cotton and maize insect pests as well as papaya and potato virus diseases. Unlike the first-generation input traits, the second-generation transgenic crops, with output/quality traits, that are ready for deployment in the near term, are capable of delivering significant nutritional and health benefits that will be very evident to consumers.

This publication is the fourth by the author in an annual review series, published as *ISAAA Briefs*, to characterize and monitor the global status of commercialized transgenic crops. The first review was published in 1996 (James and Krattiger 1996), the second in 1997 (James 1997a), and the third in 1998 (James 1998). The current publication presents similar information for 1999.

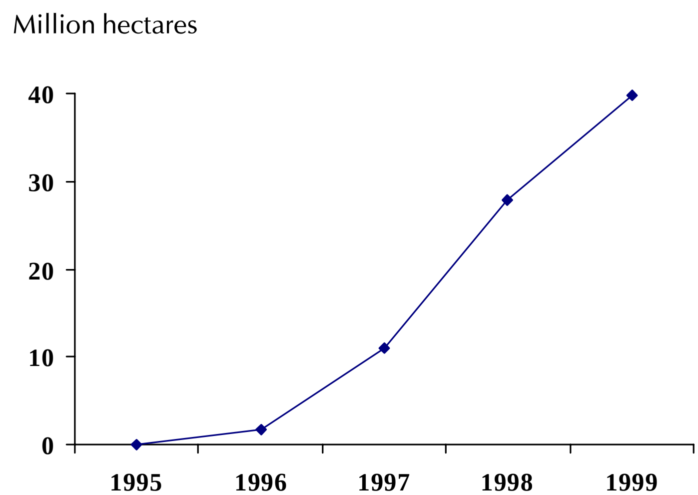
The principal aims of this publication are to:
- provide an overview of the global adoption of transgenic crops in the period 1996 to 1999;
- document detailed information on the global status and distribution of commercial transgenic crops in 1999, by region, country, crop, and trait;
- identify countries growing transgenic crops for the first time in 1999;
- rank the dominant transgenic crop/trait combinations in 1999;
- summarize and highlight the significant changes in transgenic crop development between 1998 and 1999;
- review the value of the transgenic seed market from 1995 to 1999;
- provide an update on developments in the crop biotechnology industry, particularly the continuing acquisitions, alliances, mergers, and spin-offs in the private sector, including in the area of genomics, which remains pivotal to future developments in crop biotechnology;
- provide an overview of the commercial seed industry;
- review the status of transgenic crops in selected developing countries of Asia;
- discuss future traits in biotechnology in the near term;
- review past plant breeding achievements in increasing crop productivity of the three major staples—wheat, rice, and maize—and assess the potential of a plant breeding strategy that combines conventional and biotechnology applications to meet the cereal demands of 2025;
- conclude with a brief overview of future prospects for transgenic crops in 2000 and beyond.

Previous Briefs in this series have reviewed the attributes and performance of transgenic crops, and this practice will be continued. Projects are currently under way in several countries to assess the ongoing performance of principal transgenic crops and results from these studies will be consolidated and findings published in a future Brief. Note that the words maize and corn, as well as rapeseed and canola, are used as synonyms throughout the text, reflecting the usage of these words in different regions of the world. Global figures on hectares planted have been rounded off and in some cases this leads to insignificant rounding-off approximations. In the ISAAA Briefs Series (Briefs No. 1, 5, 8, and 12) information for China was not available for 1998; the incomplete set of data for China should be borne in mind by the reader when considering 1998 data. For any comparison involving 1998 data, e.g., the number of countries reported to be growing transgenic crops in 1998 was eight (excluding China) which increased to 12 in 1999 (including China). It is also important to note that countries in the Southern hemisphere plant their crops in the last quarter of the calendar year, and transgenic crop areas reported are planted (not harvested) in the year stated. Thus, the 1999 information for Argentina is hectares planted in the last quarter of 1999 and harvested in the first quarter of 2000. Finally, note that a Preview of this publication (James 1999) with data on the global distribution of transgenic crops was distributed in October 1999; additional information has been received since October and this manuscript has been updated with the latest information, along with some editorial changes.

2. Overview of Global Status and Distribution of Commercial Transgenic Crops, 1996-1999

Information on the adoption of commercial transgenic crops was provided by many independent sources from both public and private sectors. Multiple sources of data, as well as additional and independent commercial marketing information, allowed several cross-checks to be conducted, which facilitated a rigorous verification of the estimates. For convenience and ease of interpretation, the data for the global status and distribution of commercial transgenic crops are presented in two complementary formats. Figures are used to best illustrate the changes in global transgenic area between 1996 and 1999. Companion tables provide more detailed corresponding information for 1999 and illustrate changes that have occurred between 1998 and 1999. Data in Figure 1 graphically shows the very rapid increase in global area of transgenic crops from zero in 1995 to 39.9 million ha in 1999. The adoption rates for transgenic crops in Figure 1 exhibit more than a 23-fold increase between 1996 and 1999. The high adoption rates reflect grower satisfaction with the products that offer significant benefits ranging from more flexible crop management, higher productivity, and a safer environment through decreased use of conventional pesticides, which collectively contribute to a more sustainable agriculture and higher net returns per hectare. The companion data to Figure 1, in Table 1, show that the global area planted to commercial transgenic crops increased from 1.7 million ha in 1996 to 11.0 million ha in 1997, to 27.8 million ha in 1998 and to 39.9 million ha in 1999. Thus, global transgenic crop area increased by 9.3 million ha between 1996 and 1997, equivalent to more than a 500% increase; by 16.8 million ha, or a 150% increase between 1997 and 1998; and a further 44% increase between 1998 and 1999. The 44% global increase in area of commercial transgenic crops between 1998 and 1999,

Figure 1. Global area of transgenic crops, 1995-1999



Source: Clive James (1999).

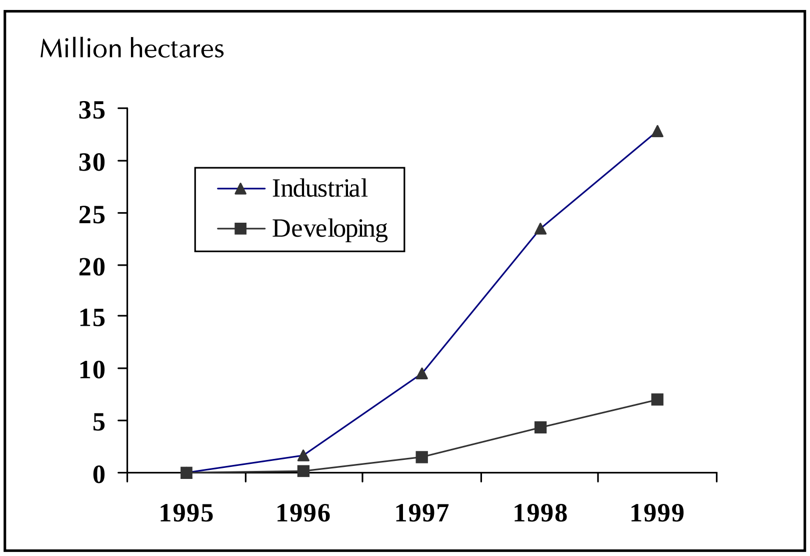
Table 1.	Global area of transgenic crops in 1996, 1997, 1998, and 1999	
	Hectares (million)	Acres (million)
1996	1.7	4.3
1997	11.0	27.5
1998	27.8	69.5
1999	39.9	98.6

Increase of 44 %, 12.1 million hectares or 29.1 million acres between 1998 and 1999.
Source: Clive James (1999).

equivalent to 12.1 million ha, represents a continuing high rate of adoption for this new technology and reconfirms the support of selected Governments and the conviction of farmers in those countries about the values of the technology. This has provided farmers the incentive to continue to plant transgenic crops.

Figure 2 graphically illustrates that from 1996 to 1999, the substantial share of global transgenic crops was being grown in industrial countries, with significantly less in developing countries. The companion data to Figure 2, in Table 2, confirm that the proportion of transgenic crops grown in industrial countries in 1999 was 82%, with 18% grown in developing countries, with most of that area (approximately 90%, equivalent to 6.7 million ha) in Argentina, and the remainder in China, South Africa, and Mexico. The relative increase in area between 1998 and 1999, expressed as a ratio, however, was higher for developing countries at 0.6 compared with 0.4 for industrial countries (Table 2); this mainly reflects the high rate of adoption of herbicide-tolerant soybeans in Argentina in 1999 and to a much lesser extent the 0.3 million ha of *Bt* cotton reported for China in 1999. The actual increase in transgenic crop area between 1998 and 1999 was 9.4 million ha in industrial countries, and 2.7 million ha in developing countries. In industrial countries, the major increase in area was due to soybeans, followed by corn, canola, and cotton; the major increase in developing countries involved the same crops, but excluding canola.

Figure 2. Global area of transgenic crops, 1995-1999, by region



Source: Clive James (1999).

Table 2. Global area of transgenic crops in 1998 and 1999, industrial and developing countries (million hectares)

	1998	%	1999	%	Increase (Ratio)
Industrial countries	23.4	84	32.8	82	9.4 (0.4)
Developing countries	4.4	16	7.1	18	2.7 (0.6)
Total	**27.8**	**100**	**39.9**	**100**	**12.1 (0.4)**

Source: Clive James (1999).

2.1 Distribution of Transgenic Crops, by Country

Between 1996 and 1999, 12 countries, 8 industrial and 4 developing, have contributed to more than a 20-fold increase (23.5) in the global area of transgenic crops. The number of countries growing commercialized transgenic crops increased from six in 1996 (USA, Argentina, Canada, Australia, China, and Mexico) to nine in 1998; to 12 in 1999 when three new countries, Portugal, Romania, and Ukraine grew transgenic crops for the first time. The countries listed in descending order of transgenic crop area (Table 3) on a global basis in 1999 are: USA, 28.7 million ha representing 72% of the global area; Argentina with 6.7 million ha equivalent to 17%; Canada, 4.0 million ha representing 10%; and China with approximately 0.3 million ha equivalent to 1%. Australia and South Africa each grew 0.1 million ha (<0.1%) of transgenic crops in 1999. The remaining balance was grown in Mexico, Spain, France, Portugal, Romania, and Ukraine each with <0.1 million ha, collectively equivalent to <1% of the global area of transgenic crops in 1999.

Figure 3 and Table 3 clearly demonstrate that in 1999, the USA retained its ranking as the country with the largest area of transgenics (28.7 million ha). Between 1998 and 1999 the USA increased its transgenic area by 8.2 million ha, but its global share remained fairly constant at just over 70% in 1998 and 1999. The USA grew more than four times the area of transgenic crops than Argentina in 1999, which occupied second place in both years. The USA increased its transgenic crop area by a factor of 0.4 between 1998 and 1999 and benefited from a broad array of crop/trait combinations, including stacked genes for herbicide tolerance and insect resistance in both corn and cotton. In the USA in 1999, the biggest increase in transgenic crop area was in soybean, which increased by almost 50%—from just over 10 million ha in 1998 to almost 15 million ha in 1999 on a global basis. Corn had the second biggest increase in absolute area, from about 8 million ha in 1998 to 10.3 million ha in 1999. An increase of almost 50% in area was realized in the USA for transgenic cotton between 1998 and 1999 when total area reached 3.2 million ha. The most significant area of transgenic cotton in the US in 1999 was herbicide-tolerant cotton (1.5 million ha), followed by equal areas (850,000 ha) of single-trait *Bt* cotton, and multiple-trait cotton with both insect resistance and herbicide tolerance.

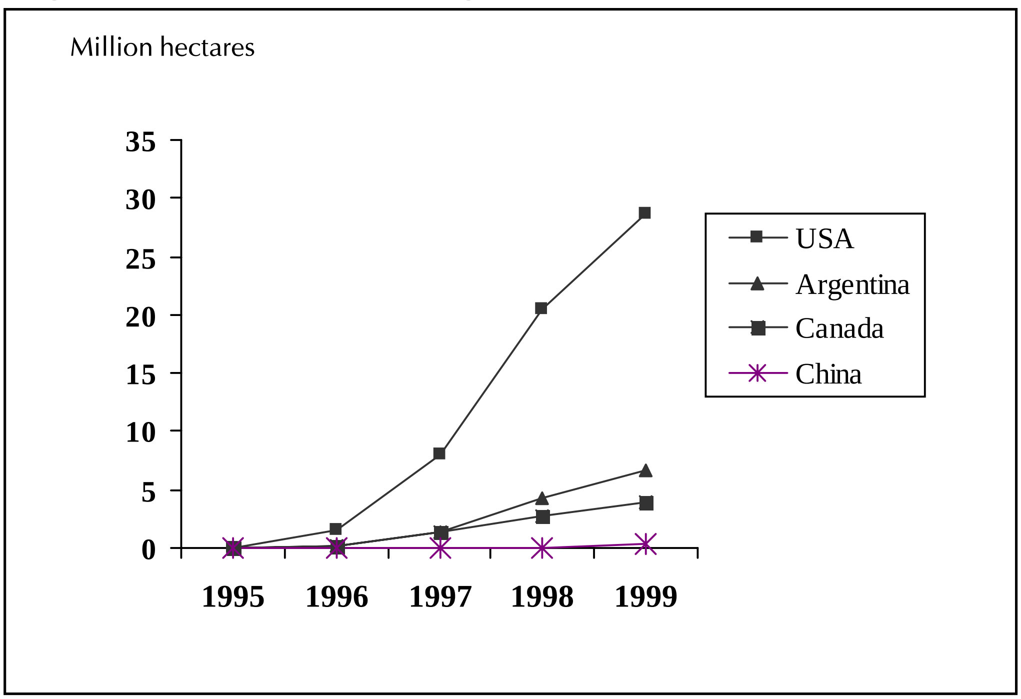
Argentina's area of transgenic crops increased 0.6-fold from 4.3 million ha in 1998 to 6.7 million ha in 1999 due to the 50% increase in herbicide-tolerant soybean and the smaller increase of almost 250,000 ha of transgenic corn. Argentina's proportion of global share

Table 3. Global area of transgenic crops in 1998 and 1999, by country (million hectares)

Country	1998	%	1999	%	Increase from 1998 to 1999 (Ratio)	
USA	20.5	74	28.7	72	8.2	(0.4)
Argentina	4.3	15	6.7	17	2.4	(0.6)
Canada	2.8	10	4.0	10	1.2	(0.4)
China	<0.1	<1	0.3	1	0.2	(3.0)
Australia	0.1	1	0.1	<1	<0.1	(- -)
South Africa	<0.1	<1	0.1	<1	<0.1	(- -)
Mexico	0.1	<0.1	<0.1	<1	<0.1	(- -)
Spain	<0.1	<1	<0.1	<1	<0.1	(- -)
France	<0.1	<1	<0.1	<1	<0.1	(- -)
Portugal	0.0	0	<0.1	<1	<0.1	(- -)
Romania	0.0	0	<0.1	<1	<0.1	(- -)
Ukraine	0.0	0	<0.1	<1	<0.1	(- -)
Total	**27.8**	**100**	**39.9**	**100**	**12.1**	**(0.4)**

Source: Clive James (1999).

Figure 3. Global area of transgenic crops, 1995-1999, by country



Source: Clive James (1999).

remained almost constant at 17% in 1999 compared with 15% in 1998. Globally, Canada retained its third place in 1999 at 10% (the same as 1998) by increasing its transgenic canola area from 2.4 million ha in 1998 to 3.4 million ha in 1999, its *Bt* corn area to approximately 0.4 million ha, and its herbicide-tolerant soybean from almost 40,000 ha in 1998 to 245,000 ha in 1999. China was ranked fourth in 1999, with approximately 0.3 million ha of *Bt* cotton, which is a significant increase compared with a total area of 63,000 ha of *Bt* cotton for 1998.

Australia grew approximately 125,000 ha of *Bt* cotton in 1999 (compared with 80,000 ha in 1998) while Mexico grew 20,000 ha of transgenic cotton (mainly *Bt* cotton) compared with 40,000 ha in 1998. South Africa was reported to have grown almost 100,000 ha of *Bt* corn in 1999 and just over 10,000 ha of *Bt* cotton. Of the two European countries, Spain and France, that grew transgenic crops for the first time in 1998, Spain increased its area of *Bt* maize from approximately 22,000 ha in 1998 to 30,000 ha in 1999 while the area in France remained the same at approximately 1,000 to 2,000 ha. Portugal, Romania, and Ukraine grew transgenic crops for the first time in 1999. Portugal grew introductory areas of *Bt* maize (about 1,000 ha); Romania and Ukraine grew introductory areas (<1,000 ha each) of *Bt* potatoes with Romania growing 14,250 ha of herbicide-tolerant soybean for the first time, equivalent to 16% of the national soybean area of 35,250 ha. Finally, Germany was reported to have grown small introductory areas of *Bt* maize in 1999, and 12,000 ha of herbicide-tolerant maize were grown in Bulgaria. These were not included in the global database, however, because they could not be verified. Thus, in 1999 transgenic crops were grown in all six continents of the world—North America, Latin America, Asia, Oceania, Europe (East and West), and Africa.

2.1.1 Countries Growing Transgenic Crops for the First Time in 1999

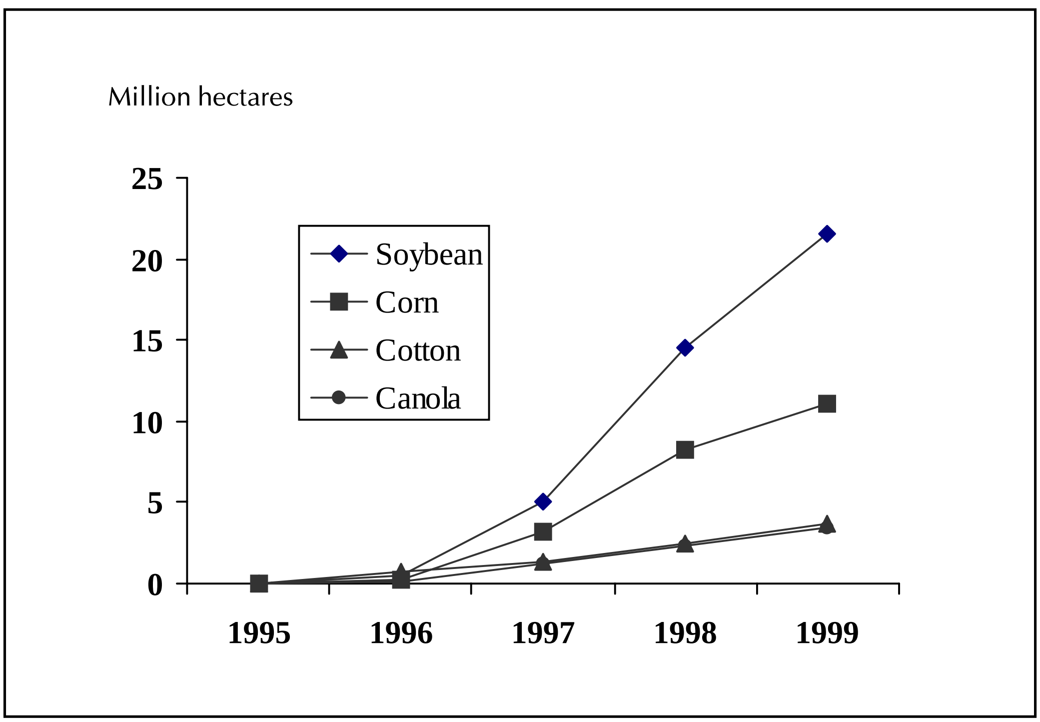
Twelve countries grew transgenic crops commercially in 1999. Three of these—Romania, Portugal, and Ukraine—grew transgenic crops for the first time. Romania grew two crops, 14,250 ha of herbicide-tolerant soybean, and introductory areas of *Bt* potatoes; Portugal grew introductory areas of *Bt* maize; and Ukraine grew introductory areas of *Bt* potatoes. There were also reports that Germany grew a small introductory area of *Bt* maize, and that Bulgaria grew an introductory area of 12,000 ha of herbicide-tolerant corn which are not included in the database because they could not be verified.

In summary, the countries listed in descending order of transgenic crop area on a global basis in 1999 (Table 3) were: USA 28.7 million ha, representing 72% of the global area; Argentina with 6.7 million ha or 17%; Canada 4.0 million ha representing 10%; China with approximately 0.3 million ha equivalent to 1%; Australia and South Africa each grew 0.1 million ha of transgenic crops in 1999. The balance of <1% was grown in Mexico, Spain, France, Portugal, Romania and Ukraine, each with <0.1 million ha. The proportion of transgenic crops grown in industrial countries was 82% (Table 3), less than that for 1998 (84%), with 18% grown in developing countries. Most of that area is in Argentina, and the balance is in China, South Africa, and Mexico. As in 1998, the largest increase in transgenic crops in 1999 occurred in the USA (8.2 million ha) where there was a 0.4-fold increase, followed by Argentina (2.4 million ha) with a 0.6-fold increase, and Canada (1.2 million ha) with a 0.4-fold increase. USA continued to be the principal grower of transgenic crops in 1999 although its share of global area was slightly lower (72%) in 1999 than in 1998 (74%). The increase in China's transgenic crop area was the largest relative change, increasing 3.0-fold from <0.1 million ha of *Bt* cotton in 1998 to approximately 0.3 million ha in 1999, equivalent to 1% of the global share; Argentina's global share of transgenic crop area increased from 15% in 1998 to 17% in 1999. Canada's share of global transgenic crop area remained the same, 10% of global area in 1998 and 1999.

2.2 Distribution of Transgenic Crops, by Crop

Figure 4 clearly shows the increasing dominance, in area planted, of transgenic soybean followed by transgenic corn during the period 1996-99. The companion data in Table 4 confirm that the top four transgenic crops on a global basis in 1999 were soybean (54%), corn (28%), with cotton and canola sharing third place at 9% each; collectively the four crops occupied more than 99% of the global transgenic crop area, with the balance of <1% occupied primarily by insect-resistant transgenic potato. Soybean retained its first ranking in 1999 as the crop with the largest area, 21.6 million ha, equivalent to 54% of the global share of transgenic crops (Table 4), up from 52% in 1998. The 0.5-fold increase in area planted with soybean between 1998 and 1999 was equal to the 0.5-fold increase in cotton. The highest absolute increase in area between 1998 and 1999 was recorded for herbicide-tolerant soybean with 7.1 million ha. This was due to two principal changes between 1998 and 1999. First, the biggest increase was in the USA where area of herbicide-tolerant

Figure 4. Global area of transgenic crops, 1995-1999, by crop



Source: Clive James (1999).

Table 4. Global area of transgenic crops in 1998 and 1999, by crop (million hectares)

Crop	1998	%	1999	%	Increase	(Ratio)
Soybean	14.5	52	21.6	54	7.1	(0.5)
Corn	8.3	30	11.1	28	2.8	(0.3)
Cotton	2.5	9	3.7	9	1.2	(0.5)
Canola	2.4	9	3.4	9	1.0	(0.4)
Potato	<0.1	<1	<0.1	<1	<0.1	(- -)
Squash	0.0	0	<0.1	<1	(- -)	(- -)
Papaya	0.0	0	<0.1	<1	(- -)	(- -)
Total	**27.8**	**100**	**39.9**	**100**	**12.1**	**(0.4)**

Source: Clive James (1999).

soybean increased by 4.8 million ha, from 10.2 million ha in 1998 to 15 million ha in 1999; this is equivalent to 50% of the 30 million ha of the US national soybean crop in 1999. Second, in Argentina soybean hectarage increased by 2.1 million ha, from 4.3 million ha in 1998 to 6.4 million ha in 1999; this is equivalent to approximately 90% of the 7.0 million ha of Argentina's national soybean crop in 1999. Additionally, transgenic soybean in Canada increased substantially from <100,000 ha in 1998 to 245,000 ha in 1999. Thus, three principal countries grew transgenic soybean in 1999—USA, Argentina, and Canada—plus introductory areas in Romania (14,250 ha) and Mexico (500 ha) for a total area of 21.6 million ha, equivalent to 54% of the transgenic crop area worldwide.

Transgenic corn retained its second ranking in 1999 with 11.1 million ha equivalent to 28% of the total global transgenic area for all crops, and up from 8.3 million ha in 1998. Thus, global transgenic corn acreage increased by 2.8 million ha, a 0.3-fold increase, between 1998 and 1999. This increase of 2.2 million ha was in the USA where transgenic corn (insect-resistant, *Bt*/herbicide-tolerant and herbicide-tolerant) increased from 8.1 million ha in 1998 to 10.3 million ha in 1999, equivalent to 33% of the 31.4 million ha of the US national corn crop in 1999. Transgenic corn also increased significantly in Argentina from 17,000 ha in 1998 to 260,000 ha in 1999, and similarly in South Africa from a small introductory area in 1998 to almost 100,000 ha in 1999. In 1999, transgenic corn was grown for the second time in Spain (30,000 ha) and France (1,000-2,000 ha), and for the first time in Portugal (about 1,000 ha). In addition, small introductory areas of *Bt* corn were reported to have been grown in Germany and 8,000 ha of herbicide-tolerant corn in Bulgaria, but these are not included in the 1999 database because they could not be verified. Approximately two-thirds of all transgenic corn in 1998 was *Bt* corn. The other traits in corn included herbicide tolerance, and multiple traits with stacked genes for herbicide tolerance and *Bt*. The total number of countries growing transgenic corn in 1999 was seven, including USA, Canada, Spain, France, Argentina, and South Africa, all of which grew *Bt* corn in 1998, and Portugal which grew *Bt* corn for the first time in 1999.

The global area of transgenic cotton increased 0.5-fold (Table 4), from 2.5 million ha in 1998 to 3.7 million ha in 1999, an increase of 1.2 million ha. The share of transgenic cotton in percentage of global transgenic crops remained constant at 9% in 1998 and 1999. The USA continues to grow most of the transgenic cotton in the world, 3.2 million ha in 1999 compared with 2.2 million ha in 1998. Transgenic cotton accounted for 55% of the 5.9 million ha of the US national cotton crop in 1999. Transgenic cotton in the US in 1999 comprised *Bt* cotton, herbicide-tolerant cotton, and cotton with stacked genes for *Bt*/herbicide tolerance. A significant area of *Bt* cotton was grown in China (245,000 ha) and Australia (125,000 ha) in 1999. Mexico continued to grow *Bt* cotton in 1999 (approximately 20,000 ha) and the introductory areas planted in Argentina and South Africa in 1998 increased to about 10,000 ha in each of the two countries in 1999.

Thus, six countries grew transgenic cotton in 1999—USA, China, Australia, Mexico, South Africa, and Argentina. With the exception of the US all countries grew only *Bt* cotton while in the US, traits included herbicide tolerance, *Bt*, and stacked genes for *Bt*/herbicide tolerance. Whereas the USA currently grows the majority of transgenic cotton planted globally (86% in 1999), the other five countries are rapidly increasing the area under transgenics and are equally important partners in a global strategy that seeks to deploy, diversify, and distribute transgenic crops to decrease dependency on conventional insecticides and overcome significant insect pest stresses that constrain crop productivity in the developing world where most of world cotton is grown.

With the exception of 135,000 ha of transgenic canola in the USA, the entire area of transgenic canola is grown in Canada where area increased from 2.4 million ha in 1998 to 3.4 million ha in 1999. Of the 5.9 million ha of canola grown in Canada in 1999, 62% was transgenic for herbicide tolerance. Transgenic canola ranks third with cotton, after soybean and corn, in the share of the global transgenic market, which was consistent at 9% in 1998 and 1999.

Transgenic potato occupied <1% of the global transgenic crop market share in 1999 with approximately 75% (20,000 ha) of global transgenic potatoes grown in the USA, 5,000 ha in Canada and the balance as introductory areas in Romania and the Ukraine.

Globally the number of transgenic crops have increased from 1 in the early 1990s to a total of 7 crops in 1999 (Table 4) which include four principal crops (soybean, corn, cotton, and canola) planted on more than 100,000 ha , plus smaller areas of three other crops that include 25,000 ha of potatoes, (*Bt* and virus resistance), <1,000 ha of squash (virus resistance), and 400 ha of papaya (virus resistance). The latter is currently limited to Hawaii, USA. Transgenic carnations (color and shelf life) are also marketed in smaller quantities.

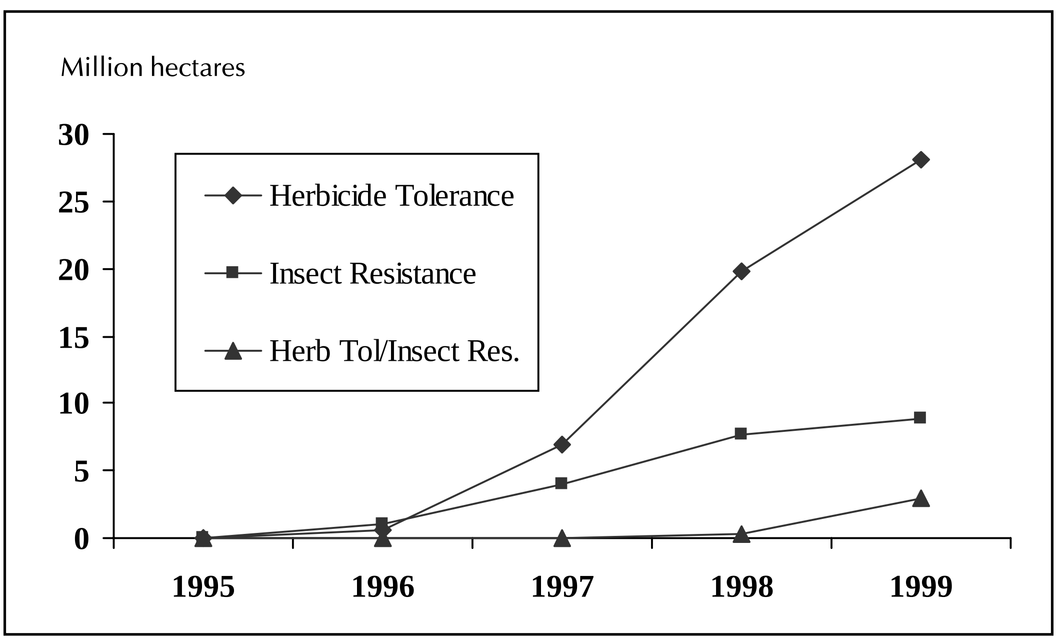
In summary, the seven transgenic crops grown in 1999 were, in descending order of area, soybean, corn/maize, cotton, canola/rapeseed, potato, squash, and papaya (Table 4). Transgenic soybean and corn continued to be ranked first and second in 1999, accounting for 54% and 28% of global transgenic crop area, respectively. Cotton (3.7 million ha) and canola (3.4 million ha) shared the third position in 1999, each occupying approximately 9% of global area. Potato, squash, and papaya occupied <1% of the global area of transgenic crops in 1999.

2.3 Distribution of Transgenic Crops, by Trait

Figure 5 demonstrates the marked increase in global area of herbicide tolerance during the period 1996 to 1999 when it reached 28.1 million ha. Insect resistance has also exhibited a significant increase in area during the same period reaching 8.9 million ha in 1999, with the stacked trait of herbicide tolerance/insect resistance starting to become evident in 1998 with 0.3 million ha, reaching 2.9 million ha in 1999. The data in Table 5 indicate that of the four trait categories in 1999, the dominant trait globally was herbicide tolerance (71%), occupying almost three-quarters of total transgenic area, followed in decreasing order of importance by insect resistance (22%), stacked traits of insect resistance and herbicide tolerance (7%), and virus resistance/other traits (<1%).

Herbicide tolerance retained its first ranking in 1999 as the trait with the largest area (28.1 million ha) with global share remaining constant at 71% in 1998 and 1999. The large increase in area of 8.3 million ha of herbicide-tolerant crops between 1998 and 1999 was the highest for all traits and reflected a 0.4-fold increase in area. This was due to three principal changes between 1998 and 1999. First, the biggest increase was in the USA, where area of single trait herbicide-tolerant crops increased by 4.8 million ha from approximately 13 million ha in 1998 to about 18 million ha in 1998. Of the 5 million-ha increase in herbicide-tolerant crops in the USA, about 95% can be attributed to the increase in single trait herbicide-tolerant soybean, and the remaining 5% resulting from a small decrease in single trait herbicide-tolerant corn and a small increase in single trait herbicide-tolerant cotton. In addition, approximately 1.9 million

Figure 5. Global area of transgenic crops, 1995-1999, by trait



Source: Clive James (1999).

Table 5. Global area of transgenic crops in 1998 and 1999, by trait (million hectares)

Trait	1998	%	1999	%	Increase	(Ratio)
Herbicide tolerance	19.8	71	28.1	71	8.3	(0.4)
Insect resistance (*Bt*)	7.7	28	8.9	22	1.2	(0.2)
Bt/Herbicide tolerance	0.3	1	2.9	7	2.6	(8.7)
Virus resistance/Other	<0.1	<1	<0.1	<1	< 0.1	(-.-)
Total	**27.8**	**100**	**39.9**	**100**	**12.1**	**(0.4)**

Source: Clive James (1999).

ha of corn and 850,000 ha of cotton, both with stacked genes for *Bt*/herbicide tolerance, were planted in the USA in 1999. The second factor that contributed to the large increase in herbicide-tolerant crops in 1999 was the increase in herbicide-tolerant soybean in Argentina, which increased by 2.1 million ha from 4.3 million ha in 1998 to 6.4 million ha in 1999. The third factor was the increase in Canada's herbicide-tolerant canola, which increased by 1.0 million ha from 2.4 million ha in 1998 to 3.4 million ha in 1999. Additionally, in Canada there were increases totaling approximately 300,000 ha for herbicide-tolerant soybean and corn. Thus, the three countries—USA, Argentina, and Canada—that grew herbicide-tolerant crops in 1998 were also the same countries that grew a total of 28.1 million ha of herbicide-tolerant crops in 1999, with the exception of Romania which grew 14,250 ha of herbicide-tolerant soybean. Bulgaria was also reported to have grown 12,000 ha of herbicide-tolerant corn but is not included in the data base because it could not be verified. Thus, USA, Argentina, and Canada account for 99% of the total transgenic crop area in the world. Of the 1999 global herbicide-tolerant crop area, soybean represents approximately 77%, canola is 13%, with cotton and corn at 5% each. A corresponding analysis by country indicates that 64% is grown in the USA, 23% in Argentina, and 13% in Canada, with a small area in Romania.

Insect resistance retained its ranking in 1999 as the trait with the second largest area (8.9 million ha) equivalent to 22% of global share of transgenic crops (Table 4), down from 36% in 1997 and 28% in 1998. The 0.2-fold increase in area planted between 1998 and 1999 was the lowest for the top three trait categories. The increase of 1.2 million ha of insect-resistant crops between 1998 and 1999 was due to modest increases in two countries. In the USA *Bt* corn increased by approximately 0.5 million ha with a similar increase in *Bt* cotton. In China *Bt* cotton increased more than three-fold to approximately 0.3 million ha in 1999. In the USA in 1999 there were approximately 7 million ha of *Bt* corn, 850,000 of *Bt* cotton, and about 20,000 ha of *Bt* potatoes.

Bt corn was grown in the following seven countries listed in order of area grown—USA, Canada, Argentina, South Africa, Spain, France, and Portugal. Similarly, *Bt* cotton was grown in the following six countries listed in order of area planted—USA, China, Australia, Mexico, South Africa, and Argentina. Finally, small areas of *Bt* potatoes were grown in 1999 in four countries that include the USA and Canada which had also planted small areas in 1998, with Romania and Ukraine planting introductory areas of *Bt* potatoes for the first time in 1999.

Australia's hectarage devoted to insect-resistant varieties in 1999 was exclusively cotton and about the same as in 1998 with approximately 125,000 ha. Similarly, Mexico's hectarage in 1999 was exclusively insect-resistant *Bt* cotton with 20,000 ha. The number of countries that grew transgenic *Bt* crops increased from 9 in 1998 to 12 in 1999 with Portugal, Romania, and Ukraine growing insect-resistant crops for the first time. Analyzing the global single-trait insect resistance area by crop, corn represents approximately 84% of global area, cotton 14%, and potato 2%. Similarly, a corresponding analysis by country indicates that of the global area for single-trait insect-resistant crop in 1999, 89% is grown in the USA, 3% in China, 2% each in Canada and Argentina, 1% each in Australia and South Africa, and the remaining 3% in Mexico, Spain, France, Portugal, Romania, and Ukraine.

The stacked traits of *Bt*/herbicide tolerance represented approximately 7% of global transgenic area in 1999 equivalent to 2.9 million ha; the increase of 2.6 million ha between 1998 and 1999, equivalent to an 8.7-fold increase was by far the biggest relative increase in area for any trait category. All transgenic crops with stacked genes in 1999 were limited to the USA (2.8 million ha) on two crops, cotton, and corn, and Canada (0.1 million ha of corn). In 1999 approximately 1.9 million ha of corn and 850,000 ha of cotton, both with stacked genes for *Bt*/herbicide tolerance, were planted in the USA. It is noteworthy that the stacked genes for *Bt*/herbicide tolerance in corn and cotton increased from 1% of global transgenic area in 1998 to 7% in 1999. If commodity prices allow farmers to purchase the more expensive package of stacked genes, these may become much more prevalent, leading to a corresponding decrease in the prevalence of single-trait varieties.

An introductory area of 200 ha of transgenic papaya, resistant to ring spot virus, was planted in Hawaii, USA, for the first time in 1998. This increased to approximately 400 ha in 1999. Small areas (<1,000 ha) of virus-resistant squash were planted in the US in 1999. The area planted to quality traits such as shelf life, delayed ripening, and modified oil in soybean and canola were <0.1% of global area.

In summary, the relative ranking of the principal transgenic traits were the same in 1998 and 1999 (Table 5), with herbicide tolerance being the highest (71%) in both 1998 and 1999. Insect-resistant crops decreased from 28% in 1998 to 22% in 1999. Stacked genes for insect resistance and herbicide tolerance, however, increased significantly in the USA in both maize and cotton, from 1% of global transgenic crop area in 1998 (0.3 million ha) to 7% or 2.9 million ha in 1999, equivalent to an 8.7-fold increase; virus resistance traits in potatoes, squash, and papaya occupied <1% and <0.1 million ha in both 1998 and 1999.

2.4 Dominant Transgenic Crops in 1999

Herbicide-tolerant soybean was the most dominant transgenic crop grown commercially in five countries in 1999—USA, Argentina, Canada, Mexico, and Romania (Table 6). Globally, herbicide-tolerant soybean occupied 21.6 million ha representing 54% of the global transgenic area of 39.9 million ha for all crops. The second most dominant crop was *Bt* maize, which occupied 7.5 million ha equivalent to 19% of global transgenic area and planted in seven countries—USA, Canada, Argentina, South Africa, Spain, France, and Portugal. The other six crops listed in Table 6 all occupy <10% of global transgenic crop area and include, in descending order of area: herbicide-tolerant canola occupying 3.5 million ha (9%), corn with stacked traits *of Bt*/herbicide tolerance in 2.1 million ha (5%), herbicide-

Table 6. Dominant transgenic crops, 1999

Crop	Million hectares	% transgenic
Herbicide-tolerant soybean	21.6	54
Bt maize	7.5	19
Herbicide-tolerant canola	3.5	9
Bt/Herbicide-tolerant corn	2.1	5
Herbicide-tolerant cotton	1.6	4
Herbicide-tolerant corn	1.5	4
Bt cotton	1.3	3
Bt/Herbicide-tolerant cotton	0.8	2
Total	**39.9**	**100**

Source: Clive James (1999).

tolerant cotton in 1.6 million ha (4%), herbicide-tolerant corn in 1.5 million ha (4%), *Bt* cotton in 1.3 million ha (3%), and finally cotton with stacked traits, *Bt*/herbicide tolerance in 0.8 million ha (2%).

2.5 Summary and Highlights of Significant Changes between 1998 and 1999

The major changes in area and global share of transgenic crops for the respective countries, crops and traits, between 1998 and 1999 were related to the following factors:

- In 1999, the global area of transgenic crops increased by 44% (12.1 million ha), to 39.9 million ha, from 27.8 million ha in 1998. Seven transgenic crops were grown commercially in 12 countries in 1999, three of which (Portugal, Romania, and Ukraine) grew transgenic crops for the first time.
- The four principal countries that grew the majority of transgenic crops in 1999 were USA (28.7 million ha, 72% of the global area), Argentina (6.7 million ha, 17%), Canada (4.0 million ha, 10%), and China (0.3 million ha, 1%). The remainder was grown in Australia, South Africa, Mexico, Spain, France, Portugal, Romania, and Ukraine.
- Growth in area of transgenic crops between 1998 and 1999 in industrial countries continued to be significant and 3.5 times greater than in developing countries (9.4 million ha versus 2.7 million ha).
- In terms of crops, soybean contributed the most (59%) to global growth of transgenic crops, equivalent to 7.1 million ha between 1998 and 1999, followed by corn with 23% (2.8 million ha), cotton with 10% (1.2 million ha), and canola with 8% (1.0 million ha).
- There were three noteworthy developments in terms of traits: herbicide tolerance contributed the most (69% or 8.3 million ha) to global growth between 1998 and 1999; stacked genes of insect resistance and herbicide tolerance in both corn and cotton contributed 21%, equivalent to 2.6 million ha; and insect resistance increased by 1.2 million ha in 1999, representing 10% of global growth in area of transgenic crops.
- Of the four major transgenic crops grown in 12 countries in 1999, the two principal crops of soybean and corn represented 54% and 28%, respectively, for a total of 82% of the global transgenic area. The remaining 18% was shared equally between cotton and canola (9% each).
- In 1999, herbicide-tolerant soybean was the most dominant transgenic crop (54% of global transgenic area, compared with 52% in 1998) (Table 6), followed by insect-resistant corn (19% compared with 24% in 1998), herbicide-tolerant canola (9%), *Bt*/herbicide-tolerant corn (5%), herbicide-

tolerant cotton (4%), herbicide-tolerant corn (4%), *Bt* cotton (3%), and *Bt*/herbicide-tolerant cotton (2%).

- The four major factors that influenced the change in absolute area of transgenic crops between 1998 and 1999, and the relative global share of different countries, crops, and traits were:
  - o first, the substantial increase of 4.8 million ha in herbicide-tolerant soybean in the USA (from 10.2 million ha in 1998 to 15.0 million ha in 1999, equivalent to 50% of the 30.0 million ha of the US national soybean crop in 1999), coupled with an increase of 2.1 million ha in herbicide-tolerant soybean in Argentina (from 4.3 million ha in 1998 to an estimated 6.4 million ha in 1999, equivalent to approximately 90% of the 7.0 million ha of Argentina's national soybean crop in 1999);
  - o second, the significant increase of 2.2 million ha of transgenic corn (insect resistance, *Bt*/herbicide tolerance, and herbicide tolerance) in the USA from 8.1 million ha in 1998 to 10.3 million ha in 1999, equivalent to 33% of the 31.4 million ha of the US national corn crop in 1999;
  - o third, the increase of 1.0 million ha of herbicide-tolerant canola in Canada from 2.4 million ha in 1998 to 3.4 million ha in 1999, equivalent to 62% of the 5.5 million ha of the Canadian canola crop in 1999;
  - o and fourth, the 1.0 million ha increase in transgenic cotton in the USA from 2.2 million ha in 1998 to 3.2 million ha in 1999 (equivalent to 55% of the 5.9 million ha of the US national cotton crop in 1999). The 3.2 million ha of transgenic cotton in 1999 comprised 1.5 million ha of herbicide-tolerant cotton with the remaining 1.7 million ha equally divided between *Bt* cotton and cotton with stacked genes of *Bt*/herbicide tolerance.
- The combined effect of the above four factors resulted in a global area of transgenic crops in 1999 that was 12.1 million ha greater and 44% more than those for 1998; this is a significant year-on-year increase considering the high percentage of principal crops planted to transgenics in 1998. Commercialized transgenic crops were grown for the second year in two countries of the European Union (30,000 ha of *Bt* maize in Spain and 1,000 ha of *Bt* maize in France) with Portugal growing more than 1,000 ha of *Bt* maize for the first time in 1999. Two countries in Eastern Europe grew transgenic crops for the first time; Romania grew introductory areas of herbicide-tolerant soybean (14,250 ha) and planted <1,000 ha of *Bt* potatoes, with Ukraine also growing *Bt* potatoes (<1,000 ha) for the first time. There may also have been a small area of *Bt* maize grown in Germany and herbicide-tolerant corn in Bulgaria (12,000 ha) in 1999, but these could not be verified and thus are not included in the global database.

3. Value of the Global Transgenic Seed Market, 1995-1999

The value of the transgenic crop market is based on the sale price of transgenic seed plus any technology fees that apply. Unlike the estimates published in the Preview (Briefs No.12) in October 1999, the most recently revised estimates from Wood Mackenzie (personal communication 1999) exclude nongenetically modified herbicide-tolerant seed. Global sales of transgenic seed have grown rapidly from 1995 onwards (Table 7). Initial global sales of transgenic seed were estimated at $1 million in 1995. Sales increased in value to $152 million in 1996 and increased by approximately 450% in 1997 to $851 million. Sales increased by another 130% between 1997 and 1998 to $1.95 billion in 1998; if sales of nongenetically modified herbicide-tolerant seeds are included, total sales increased by about 10% to $2.26 billion in 1998.

Breaking the sales down by trait category, sales of transgenic herbicide-tolerant seed increased by 180% from $425 million to $1,188 million between 1997 and 1998. The corresponding increase in insect-resistant seeds was less than half as much, increasing from $423 million in 1997 to $738 million in 1998. However, the biggest percentage increase in value between 1997 and 1998 was for seeds with stacked traits of herbicide tolerance and insect resistance, which increased by 1,000% from $3 million to $33 million. Wood Mackenzie (personal communication) estimates that the value of the market in 1998 for the respective countries was as follows: USA $1,512 million; Argentina $252 million; Canada $170 million; Australia $10 million; China $7 million; Mexico $5 million; Spain $2 million, and South Africa $1 million. Given that all the traits introduced to date are crop protection traits, it is appropriate to express the value of total sales of transgenic crops in 1998 as a percentage of the global crop protection market. Wood Mackenzie estimates that transgenic seed in 1998 accounted for 6.3% of the $31.25 billion global crop protection market at the ex-distributor market value. The author estimates that, expressed as a portion of the global commercial seed market, transgenic seed represented approximately 6% of the estimated $30 billion global commercial seed market in 1998 (FIS 1999).

Table 7. Estimated value of global transgenic seed market, 1995-1999 (US$, millions)

Year	Market value $	Increase $	Increase %
1995	1[a]		
1996	152[a]	151	+ 15,100
1997	851[a]	699	+ 459
1998	1,959[a]	1,108	+131
1999	2,750 – 3,000[b]	791 – 1,041	+ 40 to + 53

Source: [a] Wood Mackenzie 1999 (personal communication); [b] Projection by Clive James.

For 1999, the author projects the value of the transgenic seed market at $2.7 to $3.0 billion, when again the largest increase was in the USA followed by Argentina, Canada, and China on a country basis. In 1999, from a crop perspective, biggest increases in seed sales were ranked in descending order of area: soybean, corn, cotton, and canola. For traits the highest increase in absolute terms was for herbicide tolerance followed by insect resistance, but with the highest percentage increase for stacked genes of herbicide tolerance deployed in both corn and cotton. Thus, revenues for transgenic seeds have increased from $152 million in 1996 to approximately $3 billion in 1999. The global market for transgenic seed is currently projected to plateau at about $3 billion in 2000, and depending on adoption rates and public acceptance, could increase up to $8 billion in 2005, and up to $25 billion by 2010.

4. Developments in the Crop Biotechnology Industry

4.1 Acquisitions, Alliances, Mergers, Spin-offs, and Restructuring in the Agribiotechnology Industry

Acquisitions, alliances, mergers, spin-offs, and restructuring were significant features that impacted on the biotechnology industry in 1999. These developments influence directly the level of private sector investments in crop biotechnology and indirectly impact on the future adoption and acceptance of transgenic crops globally. As in the previous three years, 1999 witnessed continued acquisitions, alliances and mergers that contributed to further consolidation of the biotechnology industry. As a result of the large number of acquisitions, alliances, and mergers over the last 5 years, the structure of the private sector involved with biotechnology, seeds, and agricultural chemicals has changed dramatically. In 1999, however, some corporations chose to spin off their agribiotech component from the pharmaceutical component with a view to merging their agribiotech component with a counterpart agribiotech business from like-minded partner corporations. Restructuring has occurred in all large transnationals involved in crop biotechnology. This has resulted in a refocusing and overall net decrease of resources allocated to crop biotechnology globally; this will directly decrease the rate at which new products will become available and increase the lag time before the public can benefit from new products. This decrease in resources allocated to crop biotechnology is particularly important for developing countries, which urgently require improved crops that can produce more and better quality food to combat poverty, hunger, and malnutrition. Thus, restructuring has decreased our global capacity to increase the quantity and quality of food in a sustainable way. It is highly improbable that the decrease in allocated resources in the private sector will be offset by an increased allocation of resources by the public sector, which in fact continues to decrease resources allocated to agriculture in both industrial and developing countries.

Table 8 lists 26 acquisitions, alliances, mergers, and spin-offs mainly involving companies from the private sector with a few alliances with institutions from the public sector. The transactions listed in Table 8 range from collaborative alliances to support R&D at modest levels (up to $50 million annually), to medium-sized acquisitions, and finally mega-mergers of transnationals worth billions of dollars. The stimulus for these acquisitions, alliances, mergers, and spin-offs are driven by

Table 8. Listing of 26 selected biotechnology-driven acquisitions and alliances in 1999 of corporations involved in seeds, crop protection, and life sciences

Month/Year	Corporations involved and nature of agreement
January 1999	**BASF** acquired 40 % of **Svalof Weibull**, a Swedish seed company, to facilitate implementation of its crop biotechnology initiatives; provided BASF with access to transgenic herbicide-tolerant canola in Canada and germplasm of other crops including oilseed rape, maize, cereals, sunflowers, and peas.
January 1999	**Monsanto** signed licensing agreements with **Cheminova, Dow Agro Sciences, Novartis,** and **Nufarm** for use of glyphosate with selected transgenic RR crops including soybean, cotton, and maize.
January 1999	**Monsanto** completes acquisition of **DeKalb**.
January 1999	Joint venture between **Novartis** and **Maisadour Semences** (France) to share biotechnology applications with the latter that has seed operations in maize and sunflowers with seed sales of $70 million/annum.
February 1999	**AgrEvo** acquires **Biogenetic Technologies** (Netherlands) which in turn owns **PROAGRO**, the second largest seed company in India specializing in maize, millet, sorghum, oilseed rape, sunflower, hybrid rice, and vegetables; **MISR Hytech** in Egypt (vegetables and field crops) is also owned by PROAGRO.
February 1999	**Novartis** and proprietors of PPO (protoporphyrinogen oxidase) inhibitor-type herbicides, that include **Sumitomo** and **Rhone-Poulenc**, discuss possible cooperation to use their PPO-type herbicides on Novartis transgenic herbicide-tolerant crops with the 'Acuran' PPO gene.
March 1999	**DuPont** opted to increase its 20%, $1.7 billion equity position in **Pioneer** to 100%, for an additional $7.7 billion for a total of $9.4 billion. Pioneer, the largest seed company in the world, has 42% of the US maize market and 18% of the US soybean market and recently purchased the soybean Brazilian seed company **Dois Marcos.**
March 1999	**Monsanto** and **Zeneca** agreed to a licence that allows Zeneca to use its Touchdown herbicide (glyphosate trimesium) on various transgenic RR crops (soybean, maize, and cotton) in the US and to explore global licenses as opportunities develop.
March 1999	**Monsanto** and **Great Lakes Hybrids** (GLH) signed a research agreement re the new Monsanto gene conferring resistance to maize rootworm. The agreement will allow GLH and its research partner **KWS** to develop inbreds for production of hybrids projected for field testing in 2000/2001.

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Table 8 continued. **Listing of 26 selected biotechnology-driven acquisitions and alliances in 1999 of corporations involved in seeds, crop protection, and life sciences**

Month/Year	Corporations involved and nature of agreement
March 1999	**Zeneca** and **Japan Tobacco** agreed to a joint venture to improve yield and quality of rice as a substitute for maize as animal feed.
April 1999	**Limagrain** and **Pau-Euralis** established **SOLTIS** to develop improved sunflower varieties that will also benefit from **Biogemma's** biotechnology inputs.
May 1999	**AgrEvo** (through its hybrid vegetable subsidiary **Nunza)** acquired **Rio Colorado Seeds** (California) that specializes in hybrid onion seed.
May 1999	**AgrEvo** acquired 3 Brazilian companies (**Sementes Ribeiral, Sementes Fartura**, **and Mitla Perquisa Agricola**) for $13 million. The 3 companies account for 8% of Brazilian maize seed sales and also market soybean and sorghum.
May 1999	**Dow AgroSciences** and **Danisco** formed a joint venture for the development of canola globally, that will benefit from biotech inputs from Dow AgroSciences to improve oil, meal, and agronomic traits. Crop breeding locations will include Canada, Denmark, Germany, and France.
June 1999	**Novartis** acquired the seed activities of **Eridamia Beghin-Say** which in turn includes assets of **Agra** (Italy)**, Agrosem** (France), **Koipsel Semillas** (Spain), and seed operations in Hungary and Poland. The companies specialize in field crops and collectively have a turnover of $30 million annually.
June 1999	**Strategic Diagnostics** (USA) licensed the PAT protein technology from **AgrEvo** to develop test kits for detecting proteins in food/feed ingredients.
August 1999	**Emergent Genetics** (USA) acquired **Stoneville Pedigree Seed** from **Monsanto**. Emergent Genetics is an affiliate of **Hicks, Muse, Tate and Furst** (USA), and recently acquired the seed companies of **Daehnfeldt** in Denmark and **Indusem** in Chile.
September 1999	**AgrEvo** increases its share from 20% to 95% in **PlanTec Biotechnologie** which focuses on enhancing carbohydrate metabolism, e.g., developing higher yielding crops with improved starch for enhanced foods and feeds.
September 1999	**Rhobio** (JV between Rhone-Poulenc and Biogemma) and **CSIRO** Australia sign a research agreement that provides Rhobio with DNA pPlex switches that turn genes on and off, e.g., for insect resistance.

continued...

Table 8 continued. **Listing of 26 selected biotechnology-driven acquisitions and alliances in 1999 of corporations involved in seeds, crop protection, and life sciences**

Month/Year	Corporations involved and nature of agreement
October 1999	**AgrEvo** acquired **GeneX** and established **AgrEvoSeeds Australia** which will focus on sorghum and maize, with links on maize to **PROAGRO**, India owned by **AgrEvo** which also has interest in oilseed rape in Australia.
November 1999	**Zeneca** and **AgriPro Wheat** (USA) reached a multimillion-dollar R&D agreement to develop improved varieties of wheat using biotechnology to improve and speed up breeding programs.
November 1999	**Auxein** (a US biotech corporation) and **Griffin** (JV between Griffin and DuPont) agreed to a joint program using Auxein's AuxiGro—a plant metabolic primer that triggers general defense mechanisms to plant diseases—in combination with Griffin's conventional fungicides.
December 1999	**Novartis** and **AstraZeneca** announced their intent to spin off and merge their crop protection businesses to form a new company **Syngenta** which will rank # 1 in global crop protection sales valued at $7 billion of a total 1998 market of $31.2 billion. Approval of deal is projected for the second half of 2000.
December 1999	**Monsanto and Pharmacia & Upjohn** announced a $27 billion merger of equals. 1999 sales are valued at $16.5 billion of which $5.2 billion is agricultural sales in 1999. The agriculture business of **Monsanto** to become a separate business and 20% of it to be floated as an initial public offering (IPO) in 2000.
December 1999	Antitrust delays led **Monsanto** to cancel acquisition of **Delta and Pine Land** who will receive $81million in lieu of cancellation.
December 1999	**Aventis** started operating on 15 December with 1998 sales estimated at $4.5 billion, ranked #1 in crop protection market, with 15% share.

Source: Complied by Clive James from various sources (1999).

both pharmaceutical and agricultural considerations where the latter is affected by negative public sentiment regarding crop biotechnology in Europe, which in turn impacts on growth prospects for the future. Transactions in the private sector have an enormous effect on the future deployment of transgenic crops and have far-reaching policy and technology implications for both industrial and developing countries. Table 9 lists a sample of 15 agreements signed in 1999 involving technologies related to genomics, which continues to be pivotal to the development of crop biotechnology. A discussion of some of the major acquisitions and alliances listed in Tables 8 and 9 is instructive in that it provides an insight into the commercial issues involved and illustrates the scale and scope of the initiatives.

Table 9. Agreements signed in 1999 involving plant genomics and related technologies

Month/Year	Corporations involved and nature of agreement
February 1999	**Dow AgroSciences** and **Proteome Systems** (Australia) agreed to characterize a new class of proteins and identify new enzymes and biosynthesis pathways for developing improved crops. (Note that Proteome is an analog of genome and a fusion word of protein and genome).
February 1999	**Genoplante,** a public/private sector Genomics consortium established in France in September 1998, is now extended to include **INRA, CIRAD, CNRS, IRD, Biogemma, Rhone-Poulenc**, and **Bioplante.**
February 1999	**Novartis** invested $12.7 million in **Diversa Corporation** (California) to collaborate with development of new genes that code for desired transgenic traits (quality, performance, and insect resistance).
February 1999	**Pioneer** and **Maxygen** (Glaxo-Wellcome subsidiary) signed a $30 million plus, 5-year agreement, for Maxygen to develop genes conferring crop protection and quality traits in crops.
February 1999	**Rhone-Poulenc** and **Agritope** agreed to a $20 million joint venture in functional genomics that focuses on input and output traits—the joint venture would involve collaboration with the **Salk Institute** and **University of Edinburgh.**
March 1999	**Rhobio** (Rhone-Poulenc/Biogemma joint venture) and **Celera Genomics** (division of Elmer Perkin) signed a 3-year agreement to discover maize genes that code for desired input and output traits.
March 1999	**Plant Biosciences (John Innes Centre**) and **ExSeed Genetics (Zeneca**) signed an agreement that will provide ExSeed Genetics the option to acquire worldwide rights to improved starch technologies for maize and rice.

continued...

Table 9 continued. **Agreements signed in 1999 involving plant genomics and related technologies**

Month/Year	Corporations involved and nature of agreement
April 1999	**Rhone-Poulenc** and the **Institute of Molecular Agrobiology** (Singapore) signed an agreement to study functional genomics of rice, focusing on fungal and bacterial diseases, nutritional qualities, and yield potential of rice.
August 1999	**Novartis** and **Genzyme Molecular Oncology** agreed to use the latter's SAGE technology (Serial Analysis of Gene Expression) to study plant growth and diseases.
August 1999	**Monsanto** and **Genzyme Molecular Oncology** agreed to use SAGE technology for constructing gene libraries from crop germplasm provided by Monsanto.
August 1999	**Novartis** and **Myriad Genetics** agreed to a $34 million collaboration on cereal genomics focusing on wheat, barley, oats, rice, and maize, to improve grain quality and yield. Myriad Genetics uses ultra-high throughput capillary DNA sequencing technology to develop crop genomic data.
August 1999	**Rhone-Poulenc** and **Agritope** agreed to establish **Agrinomics LLC**, a joint venture that will use the AC TTAG Gene Discovery Program of Agritope to identify genes that code for input and output traits for food, feed, and fiber crops. Rhone-Poulenc will invest $20 million in the joint venture for 5 years.
August 1999	**Zeneca** and **Maxygen** agreed to additional collaboration in genomics focused on crop protection and quality traits. Zeneca will invest $5 million in Maxygen and provide $20 million for R&D over 5 years.
November 1999	**AgrEvo** and **DLO** (Dutch Research Institute) agreed for **PGS** and **DLO** to enter into a research alliance on functional genomics in Arabidopsis, Brassica oil seed rape, wheat, and rice.

Source: Compiled by Clive James from various sources (1999).

There were four major acquisitions, mergers, and spin-offs in the private sector in 1999. First was the announcement by DuPont in March 1999 to complete the acquisition of Pioneer Hi-bred International. Subsequent to DuPont acquiring 20% of Pioneer Hi-bred International in September 1997 for $1.7 billion, DuPont announced its intent to increase its equity position in Pioneer in March to 100% for an additional investment of $7.7 billion, for a total acquisition price of $9.4 billion. This acquisition is of major importance in DuPont's crop biotechnology strategy which is focused on developing a portfolio of output quality traits that will contribute to improved nutrition and health. Pioneer is the largest seed company in the world with 1998 sales valued at $1.8 billion. Pioneer controls about 42% of the US maize seed market and 18% of the soybean market and recently purchased the Brazilian soybean seed company, Dois Marcos. The major markets for Pioneer are USA (65%) followed by Europe (22%). Pioneer markets hybrid maize seed with *Bt* licensed from Monsanto, and soybean with the glyphosate tolerance gene also licensed from Monsanto. Pioneer and DuPont have been conducting collaborative research under the umbrella of their joint venture, "Optimum Quality Grains" (OQG) for 2 years. Specific objectives of OQG are to optimize livestock feed nutritional value of maize and oil seeds, biofuel production, and nutraceuticals. High oleic acid soybean (80% oleic acid versus 24% in conventional) has already been approved by the USA Food and Drug Agency (FDA), and other specific target products are soybean products including low linoleic, low saturate, high protein, high sucrose, and high oleic sunflowers. OQG's first product, developed through conventional breeding, is high oil corn (oil content of 7.0-7.5% versus 3.5-4.5% in conventional) which is efficiently produced through a Topcross System and estimated to occupy about 200,000 ha in the USA in 1999. Future products will use high oil maize as a platform to add enhanced technology through transgenes for traits such as high lysine, methionine, and high available phosphorus to improve swine and poultry nutrition, and reduce phosphorus levels in waste. Enhancement of animal feed is a very important market in the USA with 80% of corn being used as livestock and poultry feed.

In a presentation to the Chief Executives Club of Boston on 22 September 1999, DuPont Chairman and CEO Charles O. Holliday (1999) described biotechnology as a "critical enabling technology that is very broad and offers many platforms for building a sustainable future world." He announced that DuPont will establish a global advisory panel to guide its actions in biotechnology including regular audits and public reporting; Dr Florence Wambugu, Director of ISAAA's *Afri*Center, based in Nairobi, Kenya, has been invited to join this panel. Holliday also said that DuPont will advocate informed consumer choice through meaningful information and product assurances based on better science-based information. He committed DuPont to generating 25% of its revenues from nondepletable resources by 2010, up from 5% in 1999, and to practicing biotechnology with the same high safety standards that DuPont has adhered to over the last 200 years. Summarizing the DuPont portfolio of genetically enhanced products, he noted the commercialization of high oleic acid soybeans, with near-term pipeline products that include high oleic corn, high lysine corn and soybean as well as disease-resistant corn, wheat, and rice. DuPont is using biotechnology to develop chemicals and polymers, with the first commercial product being a "3GT" polyester based on cornstarch rather than petroleum. The interface of biotechnology and electronics is also being explored using DNA-based science to miniaturize electronic devices that may be 10 times smaller than current technology and also the use of biosensors to develop more sensitive diagnostics. Holliday reported that DuPont has invested over $14 billion in biotechnology and that 20% of total revenues are projected to be generated from biological products that would include pharmaceuticals, crop protection products, improved seeds, and food. DuPont expects growth from these products to be faster than DuPont's traditional products in the future.

The second major announcement was in December 1999 when Novartis and Zeneca declared their intent to spin off their respective crop protection activities and merge them to form Syngenta. As a result of this merger, Syngenta would be ranked # 1 in global crop protection with consolidated 1998 sales valued at $7 billion compared with Aventis with sales of $4.5 billion, Monsanto at $3.6 billion, and

Dow AgroSciences and DuPont at $2.3 billion (Wood Mackenzie, personal communication 1999). Within 3 years, savings of $525 million are anticipated and the agreement to form Syngenta is planned for completion in the latter part of 2000, subject to clearance by antitrust authorities.

The third major announcement in December 1999 was Monsanto and Pharmacia & Upjohn giving notice of their intent to merge as equals in a $27 billion deal. The 1999 sales of the new company, Pharmacia, are estimated at $16.9 billion (1999 sales), of which $11.3 billion will be in pharmaceutical sales and $5.2 billion in agricultural sales; the annual R&D budget of Pharmacia will be over 2 billion. The agricultural business of Monsanto will be set up as an independent subsidiary and approximately 20% of it is planned to be offered as an initial private offering (IPO) in the second half of 2000. The merger is planned for completion within the first half of 2000 and cost savings of $600 million per year are anticipated. Prior to announcing the merger, Monsanto indicated that because of antitrust delays, it would cancel the acquisition of the cotton company Delta and Pine Land, which will receive $81 million in lieu of cancellation. Monsanto sold Stoneville Pedigree Seed to Emergent Genetics (USA) in August. Emergent Genetics is an affiliate of Hicks, Muse, Tate and Furst (USA), and recently acquired the seed companies of Daehnfeldt in Denmark and Indusem in Chile.

The fourth and last major announcement was the initiation of business activities by Aventis on 15 December 1999. Aventis was formed as a result of a merger between AgrEvo and Rhone-Poulenc, and is currently ranked #1 in the global crop protection market with 1998 sales of $4.6 billion. However, if, and when Syngenta is approved, with estimated 1998 sales of $7 billion, Aventis will be ranked #2 with approximately two-thirds of the sales value of Syngenta.

In other acquisitions and merger activities detailed in Table 8, BASF has initiated several activities that will provide the company with significant capacity in crop biotechnology. BASF acquired the Swedish company Svalof Weibull, which will provide it with access to transgenic canola in Canada. BASF has also indicated its plan to establish a significant R&D in crop biotechnology. Novartis acquired Maisdour Semence in France, and the seed activities of Evidamia Beghin-Say which includes Agra (Italy), Agrosem (France), Koipsell Semillas (Spain), and other operations in Poland and Hungary. Novartis has also discussed cooperation with Sumitomo and Rhone-Poulenc to incorporate the Acuran PPO herbicide tolerance genes in various crops. Prior to the formation of Aventis in December, AgrEvo was active in several acquisitions including: Biogenetic Technologies in the Netherlands which in turn owns PROAGRO (India) and MISR HyTech (Egypt); Rio Colorado Seeds (California); three Brazilian companies—Sementes Ribeiral, Sementes Fartura, and Mitla Perquisa Agricola; GeneX in Australia; and increased its share from 20% to 95% in PlanTec Biotechnologie in Germany, which specializes in enhancing carbohydrate metabolism, for example, developing high-yielding crops with improved starch; AgrEvo also licenses its PAT gene to Strategic Diagnostics (USA), which will develop test kits for detecting related proteins in food/feed ingredients. Monsanto signed licenses with several companies including Cheminova, Dow AgroSciences, Novartis, Nufarm, Zeneca, and Cyanamid for use of glyphosate on several herbicide-tolerant transgenic crops and signed a research agreement with Great Lakes Hybrids to incorporate a new Monsanto gene conferring resistance to corn earworm. Zeneca was also involved in several deals including a joint venture with Japan Tobacco to improve yield and quality of rice as a substitute for maize as animal feed, and with Agri ProWheat (USA) to develop improved wheats using biotechnology. Dow AgroSciences formed a joint venture with Danisco (Denmark) to develop improved canola for marketing globally, and Limagrain and Pan-Euralis established SOLTIS to develop improved sunflower varieties that will also benefit from Biogemma's biotechnology inputs. In other private sector negotiations, Rhobio and CSIRO signed an agreement that provides Rhobio with DNA pPlex switches that turn genes on and off, and that confer traits such as herbicide tolerance and insect resistance; Auxein and Griffin agreed to the use of metabolic primers that confer general defense mechanisms to diseases.

In summary, 1999 was an active year for acquisitions, alliances, and mergers, with spin-offs being implemented or considered as an option by several companies. Whereas the general restructuring that has taken place in all large transnationals was designed to provide more focus particularly on quality traits, it has resulted in a decrease in resources allocated to crop biotechnology, and several R&D programs have been put on hold, or assigned less resources, which will delay delivery of new products.

4.2 Genomics

The study of genomes is known as genomics and involves the mapping, sequencing, and analysis of genomes to determine the structure and function of every gene in an organism. For convenience, genomics research and studies may be categorized into three separate but complementary components:

Structural genomics - the structure and organization of genomes

Functional genomics - relating genome structure and organization to plant function

Application genomics - application of genomic knowledge for the development of improved plants.

Genomic information can be used to improve useful plant traits through genetic engineering to increase food and fiber production, and provide a safer and healthier environment and a sustainable source of renewable energy and chemicals. A general overview of genomics was included in Briefs No.8, "Global Review of Commercialized Transgenic Crops: 1998" (James 1998). This review covers a progress report on agreements signed in 1999 involving plant genomics and related technology (Table 9).

Genomics is of strategic importance and is a prerequisite for any organization seeking to develop a competitive capacity for developing transgenic crops. It is catalyzing a new generation of alliances between transnationals and smaller genomic companies in the public sector and some public institutes. The heightened interest in the human genome program during 1999, and the competition between public and private sector entities to complete the project first, has highlighted the importance of genomes to the public at large. Similarly, increased investments in genomics for developing pharmaceuticals has spurred interest in crop genomes, which has also been stimulated by public and private sector entities vying to complete programs on important crops. The interest in genomics is heightened with the planned completion of the *Arabidopsis* program in 2000 and the planned completion of the rice genome project brought forward from 2004 to possibly 2002. As progress continues in genomic programs, emphasis has switched from the early focus on structural genomics to functional and application genomics, which are investments that will lead directly to improved crops; the agreements listed in Table 9 reflect the greater emphasis on functional and application genomics.

Novartis invested in Diversa Corporation to develop new genes for desired traits and the use of the Serial Analysis of Gene Expression (SAGE) technology from Genzyme Molecular Oncology to study plant growth and diseases. Novartis also has an agreement with Myriad Genetics focusing on quality and yield in cereals.

In addition to Novartis, Monsanto also has an agreement with Genzyme Molecular Oncology to use SAGE Technology for constructing gene libraries from crop germplasm provided by Monsanto. Rhone-Poulenc and Agri Tope established Agrinomics LLC to develop a gene discovery program for input and output traits for feed and fiber crops, and through Rhobio (Rhone-Poulenc joint venture with Biogemma) has an agreement with Celera Genomics to discover maize genes that code for desired input and output traits. Rhone-Poulenc also has an agreement with the Institute of Molecular Agribiology in Singapore to study functional genomics of rice, focusing on fungi and bacterial diseases, nutritional qualities and yield. Zeneca (Ex Seed Genetics) has signed an agreement with Plant Biosciences (John Innes Centre) to have an option on the worldwide rights for improved starch technologies for maize and rice, and with Maxygen on genomes of crop protection and quality traits. Maxygen (Glaxo-Wellcome subsidiary) also has an agreement with Pioneer to develop genes conferring crop protection and quality traits. Other corporations that have negotiated genomic agreements include Dow AgroSciences and Proteome Systems Australia to characterize a new useful class of plant proteins; AgrEvo and DLO Dutch Research Institute works on functional genomics in Arabidopsis, Brassica, oil seed rape, wheat, and rice. Finally, Genoplante, a private/public sector genomics consortium that includes INRA, CIRAD, CNRS, IRD, Biogemma, Rhone-Poulenc, and Bioplante, was established in France.

The complex set of agreements between genomic companies providing services to transnationals who are users of the technology is resulting in an intricate web of proprietary technologies, elements of which are owned by more than one party. The shift of emphasis from structural genomes to functional and applied genomics has also been accompanied by a shift in focus from input to output traits. Much more emphasis on the latter can be expected in the future. It is anticipated that genomics will become even more pivotal in 2000 and beyond as genomic information for major economic crops such as rice and maize become available and used to innovate and accelerate crop breeding programs. It is vital that private and public sector investments in plant genomics continue to grow so that global food security can fully benefit from the rapid advances in genomics; it is particularly important for public sector institutes and international research organizations involved in crop improvement to gain a firm foothold in genomics; failure to do so will seriously impact on their continued comparative advantage in crop improvement activities. Most important, scientists from developing countries, where the need for food is greatest, must be exposed to these new advances through collaborative projects and hands-on training so that awareness of genomics is increased and capacity in the science is achieved in countries of the South.

Given that the seed is the vehicle for incorporating and deploying transgenic traits, it is instructive to characterize the global commercial seed market to gain a sense of the scope, scale, and size of the relative subsegments of the global market classified by country, or seed, or exports. The global commercial seed market was valued at $30 billion in 1998 (FIS 1999) with almost 30% of the market in developing countries. Six of the top 10 country markets (Table 10) are in the industrial countries: USA ($4.5 billion), Japan ($2.5 billion), Commonwealth of Independent States ($2 billion), France ($1.5 billion), Germany ($1.0 billion), and Italy ($650 million). The four developing countries in the top 10 are China ($2.5 billion), Brazil ($1.2 billion), with Argentina and India sharing equal

Table 10. Estimated values (US$ millions) of commercial markets for seed and planting materials from selected countries, 1998

Country	Internal commercial market	Country	Internal commercial market
USA	4,500	Austria	170
China	2,500	Morocco	160
Japan	2,500	Sweden	150
CIS	2,000	Czech Republic	150
France	1,500	Egypt	140
Brazil	1,200	Greece	140
Germany	1,000	Belgium	130
India	900	Chile	120
Argentina	900	Slovakia	90
Italy	650	Switzerland	80
United Kingdom	570	Finland	80
Spain	450	Ireland	80
Poland	400	Portugal	60
Canada	350	Bangladesh	60
Mexico	350	Slovenia	30
Netherlands	300	New Zealand	30
Australia	280	Zimbabwe	30
Hungary	200	Kenya	18
Denmark	200	Zambia	6
South Africa	190		
Total			**$ 22,664**[a]

[a] This total represents the sum of the commercial seed markets of the listed countries. The commercial world seed market is assessed at US$30 billion.

Source: FIS (1999).

markets at $900 million each. Of the nine countries that grew transgenic crops in 1998, all are in the top 20 countries in terms of seed sales. Nine of the 12 countries growing transgenic crops in 1999 were in the top 20 countries for seed sales with three exceptions—Portugal, Romania, and Ukraine.

Considering seed exports worldwide, the global market is valued at $3.5 billion equivalent to about 10% of the global market valued at $30 billion (Appendix Table 1A). Maize is the most important seed export, valued at $530 million annually. The top five crops that have export sales of more than $75 million annually are maize ($530 million), herbage crops ($427 million), potato ($400 million), beet ($380 million) and wheat ($75 million). Of the top 10 countries based on seed export, the top eight are industrial countries with annual seed exports valued from $700 to $100 million. Given the ongoing debate in Europe on transgenic crops, it is noteworthy that approximately half of the global seed export sales are from European countries. Out of a total global market of $3.5 billion, the USA is ranked first with $700 million (Appendix Table 2A), followed by six European countries—Netherlands ($620 million), France ($532 million), Denmark ($190 million), Germany ($185 million), Belgium ($111 million), and Italy ($103 million) for a total of $1.7 billion, and Canada at $100 million. The other two countries that export seeds are developing countries from Latin America: Chile with annual sales of $75 million, and Argentina, $44 million.

Seed consumption has been stagnant globally for the last 20 years except for Asia where consumption increased by 18% (Rabobank 1994); one-third of the seed used in Asia is rice, and on a volume basis two-thirds of the 120 million t of seeds traded annually are cereals. The annual sales for major cereals are wheat (35 million t), barley (11.1 million t), and maize (6.8 million t). It is estimated that there are 1,500 seed companies globally, of which 600 are based in the USA and 400 in Europe. For 1997, sales of the 20 principal companies that are active internationally had a total market of $7.8 billion (Caillez 1997).

Until the 1960s the seed industry comprised traditional seed companies that specialized in the improvement, production, and distribution of seed. During the late 1960s, several transnational corporations with activities in farm chemicals and pharmaceuticals acquired seed companies to capture the range of products and services for the agricultural industry within one corporate structure, thus providing them with the necessary R&D critical mass and benefiting from economies of scale. After a decade or so, however, some of the transnationals sold their acquired seed operations, for several reasons: incompatibility with an evolving business strategy, lower margins than expected in seed operations where they lacked business linkages and experience, and a realization that opportunities for using the seed industry to capture and market proprietary transgenic crops was a longer-term venture than they had anticipated. In the 1980s and 1990s, acquisitions and mergers have resulted in fewer but larger companies with interest in seeds, a trend that is expected to continue into the next decade. This will ultimately result in a few very large companies dominating the international market; spin-offs from large companies will tend to consolidate agricultural activities related to chemicals, biotechnology, and seeds in discreet businesses. This trend is fueled by long-term investments in research that are necessary to ensure competitiveness and an international marketing structure to effectively compete in the global market.

6. Status of Transgenic Crops in Selected Developing Countries of Asia

From a global perspective, the major impact of transgenic crops to date has been in North America (USA and Canada), followed by Latin America (Argentina and Mexico), Asia/Oceania (China and Australia), and South Africa. Asia gained an early lead when China commercialized its first transgenic crops in the early 1990s. A review of current developments in Asia/Oceania provides the basis for cautious optimism. China and Australia are both commercializing transgenic crops, and an impressive portfolio of products is being field tested in China. India has conducted extensive field tests of transgenic crops, and may approve its first commercial release of *Bt* cotton on limited introductory areas in 2000. Although Japan has not commercialized transgenic crops, by 1998 it had approved 20 products derived from transgenics for food use, and 15 products for feed use (James 1998). The latest information confirms that 9 additional transgenic crops and their derived food products have been approved for import and use in Japan, bringing the total to 29 products.

Of the ASEAN developing countries, Thailand was the first to initiate field testing of transgenic crops with delayed ripening tomato in 1995, followed by *Bt* cotton in 1996; the Thailand national program is expected to have its own virus-resistant transgenic papaya ready for field testing in the near term; this is a product from an ISAAA-brokered biotechnology transfer project with the coat protein gene conferring resistance to papaya ring spot virus (PRSV) donated by Monsanto to Indonesia, Malaysia, Philippines, Thailand, and Vietnam in a Southeast Asia Regional Program (Hautea et al 1999). Malaysia has field tested transgenic rubber with the GUS gene and Indonesia has completed transgenic field trials of *Bt* cotton, herbicide-tolerant cotton, herbicide-tolerant maize, *Bt* maize, and herbicide-tolerant soybean. In the Philippines, the first transgenic crop field trial ever to be conducted in the country was planted on 15 December 1999 at a site in General Santos, in Mindanao featuring *Bt* maize for the control of Asiatic corn borer. Thus, of the five rapidly developing countries of ASEAN, all, except Vietnam, have successfully conducted field trials of transgenic crops, which is a watershed in the development and deployment of transgenic crops.

Asia has 60% of the world's population and the greatest need for food, feed, and fiber; it is also home to 50% of the world's 1.3 billion poor, where an estimated 12,000 people a day die from chronic malnutrition. For the developing countries of Asia, where transgenic crops can make a vital contribution to food security, there are indications that a momentum is under way that will facilitate the adoption of transgenic crops in the region in the near term. This momentum is greatly influenced and can be enriched by sharing the experience of China on transgenic crops, particularly *Bt* cotton, with other Asian countries. The experience of China is important because it demonstrates a strong commitment to the science, tangibly expressed as significant R&D support, and its pragmatism and leadership in assigning a strategic role to biotechnology/ transgenic crops in its national food security strategy. The experience of at least 1.5 million small farmers in China growing *Bt* cotton is an important experience to share with countries in Asia, because, first it is an Asian experience, second it is a small- rather than a big-farmer experience, and third it is an experience based on two different and competing products—one developed and patented by Chinese scientists from the public sector and another by a transnational, Monsanto/Delta and Pine Land.

It would be particularly appropriate and important for China to share its *Bt* cotton experience with India which is currently considering commercializing *Bt* cotton, and with Indonesia and Thailand which have already field tested *Bt* cotton. The Chinese experience with *Bt* cotton is encouraging because it offers significant agronomic, economic, and environmental benefits; the latter has resulted in significant benefits to growers, the society, and the country by almost eliminating the need for large volumes of polluting insecticides for the control of bollworm, and decreasing health hazards to farmers and society at large.

The prospect of India commercializing transgenic crops in the near term, plus the fact that most ASEAN countries have now completed transgenic crop field trials, reflects a growing interest, pragmatism, and maturity among countries on the evolving role of transgenic crops to food, feed, and fiber security in the region. Asia has a significant advantage in that many of its national programs have infrastructure that can assimilate and accelerate the adoption of technology, and transgenic crops could be adopted in a timely manner following successful field trials to openly demonstrate the benefits and the safety of products to regulators and the public. The economic recovery in Southeast Asia has facilitated more R&D in crop biotechnology and in turn the adoption of transgenic crops. Given that at least half of the 24,000 people that die every day from chronic malnutrition are Asians and that transgenic crops have the potential to reduce this suffering, countries in Asia deserve the assistance they are requesting from international institutions with capability in various aspects related to transgenic crops, including access to technology, training, biosafety, food safety, and intellectual property rights. Within the region, China is now in a position to exert leadership by sharing its transgenic crop experiences with neighboring countries. International institutions that can also assist include multilateral aid agencies such as the World Bank, the Asian Development Bank, bilateral agencies of countries such as USA, Australia, and Japan, international centers of the Consultative Group on International Agricultural Research (CGIAR 1998), technology transfer organizations such as ISAAA, and multinationals involved in crop biotechnology, all of whom are active in the region.

Asia is unique in that it is a region where one crop, rice, plays such a dominant role. Of the three major staples (wheat, rice, and maize), the greatest concentration of a single staple, rice, is in Asia. Over 90% of the world's 150 million ha of rice is grown in Asia. Biotechnology offers unique opportunities for improving rice productivity ranging from the use of tissue culture and molecular markers to facilitate more effective conventional breeding programs, to incorporation of genes for overcoming biotic and abiotic stresses, improving quality, and improved hybridization technology. National programs such as China, international public sector research organizations such as IRRI, transnational private sector and industrial countries such as USA and Japan, and the Rockefeller Rice Biotechnology Program, collectively, have an impressive portfolio of biotechnology applications that could contribute to improved rice production and nutrition in Asia. Given rice's unique role in Asian diets, tradition, and culture, the introduction of transgenic rice could make a critical contribution to food security in the region during the next decade. In the following paragraphs four topics which are relevant to Asia are reviewed: an overview of crop biotechnology in China, the most recent results of *Bt* cotton field trials in India, an assessment of the potential benefits of *Bt* corn in the Philippines, and a summary of the recently completed 10-year Rockefeller Program on rice biotechnology.

6.1 Crop Biotechnology in China

China faces a formidable challenge to feed 1.3 billion people, equivalent to 20% of the world's population, using only 7% of the world's cultivable land of 1.5 billion ha. China's population is expected to peak at about 1.6 billion in 2030 when it will require 60% more grain due to increased population and change in diet, which will depend on more meat. Given that cultivable land area will remain the same, or decrease slightly, increasing productivity through yield per hectare is the only option for increasing domestic production; this will allow import of grains to be maintained at reasonable levels rather than the 250 million t per annum of grain imports predicted by some observers. To achieve the necessary increases in productivity, China is fortifying its conventional technology base with biotechnology, including transgenic crops, which represent a strategic element in China's food security strategy. China's investment in crop biotechnology started during the 6th Five Year Plan (1981 to 1985), when preparatory work was initiated to plan national research programs and the training of biotechnologists. During the 7th Five Year Plan (1985 to 1990), the well-publicized 863 High-Tech Program was initiated and biotechnology was assigned the highest of seven national priorities (Rongxiang 2000). During the 7th Five Year Plan the first generation of transgenic crops were generated which included the single-construct tobacco mosaic virus (TMV) and double-construct TMV/cucumber mosaic virus (CMV)-resistant tobacco using coat protein technology, CMV-resistant tomato using satellite RNA, insect-resistant tobacco using the *Bt* gene, and atrazine-tolerant soybean using the *psb* gene. New transformation techniques, including the pollen tube method to introduce DNA into cotton as well as PEG mediated transformation of soybean and regeneration procedures were developed.

In the 8th Five Year Plan (1991 to 1995) the crop biotechnology program was broadened to include important crops such as rice, maize, cotton, tomato, pepper, papaya, sugar beet, soybean, and poplar. Similarly a broad range of traits was targeted including virus resistance, bacterial resistance, insect resistance, herbicide tolerance, salinity tolerance, delayed ripening, male sterility, and various quality traits including enhancement of essential amino acids. Work was also undertaken on a broader range of transformation methods including *Agrobacterium* (Ti and Ri), particle bombardment, electroporation, and the use of laser and ultrasonic techniques. It was during the 8th Five Year Plan that the first commercial planting of transgenic tobacco (TMV) was undertaken in China which was the first country in the world to grow large areas of transgenic crops commercially. In 1992, transgenic tobacco, resistant to cucumber mosaic virus incorporating a single coat protein construct, was sown on approximately 40 ha for seed increase. In 1994-95 a double construct (CMV and TMV) was developed and introduced into commercial production. The virus-resistant transgenic tobacco in China resulted in significant benefits which included a yield increase averaging 5-7% more leaves for processing, with savings of 2 to 3 insecticide applications from the normal program of 7 applications.

In July 1996 the Ministry of Agriculture established the Office of Genetic Engineering Safety Administration (OGESA) to regulate field testing, environmental release, and commercialization of transgenic organisms. In May 1997 the Safety Committee, which meets twice a year, started to review applications. Between 1997 and June 1999, out of almost 200 applications, 26 had been approved for commercialization, 59 for environmental release, and 73 for field trials, with 34 applications pending. More than 80% of the applications in 1997 were for crops, with 15%

for microorganisms and 5% for animals. Corresponding data for 1998 showed that crop biotechnology applications continued to represent the majority (>60%) of applications with applications for microorganisms increasing to 33%. The number of biotechnology product applications submitted to OGESA are increasing annually and with a few exceptions, all applications are being submitted by the 100 or more laboratories in the country that are currently pursuing R&D work on various aspects of biotechnology.

The status of transgenic crop products approved for commercialization in China is summarized in Table 11 (Chen 1999). In 1999, five transgenic crops were approved for commercialization: *Bt* cotton (two products, one from CAAS and the other from Monsanto/ Delta and Pine Land), virus-resistant tomato (Peking University), delayed ripening tomato (CCAU), virus-resistant sweet pepper (Peking University), and novel colored petunias (Peking University). *Bt* cotton area in China in 1999 was estimated conservatively at approximately 250,000 ha. The actual area could be significantly greater due to farmer-to-farmer exchange of seed. Individual estimates of area for the other four transgenic products are not available. Chen (1999), however, estimates that the total area of commercialized transgenic crops, including *Bt* cotton, in China in 1999 could have been 400,000 ha.

The transgenic crop products approved for large- and small-scale field trials (Table 11) cover a broad range of 12 of China's most important crops. They include rice with the *Xa21* gene, which is viewed as a priority, *Bt* cotton, *Bt* corn for the control of Asiatic corn borer, wheat, (virus resistance and quality traits), potato (*Bt* and quality traits including improved starch), tobacco for insect resistance (*Bt*) and virus resistance, soybean for insect resistance and herbicide tolerance, tomato and sweet pepper for virus and disease resistance, and finally poplar, orange, and eucalyptus for insect resistance. Sweet potato is conspicuous by its absence, given that China grows 5.8 million ha, equivalent to 65% of the global area of sweet potato (9 million ha), and that insect weevils are serious pests along with virus diseases. Similarly, rapeseed/canola, which is an important crop in China occupying 6.9

Table 11. Status of transgenic crops approved for commercialization, large- and small-scale trials in China, as of June 1999

Commercialization	
Bt cotton	
Virus-resistant tomato	
Delayed ripening tomato	
Virus-resistant sweet pepper	
Novel colored petunias	
Large-scale field trials	
Cotton	*Bt*
Tobacco	*Bt* and virus resistance
Potato	*Bt* and quality
Soybean	Insect resistance and herbicide tolerance
Tomato	Virus resistance and disease resistance
Sweet pepper	Virus resistance
Poplar	*Bt*
Small-scale field trials	
Rice	Bacterial disease (*Xa21*) and insect resistance
Wheat	Virus resistance (BYDV) and quality
Corn	*Bt* and herbicide tolerance
Orange	Insect resistance
Eucalyptus	Insect resistance

Source: Chen (1999).

million ha (28% of world hectarage of 25 million ha) is not reported as approved for field trials although the transgenic applications are well advanced on this crop.

Table 12 classifies the 121 transgenic crop applications approved by OGESA from 1997 to June 1999 and indicates the relative importance of different transgenic crops and traits. Given that cotton is the major transgenic crop already commercialized in China, it understandably represents the highest percentage (33%) of approvals for environmental release, field testing and commercialization. Rice is ranked second (26%) and the *Xa21* gene that confers resistance to bacterial blight of rice is assigned high priority and is a candidate to follow *Bt* cotton as a transgenic crop to have impact at the national level. Some traits such as virus resistance and delayed ripening in tomato (ranked third at 10%) have already been approved for commercialization as is the case with virus-resistant tobacco (6%) and virus-resistant sweet pepper (5%). Potato (ranked fourth at 7%) is an important crop in China , occupying 3.2 million ha and can benefit from *Bt* to control tuber moth, and quality traits to improve starch and quality. Corn, which surprisingly is ranked only an equal fifth with sweet pepper, is an extremely important crop in China where corn yields, that are already high, could benefit significantly from control of Asiatic corn borer. Despite the fact that only a few applications have been approved for corn, it is reported that public and private sector *Bt* products have been developed and it is likely to be the next transgenic crop along with *Bt* cotton and *Xa21* rice that will have impact at the national level in the near term. Given that China has over 20 million ha of corn compared with 4 million ha of cotton, the introduction of *Bt* corn, alongside *Bt* cotton will pose new challenges in terms of management of the durability of *Bt* and other genes such as *CpTi* which has already been introduced as a

Table 12. Transgenic crops approved for environmental release, field testing, or commercialization in China, 1997 to June 1999, categorized by crop and trait

Crop	Percentage approved
Cotton	33
Rice	26
Tomato	10
Potato	7
Tobacco	6
Corn	5
Sweet pepper	5
Wheat	1
Soybean	1
Petunia	1
Papaya	1
Chinese medical herb	1
Peanut	1
Melon	1
Brassica oleracea var. *chinensis*	1
Total	**100**

Trait	Percentage approved
Insect resistance	52
Virus resistance	21
Bacterial resistance	8
Fungus resistance	4
Prolonged shelf life	3
Nutritional quality	3
Herbicide tolerance	2
Cold tolerance	2
Salt tolerance	2
Developmental control	2
Mutation	1
Total	**100**

Source: China National Biotechnology Program (1999).

stacked gene to increase durability in the *Bt* cotton developed by Chinese scientists.

In terms of traits, unlike the USA and Canada where herbicide tolerance dominates, Table 12 shows that for China, the highest percentage of approvals for field testing, environmental release, and commercialization is for insect resistance (52%), followed by virus resistance (21%) and bacterial disease resistance (8%). This ranking of the top three traits reflects the many field experiments conducted prior to the commercialization of *Bt* cotton, virus-resistant tobacco, tomato and sweet pepper, and the work under way on *Xa21* gene in rice for bacterial resistance and *Bt* corn. Resistance to fungal diseases (ranked fourth) is assigned medium priority along with prolonged shelf life and nutritional quality (equal at 3%), with fewer applications approved for herbicide tolerance, cold tolerance, and salt tolerance. The availability of labor for hand weeding may reflect the lower activity in herbicide tolerance at this time, but this could change rapidly as urbanization and industrialization accelerate in China. Conspicuous by their absence are traits that would confer better resistance to drought, but this reflects the state of the technology and the degree of difficulty in identifying appropriate genes for drought, rather than the importance of productivity constraints associated with water stress which is the top priority for China. Major gains in productivity will result from applying biotechnology to develop crops that use water more efficiently and is particularly important for China where 60% of the cultivable land is rainfed and subject to a significant degree of drought. Hence, development of drought-tolerant crops is the top priority for China this century (Xu 2000) as it is for most other countries in the world. Although water covers 70% of the Earth's surface, only about 2.5% is fresh water. Only <1% of the fresh water is readily accessible and this represents about 0.007% of all the water on earth (WMO 1997). Agriculture accounts for 93% of the global consumptive use of water through irrigation or rainfall. Irrigated agriculture (which consumes 70% of global water withdrawals) on 270 million ha (about 17% of 1.5 billion ha of cultivable land) produces 40% of world food production while the remaining 83% of cultivable rainfed land, equivalent to 1.230 billion ha of rainfed agriculture, produces the other 60% (Borlaug 2000). The UN's 1997 analysis of fresh water resources estimates that about one-third of the world's population lives in countries with moderate to high water stress now. It is projected that as much as two-thirds of the world's population could be under stress conditions by 2025 (WMO 1997).

In summary, China has assigned high priority to crop biotechnology, which is a critical element in its food security strategy. Chen (1999) projects that within the next 10 years, about 20-50% of five of China's principal crops, grown on a total of 98.8 million ha, could be planted to transgenic crops to provide sustenance for its people. The five crops are rice (31.2 million ha), wheat (28.8 million ha), corn (25.9 million ha), soybean (8.2 million ha), and cotton (4.2 million ha); absent from this list is rapeseed, which occupies 6.9 million ha in China. To put the 20-50% adoption rate for transgenic crops in China into a global perspective, a 20% adoption rate of transgenics for the above five principal crops would be equivalent to half the global transgenic crop area of 39.9 million ha planted in 1999. At a 50% adoption rate for transgenics for the same five crops, China would have a transgenic crop area equivalent to approximately 50 million ha, 10 million ha more than the total global area of 39.9 million ha planted to transgenic crops in 1999.

6.1.1 Bt Cotton in China

Cotton is the most important cash crop in China but is subject to very heavy damage by bollworm (*Helicoverpa armigera*). In the past, area planted to cotton in China was as high as 6.7 million ha, but severe damage due to cotton bollworm reduced this by 40% to an estimated 4.0 million ha in 1999. An important implication is that China is now an importer of cotton whereas formerly it was an exporter. Loss due to cotton bollworm in 1992 (Jia 1998) was valued at the national level to be 10 billion RMB equivalent to US$1.2 billion (calculated at the official 1999 exchange rate of 8.27 RMB = US$1.00).

There are two suppliers of *Bt* cotton in China. The first is the Chinese Academy of Agricultural Sciences (CAAS) in collaboration with provincial academies and seed distribution organizations. CAAS has developed a range of *Bt* cottons products under the aegis of the well-publicized 863 High-Tech Program. Work on the *Bt* gene was first undertaken at the Biotechnology Centre of the Chinese Academy of Agricultural Sciences in Beijing. By 1996 a total of 10 transgenic *Bt* cotton varieties had been developed and a total of 17 field trials were conducted occupying 650 ha. In 1997, the Biosafety Committee of the Ministry of Agriculture approved commercialization of the first *Bt* cotton and the area planted was extended to 10,000 ha in 1998. The first commercial plantings of the CAAS *Bt* cottons in 1998 featured a single *Bt* gene (*Cry1B/Cry1C*) on 10,000 ha planted in four provinces (Anhui, Shangdong, Shanxi, and Hubei) (Jia 1998, James 1998). By 1999, the CAAS single *Bt* cottons, and the stacked *Bt*/*CpTi* cottons (designed to provide more durable resistance), occupied an area 12-fold greater than 1998 to cover a total 120,000 ha, and planted in nine provinces compared with four in 1998. It is estimated that at least 750,000 small farmers grew CAAS *Bt* cottons in 1999, most of which carried the single *Bt* gene. The single *Bt* cottons were planted in the nine provinces of Shangdong, Shanxi, Anhui, Jiangsu, Hubei, Henan, Hebei, Xinagjiang, and Lianoning. The CAAS cotton with stacked genes was planted in the four provinces of Shangdong, Shanxi, Anhui, and Hubei in 1999 (Jia, personal communication 1999). Preliminary estimates of the benefits associated with *Bt* cotton in 1998 (Jia 1998, James 1998) indicate that the net benefits to farmers are due to significantly reduced need for insecticides and associated labor costs of applying them. Savings were estimated at 1,200 RMB to 1,500 RMB per hectare, equivalent to $145 to $182 per hectare. This is a substantial increase in income for a small resource-poor farmer who is planting, on average, approximately 0.15 ha of *Bt* cotton. These preliminary estimates of economic gains do not include the additional significant social, environmental, and health benefits associated with reduced applications of pesticides, which pose very serious health hazards to small producers applying many insecticide sprays to control cotton bollworm in China. A comprehensive and rigorous survey was conducted in Shangdong and Hubei provinces by CAAS in 1999 to assess the impact of both CAAS and Monsanto/Delta Pine *Bt* cotton grown by 1.5 million small farmers; the study will be published in 2000 and the findings will be reported in a Brief.

The CAAS *Bt* cotton is being carefully monitored to develop the most effective means for achieving durable resistance within the context of a *Bt* management strategy. Results indicate that field performance of *Bt* cotton is superior to non-*Bt* cotton with no indication that resistance to *Bt* is developing. The multiple cropping system and the spatial distribution of *Bt* cotton planted on small farms in China contribute to a natural "refuge." Jia (1998) projects that the current *Bt* cotton may provide adequate levels of resistance for up to 8 or 9 years, during which alternative strategies of control will be developed and implemented.

One of the current alternative strategies being employed is the use of the *Bt* gene in conjunction with the *CpTi* gene, which encodes for an insecticidal protein with an independent mode of action from *Bt*. This strategy is being employed to provide better control and delay resistance development .

The second supplier of *Bt* cotton in China is Monsanto/Delta Pine whose product is based on the variety 33B, which carries the *Cry1A(c)* gene. In 1998, this occupied 53,000 ha in Hebei province and increased almost 2.5-fold to approximately 125,000 ha in 1999. It is grown by an estimated 750,000 small farmers and occupy the same area as the Chinese *Bt* cotton in 1999. Unlike the Chinese product, however, the Monsanto/Delta Pine product was grown in only one province, Hebei, in 1999 but with plans to expand to other provinces in 2000. Significant benefits in terms of net return per hectare are also being reported for the Monsanto/Delta Pine product. Details of the planting are planned for publication in 2000. Preliminary data indicate that the *Bt* cotton had a yield advantage of 25% over conventional cotton which required 14 insecticide sprays compared with an average of less than 1 spray for *Bt* cotton, with approximately 70% of farmers applying no insecticide sprays on *Bt* cotton.

Taking into account the *Bt* cottons deployed by both CAAS and Monsanto/Delta Pine in China there has been remarkable progress with both products since the *Bt* cottons were first deployed. In 2 years, *Bt* cotton in China has increased from small introductory areas in 1997 to 63,000 ha in 1998, to 245,000 ha in 1999 (a 3.9-fold increase in 1 year), with an estimated total of at least 1.5 million small farmers benefiting from both CAAS and the Monsanto *Bt* cotton products. The 245,000 ha estimate for 1999 is considered conservative because it is based on seed sales. It is difficult to estimate the additional area planted with farmer-saved and farmer-traded *Bt* cotton seed which is judged to be significant. The important point is that at least 1.5 million small farmers grew *Bt* cotton in China in 1999. The initial 400,000 small farmers who first adopted *Bt* cotton in 1998 derived significant and multiple benefits from the technology. Because farmers who adopted *Bt* cotton in 1998 were very satisfied with the experience, they were keen to continue the practice in 1999 and were joined by more than 1 million other small cotton farmers, which in turn led to the planting of 245,000 ha of *Bt* cotton in 1999. This is equivalent to 6% of the Chinese national cotton area of 4 million ha in 1999. Based on experience to date, the *Bt* cotton area in China is expected to significantly expand again in 2000.

6.2 The Cotton Crop in India and the Potential Benefits of *Bt* Cotton

Cotton is the leading plant fiber crop in the world and the most important fiber crop in India. India has a larger area of cotton than any other country in the world, approximately 9 million ha. This represents 24% of the world total cotton area and occupies 5% of India's total cultivated land area. Cotton yield in India, however, averages only 236 kg/ha and is one of the lowest in the world. As a result of low yields, cotton production in India represents only 13% of total world production. It is estimated that the income of approximately 60 million people living in India is derived from the production, processing, and/or export of raw cotton and cotton textile goods (Bell and Gillham 1989). Some of the major constraints to cotton production in India are water availability at crucial stages of crop development, inadequate insect and disease control measures, low fertilizer inputs, and limited use of hybrid seeds.

India has addressed the need for increased cotton production under a series of 5-year plans. The strategy for increasing cotton production has the following thrusts: accelerate the use of improved technology in both irrigated and rainfed areas, with emphasis on use of pure seed, optimum agronomic practices, and integrated pest management; cultivate more cotton in rice fallow and nontraditional areas; expand the irrigated area of cotton production; and increase the use of hybrid cotton. Targets for the 5-year plans have largely been met and India has graduated from being a large net importer of cotton, to being a major exporter of high-quality cotton suitable for spinning into higher count yarns. Today, cotton is grown in four regions in India encompassing the states of Punjab, Rajasthan, and Haryana in the north; Maharashtra and Madhya Pradesh in the central region; Gujarat in the northwest coastal region; and Andhra Pradesh, Karnataka, and Tamil Nadu in the southern region. In the north, cotton is an important cash crop where approximately 95% of the crop is irrigated, and yields are generally higher than the other regions. The principal variety is J-34, a short staple cotton suitable for spinning into 24 to 28 count yarns. In the central states, cotton is considered the most important cash crop. Even though some of the cotton production in the central area is irrigated, production depends largely on monsoon rains. The northwest coastal state of Gujarat is also dependent on monsoon rains for cotton production, because water salinity prevents extensive irrigation. The southern states are the most important from the standpoint of high quality cottons.

The rationale for developing *Bt* cotton in India is that cotton production is constrained by damage by insect pests, particularly lepidopterans, which are the most important. The most serious pest is the American bollworm, which can be very destructive, and is equally damaging to legumes, tomato, and several other crops. Annual losses caused by bollworm alone are estimated at approximately US$300 million (King 1994). Other important lepidopteran insect pests of cotton in India are the pink bollworm (*Pectinophora gossypiella*), spotted bollworm (*Earias vittella*), spiny bollworm (*Earias insulana*), and tobacco caterpillar (*Spodoptera litura*). To date, chemical control has been the most common practice and is often the only option. It is estimated that insecticides valued at $700 million are used on all crops annually in India, of which nearly 50% is used on the cotton crop alone (Dhar 1996). Because of heavy and indiscriminate use of all categories of insecticides, pests have developed resistance to most of the commonly used insecticides in the country. Conway (1997) reported that 450 pest species had developed resistance to one or more pesticides. Because of the undesirable effects of chemical pesticides, emphasis is now placed on integrated pest management (IPM) where nonchemical crop management practices are used in conjunction with selective insecticides for insect pest control. *Bt*, with appropriate management, provides an effective alternative and environmentally superior control of bollworm and other lepidopteran insect pests of cotton (Wilson et al 1994, Luthy et al 1982). *Bt* cotton with the *Cry1Ac* gene has been tested in India for several seasons and results for 1998-99 are detailed in Table 13.

Extensive and fully replicated field trials of *Bt* cotton have been conducted under the guidance of the Department of Biotechnology of the Government of India. These trials meet the requirements of the government for commercialization. Information from two sets of *Bt* cotton trials conducted in 1998-99 are reported here (Barwale, personal communication 1999). Trial results are summarized in Table 13. Set A trials were conducted at 15 sites in seven Indian states in 1998-99 featuring four cotton hybrids, one containing the *Bt* gene, and one without *Bt*. Set B trials featuring one cotton hybrid (MECH-1) with and without *Bt*, were conducted at 25 sites in nine Indian states in kharif 1998-99.

Table 13. Summary of *Bt* cotton trials conducted in India, 1998-99						
Trial	Yield (kg/ha)	% yield increase *Bt* hybrids	No. of bollworm larvae/10 plants		Fruiting body damage (%)	
			0-60 days from planting	61-90 days	0-60 days	61-90 days
Set A trials (15 sites)						
Mean *Bt* hybrids	1464	40	1.2	1.7	2.5	2.5
Mean non-*Bt* hybrids	1045	-	6.1	6.4	8.7	11.4
LSD (0.05)	214	-	2.5	2.4	4.5	7.2
Set B trials (25 sites)						
Mean *Bt* hybrid	1694	37	1.0	-	1.7	-
Mean non-*Bt* hybrid	1238	-	7.9	-	9.0	-

Source: Barwale (personal communication 1999).

Results from both studies indicate that *Bt* cotton hybrids significantly outyielded their non-*Bt* counterparts by 40% in Set A trials and 37% in Set B trials. Results confirm significantly less bollworm larvae on *Bt* cotton hybrids compared with their counterparts during the two periods 0-60 days (1.2 vs 6.1) and 61-90 days (1.7 vs 7.4) after sowing. Similarly, damage to fruiting bodies was significantly lower for *Bt* cotton hybrids compared with their counterparts in both sets of trials. Populations of sucking pests (aphids, jassids, and whitefly) and beneficial predators (ladybirds, green lacewing bug, spiders) were monitored in both *Bt* hybrids and non-*Bt* hybrids. No differences were noted between *Bt* hybrids and non-*Bt* hybrids. In Set B trials standard cotton cultivation practices were followed at each site including application of insecticides when the economic threshold levels for pests were exceeded. Application of up to seven insecticides was necessary for non-*Bt* hybrids at all sites, whereas *Bt* hybrids required no sprays in most sites except two sites where 1 to 3 sprays were applied.

Results from these two sets of extensive *Bt* cotton trials in India in 1998-99 confirm *Bt*'s effectivity against bollworm, the major insect pest of cotton in India, resulting in significant reduction in insecticides; substantial social, environmental, and human health benefits; increased and more stable yields; and increased net returns per hectare. Given that India is a large producer of cotton (9 million ha), the importance of providing effective control of bollworm has significant economic advantages and positive environmental implications for India and the textile industry.

6.3 Potential Benefits of Bt Corn in the Philippines

The first transgenic crop field trial ever in the Philippines was planted on 15 December 1999 in General Santos City in Mindanao. The field trial featured *Bt* corn and was harvested in March 2000. A recent study by Gonzalez (2000) assessed the potential benefits from applying biotechnology, more specifically the use of *Bt* for the control of Asiatic corn borer

(*Ostrinia furnacalis*). The Philippines produces approximately 4.5 million t of corn (1.8 million t white and 2.4 million t yellow) domestically every year, and on average it imports 300,000 t at a cost of US$55 million in 1998. Yield losses due to Asiatic corn borer in the Philippines ranged from 8% in the dry season to 27% in the wet season (at least twice as high as reported for European corn borer losses in the USA), which resulted in yield losses of 327,000 to 881,000 t annually during the wet and dry seasons from 1980 to 1998 (Gonzalez 2000). Thus, corn imports, which averaged 316,000 t from 1990 to 1998, have the potential to be more than offset by production increases from controlling Asiatic corn borer with transgenic corn using *Bt* which is known to give effective control. In addition, if corn farmers in the Philippines use *Bt* corn they would not have to revert to using insecticides which are not only costly ($13/ha, based on 0.45 kg of a.i./ha), but are hazardous to the health of small resource-poor farmers, and detrimental to the environment.

Analyses indicated that for every 1% increase in yield due to control of Asiatic corn borer, increase in net farm incomes were 1.3-3.1% higher in 1995-96 and 1.5-55.5% higher in 1997-98. Thus, adopting *Bt* corn for control of Asiatic corn borer will probably result in multiple benefits: a high multiplier impact on incomes of one of the poorest groups in the farming sector—the resource-poor small farmers; substitute corn imports resulting in significant foreign exchange gains averaging $58 million annually; eliminating the need for insecticides in a food crop consumed by the poor and a feed crop that is increasingly important for the Philippine economy. The potential advantages of eradicating losses due to corn borer (*Ostrinia furnacalis*) with *Bt* in a country such as the Philippines has much more significance and implications than eradicating losses due to the European corn borer in the USA or Canada. Gonzalez (2000) concludes that the increase in the international competitiveness of the Philippines in corn production, that would accrue from the use of *Bt* corn, would be significant and critically important at a time when open international trade protocols will apply under GATT-WTO and APEC agreements.

6.4 The Rockefeller Foundation International Rice Biotechnology Program

This Rockefeller Foundation Program is particularly significant to Asia because it is focused on rice—the principal crop in the region. In September 1999, Rockefeller Foundation (RF) sponsored the last general meeting of the International Program on Rice Biotechnology at Phuket, Thailand. The meeting, attended by 400 scientists active in various aspects of rice biotechnology, marked the completion of a 15-year, $100-million innovative program, which has proven to be extremely productive. The two-thrust program first supported biotechnology research conducted by leading scientists at 46 laboratories in industrial countries. The second thrust concentrated on training 400 Asian scientists from developing countries in the industrial laboratories once the technologies had been developed (Normile 1999). At the outset of the program 70% of the funding was provided to laboratories in industrial countries, falling to 10% in later years when 60% of the funding was allocated to labs and international centers in developing countries. The remainder was allocated to training and education. As a result of the RF program several countries, including China, India, and Korea, have already integrated biotechnology into their national rice improvement program; the participation of other countries in the program such as the Philippines, Thailand, and Vietnam, is moving in the same direction. The program has achieved several successes including tissue-cultured disease-resistant rice, which is already deployed in China. The most outstanding technological success, however, was the incorporation of several genes simultaneously that code for beta-carotene, the precursor of vitamin A, by Dr Ingo Potrykus and Dr Peter Beyer. This breakthrough is described elsewhere in this Brief. The Rockefeller Program has delivered significant multiple benefits that include technological breakthroughs, capacity building in crop biotechnology in key national programs in Asia, and establishment of an international network of like-minded scientists who can now continue to collaborate to facilitate the transfer of knowledge and technology in pursuit of mutual goals and objectives, and food security.

The Rockefeller Foundation's future strategy will focus on traits, rather than crops, particularly on the more important and prevalent constraints to productivity such as drought tolerance, which is pervasive and affects all crops. The Foundation will also assign high priority to facilitating the adoption of improved varieties by farmers and to building capacity in crop biotechnology in national programs in sub-Saharan Africa.

6.5 Summary

With 60% of the world's population in Asia (Table 14), IFPRI's 2020 projections call for increased cereal demand (for food and feed) for the region because of population growth and rising incomes, with corresponding changes in diets with more meat. Higher consumption of meat products will require increased livestock herds and poultry, which in turn will require increased quantities of high quality feeds. Whereas today most Asian countries are rural, with more than half their working population involved in agriculture, this is changing fast. Urbanization is occurring at twice the rate of population growth and it is projected that most Asian countries will have more people living in urban areas than the rural areas in 2020. This migration from rural to urban areas will have a significant impact on agriculture, which will require management practices that are less dependent on labor and more dependent on mechanization. The challenge facing Asia is in some ways more formidable than the corresponding challenge in other regions of the world because the ratio of arable land to population (Table 14) is lowest

Table 14. Share (%) of world population and arable land

	% world population	% arable land	Arable land/ population ratio
USA & Canada	5.1	17.2	3.4
Former Soviet Union	5.1	16.9	3.3
Other regions	3.4	5.7	1.7
South America	5.6	6.6	1.2
Europe	9.0	9.1	1.0
Africa	12.6	12.6	1.0
Asia	59.2	31.9	0.5

Source: FAO Stats (1999).

in Asia at 0.5 compared with 1.0 for Africa and 1.2 for South America. As expected the highest ratios are for USA and Canada at 3.4, which is more than six-fold greater than those for Asia, the Soviet Union, and Europe.

Crop biotechnology, including transgenic crops, has much to offer the developing countries of Asia and should be an essential component of an Asian regional food security strategy that integrates conventional and biotechnology crop improvement applications to produce more food in the continent where the need is greatest, and where the welfare value of food is the highest. Denying the poor and malnourished in Asia new technologies is synonymous to condemning them to continued suffering from malnutrition which eventually may deny the poorest of the poor their right to survival.

7. Future Biotechnology Traits

The R&D pipeline is full of new and novel products that can be commercialized in the near term from 2000 onwards. The recent restructuring in the private sector will impact on the scope, scale, and time frame when these R&D products will be commercialized, but a steady stream of new products is expected to become available during the next 5 years. Table 15 lists approximately 40 input traits and 30 output traits, a proportion of which are likely to become available in the near term, in the next 5 years or so. The intent in listing these products in Table 15 is not to provide an exhaustive list, but to provide the reader with a sense of the characteristics of the range and type of products. Availability of these products will be significantly influenced by the pace of development of transgenic crops during the next 5 years, the magnitude of investments by the private and public sectors, and general public acceptance of transgenic products. Public acceptance could be significantly affected by the availability of output traits that offer healthier and more nutritious foods that provide evident benefits to consumers.

7.1 Input Traits

Transgenic crops that are currently commercialized incorporate the first generation of traits called “input traits” that confer agronomic advantages. These include the principal trait of herbicide tolerance, with insect resistance as a second category plus a few virus-resistant products. The listing of input traits in Table 15 projects that herbicide tolerance will be extended to crops including rice, wheat, potato, fodder beet, sugar beet, sugarcane, alfalfa, tomato, lettuce, and sunflower. Similarly, insect-resistant products will cover a much broader range of pests that cause economic losses on crops in different regions of the world. For example, the current range of *Bt* corn products are principally designed to control the European corn borer, but also provides some control of other insect pests of corn such as earworm. The next range of insect-resistant products for corn will be specially tailored to control specific pests in particular regions. Accordingly, *Bt* and other gene products will be tailored to control fall armyworm in the USA and Latin America

Table 15. Listing of selected potential transgenic crops for commercialization in the near to midterm, from 2000 onwards

Input traits	Benefits
Corn/Maize	
Rootworm resistance	Reduced losses valued at >$1 billion/annum in USA alone
Fall armyworm resistance	Control of pest in USA and Latin America
Earworm resistance	Control of pest in USA and Latin America
Asiatic corn borer resistance	Control of pest in Asia
African stem borer resistance	Control of pest in Africa
Fungal resistance	Control of *Fusarium* head scab and mycotoxins
Cotton	
Second generation genes for bollworm resistance	Contributes to more durable deployment of genes for pest
Boll weevil resistance	Control of an important and prevalent cotton pest
Soybean	
Insect resistance	Pod borer and looper control
Stacked gene *Bt*/ herbicide tolerance	Reduced yield losses to insect pests and weeds
Canola	
Hybridization genes	Improved hybridization technology
Virus resistance	Control of beet yellow virus and/or turnip yellow virus
Potatoes	
Herbicide tolerance	Improved weed control
Insect resistance	Control of Colorado beetle for varieties for E. Europe
Virus resistance	Control of multiple viruses
Fodder beet	
Herbicide tolerance	Improved weed control
Sugar beet	
Herbicide tolerance	Improved weed control
Rice	
Herbicide tolerance	Improved weed control
Bacterial disease resistance	Control of bacterial leaf blight
Insect resistance	Control of rice stem borer
Delayed senescence	Increased productivity

continued...

Table 15 continued. **Listing of selected potential transgenic crops for commercialization in the near to midterm, from 2000 onwards**

Input traits	Benefits
Wheat	
Fungal disease resistance	Reduced yield losses due to *Fusarium* and other diseases
Virus resistance	Control of barley yellow dwarf virus
Herbicide resistance	Improved weed control
Sunflower	
Insect resistance	Control of *Lepidpoteran* pests
Herbicide tolerance	Improved weed control
Fungal disease resistance	Control of *Sclerotinia* and *Verticillium*
Tomatoes	
Insect resistance	Reduced losses to looper, hornworm, and fruitworm
Virus resistance	Improved control of CMV virus disease
Virus resistance	Improved control of TMV virus disease
Herbicide tolerance	Improved weed control
Sugarcane	
Herbicide tolerance	Improved weed control
Insect resistance	Control of sugarcane borer
Sweet pepper	
Virus resistance	Control of CMV virus
Sweet potato	
Insect resistance	Control of sweet potato weevil
Virus resistance	Control of feathery mottle virus
Bananas	
Disease resistance	Control of black sigatoka fungal disease
Cassava	
Virus resistance	Control of cassava mosaic virus
Alfalfa	
Herbicide tolerance	Improved weed control
Apple	
Insect resistance	*Bt* gene for control of insect pests
Lettuce	
Herbicide tolerance	Improved weed control
Poplar	
Insect resistance	*Bt* gene for control of insect pests

continued...

Table 15 continued. **Listing of selected potential transgenic crops for commercialization in the near to midterm, from 2000 onwards**

Output traits	Benefits
Corn/Maize	
High oleic oil	Healthier nutritional profile
Modified starch	Improved quality
High lysine	Feed with improved nutritional profile
High methionine	Feed with improved nutritional profile
High tryptophan	Feed with improved nutritional profile
High oil (normal) + other traits	Feed with improved nutritional profile
Low phytate	Reduces need for phosphate supplements
Soybean	
High oleic oil	Healthier and more nutritious food products
Improved proteins	Improved flavor and texture
High stearate	Healthier and more nutritious food products
Higher sucrose	Healthier and more nutritious food products
Low saturate oil	Healthier and more nutritious food products
Low linoleic oil	Healthier and more nutritious food products
Low phytate	Reduces need for phosphate supplements
Enhanced vitamin E	Remedy for vitamin E deficiency
Canola	
High stearate oil	Healthier food products
High oleic oil	More nutritious food ingredients
Low polyunsaturated oil	Healthier and more nutritious food products
High beta-carotene	Remedy for vitamin A deficiency
Potatoes	
Modified starch	Improved quality
Improved storage quality	Less postharvest losses
Higher solids	Lower water content and absorbs less oil in cooking
Sunflower	
High oleic oil	Healthier and more nutritious food products
Wheat	
Improved quality	Better health profile and processing qualities
Cotton	
Improved fiber quality	Better quality cotton fabrics
Rice	
Modified starch	Improved quality
Enhanced vitamin A	Remedy for vitamin A deficiency – affects 400 million
Enhanced iron content	Remedy for anemia – afflicts 3 billion people
Papaya	
Delayed ripening	Reduces postharvest losses

Source: Compiled by Clive James (1999).

where the pest is particularly important. Similarly, specific products will be available for the Asiatic corn borer in Asia and the African stem borer in Africa. Products with more than one *Bt* gene will increase the durability of *Bt* resistance and products with *Bt* and other mechanisms of resistance will provide further security and offer new possibilities for optimizing the durability of deployed genes. Genes that confer resistance to insects will be available to cover a broad range of crops including rice, soybean, sunflower, tomato, sugarcane, sweet potato, apple, and poplar. Many observers have been justifiably concerned that most, if not all, transgenic products commercialized to date have been developed to meet the demands of large farmers in industrial countries and not the small resource-poor farmers in developing countries. It is therefore noteworthy that some of the new products that are likely to be available, such as insect-resistant sweet potato and virus-resistant cassava, are crops that are almost exclusively used by small resource-poor farmers in developing countries.

Virus resistance, which is particularly important for developing countries where seed certification schemes are not very effective, is likely to be available for a broader range of viruses, and for more crops. Virus-resistant products are likely to be deployed for CMV and TMV in tomato, CMV in sweet pepper, barley yellow dwarf virus (BYDV) in wheat, possibly beet yellow virus and turnip yellow virus in canola/rapeseed, and cassava mosaic virus in cassava. Some products will become available for the control of fungal pathogens. Gene discovery programs for pathogens such as *Phytophthora infestans* of potato have been conducted for several years but as yet no products have been commercialized. There is a possibility that in the near term, genes may be available for the control of *Fusarium* diseases in corn and wheat that are associated with mycotoxins; black sigatoka disease of bananas; and *Sclerotinia* and *Verticillium* diseases of sunflower. The *Xa21* gene for bacterial blight of rice is also being tested in field trials and could be ready for deployment in the near term. Genes for delaying senescence—the stay-green effect—also have significant potential for increasing productivity as a result of prolonging photosynthetic activity, and there is a candidate gene that may be available in rice. Finally, male sterility, restorer and other hybridization genes being used in canola have potential for many other crops including rice and maize in the near term and wheat in the midterm. Genes for aluminum tolerance have been identified for deployment in crops growing in acid soils but will probably not be available until the midterm.

Beyond the near term, preliminary findings look promising for several traits including drought resistance and genes that can increase the efficiency of fertilizer uptake, more specifically nitrogen. Fertilizer, particularly nitrogen, played a critical role in both the wheat and rice Green Revolutions initiated in the 1960s. Undoubtedly the use of nitrogen will continue to play a key role in many applications of new technologies in the first decade of the new millennium as the longer term target of doubling food production by 2050 becomes an increasingly pressing need. Of the 130 t of fertilizer used annually on crops, 60% of the volume and 70% of the $50 billion cost is represented by nitrogen fertilizers (James 1997b). The challenge is to optimize the use of nitrogen fertilizers through developing crop varieties that are more responsive to nitrogen. A significant increase in the efficiency of nitrogen uptake would allow food production to be increased significantly with a minimal increase in nitrogen fertilizer use; this would coincidentally mitigate the environmental concerns resulting from high nitrate levels in groundwater in areas where very intensive agriculture is being practiced.

Collaborative research at the University of Florida and Monsanto led by Robert Schmidt at Florida (Anonymous 1999) has led to the isolation of a gene from the algae *Chlorella sorokiniana* that may enable crops to use nitrogen more effectively, increasing yields by up to 29%. The research was initiated by Schmidt who postulated that if algae have a comparative advantage over bacteria in nitrogen uptake when they are coinhabitants of a pond, the gene in algae that confers this advantage may also confer the same advantage on higher plants. Schmidt found that upon exposure to high levels of nitrogen fertilizer *Chlorella sorokiniana* generated high levels of the enzyme glutamate dehydrogenase (GDH). Whereas GDH is also found in higher plants its involvement in algae is quite different. In algae it contributes to increased efficiency of the process that converts ammonium into glutamate in the chloroplast where sunlight is converted to energy. The GDH gene, isolated from *C. sorokiniana* at the University of Florida, was incorporated by Monsanto into transformed wheat. Research findings to date indicate that the GDH-transformed plants are more robust, larger, and yield up to 29% more grain than untransformed wheat, when exposed to the same level of nitrogen. Alternatively, GDH-transformed plants can yield the same as untransformed plants on less fertilizer. The implications for this work in both industrial and developing countries is far reaching vis-à-vis efficiency of nitrogen uptake, and environmental concerns on high levels of nitrates in aquifers, rivers, and coastal waters where high nitrogen levels are used. The potential application of the GDH technology for crops generally, particularly in developing countries where the need to increase food production is urgent, could be extremely important. Developing countries are estimated to consume almost two-thirds (equivalent to 50 million t at a cost of $22 million annually) of the 80 million t of nitrogen, valued at $35 billion annually on a global basis (James 1997b). Thus the impact of GDH technology, in conjunction with supplemental nitrogen technologies, could be enormous. Expectations of products such as GDH must be tempered by a realistic assessment which acknowledges that whereas the product has tremendous potential, it is still in the early stage of R&D and must undergo several years of development before it qualifies as a candidate product for regulatory approval and commercialization in the midterm.

7.2 Output Traits

The "output traits" represent the second generation of traits for transgenic crops, conferring improved "quality" characteristics that will result in benefits to consumers, food processors, and producers. Unlike input traits that have delivered multiple agronomic and productivity-related gains to producers, the benefits of output traits will be evident to consumers. Benefits will include improved shelf life, and more nutritious, healthier, and tastier foods. Because these benefits will be evident to consumers, quality traits have the potential to positively impact on public acceptance; this could be particularly significant in countries of the European Union where the debate continues on public acceptance of food products derived from transgenic crops. The ability to modify food specifications with quality traits also offers significant benefits to food processors, who can gain from modifications that will facilitate more efficient food processing and the development of new products.

The first output/quality trait introduced into transgenic crops was the delayed ripening trait in Flavr Savr tomato. The delayed ripening/altered shelf-life genes have enormous potential for tropical fruits and vegetables in developing countries where postharvest losses are high because of high temperatures and humidity, inadequate transportation from farm to market, and lack of appropriate or refrigerated storage. Delayed ripening genes are being incorporated in papaya in a project brokered by ISAAA for five countries in Southeast Asia with technology donated by Zeneca and the University of Nottingham. The delayed ripening technology is applicable to a broad range of perishable food products.

For convenience, the quality traits that are likely to become available in the near term can be classified into five arbitrary categories. The first category, featuring healthier and more nutritional food and feed products, is exemplified by the high oleic soybean (Table 15). The other products listed in Table 15 that fall into the same category include corn with high oleic oil, high lysine, high tryptophan, high methionine, low phytate, and high oil through traditional breeding stacked with various transgenic quality traits; soybean with high oleic oil improved proteins, high stearate oil, higher sucrose, low saturate oil, low linoleic oil, and low phytate; canola with high stearate oil, high oleic, low polyunsaturated oil and low phytate; sunflower with high oleic oil; and potatoes with high solids. The second category includes gene products that are being developed as potential remedies for vitamin deficiencies. The most advanced product in this class results from the successful and well-publicized research of Dr Ingo Potrykus and Dr Peter Beyer (described elsewhere in this Brief) who identified genes that coded for higher levels of beta-carotene (precursor of vitamin A) and incorporated these in rice (Guru 1999). Research is also under way on high beta-carotene canola and on genes encoding for vitamin E and preliminary work on vitamin C. The third category includes traits that enhance levels of microelements and offer potential remedies for microelement deficiencies. Again, the work of Dr Potrykus et al in enhancing iron levels in rice is the most advanced, and offers a potential remedy for anemia that is estimated to affect up to 3 billion people. The fourth category includes traits with improved chemical structure that result in better flavor, taste, or structure and/or enhance the quality or storage of food/feed products like starch or proteins for food, feed, or industrial processing. Products listed in Table 15 in this category include corn with modified starch, potatoes with modified starch and improved storage quality, wheat with improved quality, and papaya with delayed ripening. The fifth and final category includes traits that improve fiber qualities, such as improved fiber quality in cotton.

As in input traits, the list of output traits listed in Table 15 is not intended to be exhaustive and the reader is referred to the extensive literature that is being published in this rapidly developing area of research involving second generation output/quality traits. The most advanced output trait product listed in Table 15 is high oleic soybean, which is already registered and approved by the Food and Drug Agency in the USA. The characteristics of high oleic soybeans and potential benefits to the consumer are briefly summarized here. Vegetable oils and animal fats contain three types of fatty acids—saturated (considered unhealthy), monounsaturated (considered healthy), and polyunsaturated (considered healthy). Oleic acid is a monounsaturated fatty acid, considered healthy. Conventional soybean oil contains relatively low levels of oleic acid (24%) and 60% polyunsaturated fatty acids. Conventional soybean oil is oxidatively and thermally unstable. Oxidative instability in conventional oil can be overcome by hydrogenation which results in more monounsaturated fatty acids, and is often associated with fairly high levels of trans-fatty acids. There is increasing evidence that trans-fatty acids, like saturated fatty acids, are unhealthy because they lead to higher cholesterol levels, the principal indicator of risk to coronary heart disease.

The fatty acid composition of high oleic soybean oil is substantively different from conventional commodity soybean oil. High oleic soybean oil has a 30% lower level of saturated fatty acids, a much higher level (80% plus) of monounsaturated fatty acids, and a much lower level of polyunsaturated fatty acids. Unlike conventional soybean oil, high oleic oil is highly stable. High oleic soybean offers the following advantages to the consumer: 30% lower saturated fat than conventional soybean oil; provides an alternative to other high stability oils or partially hydrogenated vegetable oils, which contain very high levels of saturated or trans-fatty acids (considered unhealthy); decreases the need for chemical hydrogenation which produces trans-fatty acids; it is a product that is oxidatively stable—a natural oil which resists rancidity and provides a longer shelf life for oil-containing shelf-stable foods; a fatty acid profile similar to that of olive oil and canola oil, considered important for a healthy diet; a product with 80% plus oleic acid-high monounsaturates (oleic acid) have been shown to reduce blood cholesterol levels (lowering of LDL—the bad cholesterol, without reducing levels of HDL—the good cholesterol).

8. Past Achievements and Future Potential of Plant Breeding, including Biotechnology, for Increasing Crop Productivity of the Major Staples: Wheat, Rice, and Maize

It is widely recognized in the international scientific and development community that using conventional technology alone will not result in the doubling or tripling of food production in the next 50 years. A combination of conventional and biotechnology applications has the potential to achieve global food security. Acknowledging that past experience is often the best guide for the future, it is useful to review past achievements to increase crop productivity through plant breeding in the context of a seamless web that can provide continuity for combining both conventional and biotechnology applications to achieve future food security. Achievements in conventional plant breeding in the three most important food crops in the world—wheat, rice, and maize—are reviewed, in conjunction with a discussion of potential benefits that future conventional and biotechnology applications offer. The review is appropriate from a food security standpoint in that collectively the three major staples total 1.5 billion t of grain annually, and supply mankind with almost two-thirds of total calories. Wheat is grown on more land than any other crop (about 225 million ha), followed by rice (150 million ha), and maize (about 140 million ha). In terms of usage as food, 85% of rice is used directly for human consumption compared with 60% of wheat and 25% of maize.

First, achievements in wheat breeding are reviewed, with some brief comments on the successful wheat breeding program in the UK, with a more detailed coverage of the CIMMYT International Program on Wheat Breeding. Second, an overview is provided of the IRRI International Rice Program from the 1960s to 1990s. Third, to complete the picture on cereals, the success of maize breeding in the USA is reviewed. To conclude, past achievements and future potential of plant breeding programs in wheat, rice, and maize are discussed within the context of unpublished information from IFPRI (Rosegrant, personal communication 1999) which projects world demand for cereals in 2025. The challenge that cereal demands in 2025 poses to plant breeding in the 21st century is evident, considering that global food security has to be achieved for 8 billion people while at the same time protecting the environment, natural resources, and biodiversity.

8.1 Wheat Improvement

Current global wheat production is 560 million t which represents more than one-quarter of the total world cereal output, and is the principal source of calories for 1.5 billion people. The global area of wheat is approximately 225 million ha, half of which is grown in industrial countries and half in developing countries. Excluding China, about 45% of the wheat area in developing countries is irrigated. Eighty percent of China and 75% of India's wheat crop are irrigated. About 90% of the growth in world cereal production since 1950 has been generated from gains in productivity (Mitchell 1997). For the future, virtually all the increase in production will have to come from increasing yield as opposed to bringing new land into production; there are only a few areas left worldwide, like the cerrados of Brazil, that offer opportunities for expanding arable area.

8.1.1 Wheat Breeding in the UK

During the period 1948 to 1997, average farm wheat yields in the UK increased three-fold from about 2.5 t to 7.5 t (Austin 1998). This increase is equivalent to an average annual gain of 110 kg/ha/year, and there is no indication that the rate of increase is slowing. The 110 kg/ha represents not only genetic gain, but also gains from agronomic practices and beneficial interactions of these factors. These gains have been associated with

- the adoption of shorter stature varieties, carrying the rht D16 dwarfing gene, which are not prone to lodging
- earlier sowing and earlier anthesis than older varieties
- high rates of fertilizer application (28 kg in 1950 to 185 kg in 1985)
- herbicide applications
- fungicide applications

Data from recent trials with promising cultivars indicate that further genetic gains are being realized and improved crop protection would lead to even higher yields. For the longer term, significant genetic gain in yield may be possible though biotechnology if new cultivars can be developed with faster growth rates and greater biomass at maturity. Modifying the photosynthetic enzyme rubisco may achieve this; however, higher levels of nitrogen will be required to realize higher yields (Austin 1998).

8.1.2 CIMMYT/International Wheat Program

The first semidwarf variety, Pitic 62, was released by CIMMYT in 1962 (Rajaram and Braun 1999). The major milestones in yields of CIMMYT wheat during the period 1962 to 1996 are summarized in Table 16. Yield, as measured under irrigation in Obregon, Mexico, increased from 6.5 t/ha in 1962 to 8.0 t/ha in 1980 with the introduction of the Veerys, and to 9.0 t/ha in 1996 with Super Seri. The Veery yield increases were associated with the introduction of the 1B/1R translocation from rye.

Table 16. Major milestones in yields of CIMMYT spring wheats at Obregon, Mexico

Year	Yield	Variety
1962	6.5 t/ha	Pitic 62
1970	7.0 t/ha	
1980	8.0 t/ha	Veery 1B/1R
1990	8.5 t/ha	
1996	9.0 t/ha	Super Seri, LR 19

Source: Rajaram (1999), Sayre (1997).

Similarly, the yield increase in Super Seri was associated with the introduction of the *LR19* gene for leaf rust introduced from *Agropyron elongatum* (Reynolds et al 1998). Thus, like the earlier 1B/1R translocation from rye, yield increases have again been associated with the broadening of the germplasm base, which is consistent with the science underpinning transgenic crops. In a separate set of experiments at CIMMYT (Sayre et al 1997), it was estimated that during the period 1964 to 1990, yield potential of wheat, as defined by Evans and Fischer (1998), increased by 0.9%/year, equivalent to 67 kg/ha/year, which is an impressive gain over a 26-year period.

The area planted to improved varieties of wheat in all least developing countries (LDC) on all continents (Byerlee 1994) increased steadily from 20% in 1970 to 59% in 1983, to 78% in 1994 (Table 17). Adoption rates were highest in Asia, increasing from 42% in 1970 to 91% in 1994; this data excludes China where 70% of the wheat area was planted with improved varieties in 1990. Latin America had lower rates of adoption than Asia in 1970 but by the 1990s, it had reached similar levels, exceeding 90%. The high rates of adoption reflect the multiple benefits that the improved varieties offer farmers, including yield stability and improved tolerance to drought. Dalrymple (1977) estimated that benefits associated with the early Green Revolution wheat in Asia released during the period 1960 to 1973 was equivalent, in 1973 alone, to an annual production increase of 8.7 million t valued at $1.9 billion in 1990 dollars. The benefits in the post-Green Revolution period, 1977 to 1990, have continued and actually increased. Byerlee and Moya (1993) estimated that benefits in all LDCs during the period 1977 to 1990 were equivalent to an annual increase in production of 15.3 million t valued at $3.0 billion in 1990 dollars. The data (Table 18) show that 60% of the global LDC gains were in South Asia, 22% in Latin America, 17% in West Asia/North Africa, and 1% in sub-Saharan Africa.

Table 18. Estimated benefits of post Green Revolution wheat released in developing countries between 1977 and 1990

Region	Production (million t)	Value (1990, US$ millions)
Sub-Saharan Africa	0.1	31
West Asia/North Africa	2.5	515
South Asia	9.3	1,822
Latin America	3.4	662
Total	**15.3**	**3,030**

Source: Byerlee and Moya (1993).

Table 17. Area planted (%) to improved varieties of wheat

	1970	1977	1983	1990	1994
All LDCs	20	41	59	70	78
Asia[a]	42	69	79	88	91
Latin America	11	24	68	82	92

[a] Excluding China with 70% in 1990.

Source: Pingali and Rajaram (1998).

8.2 Rice Improvement

Rice is largely associated with countries of Asia, extending from Pakistan to Japan. Approximately 95% of the world's rice is produced in Asia and it is an integral part of the culture of the continent. Rice occupies approximately 150 million ha, which is one-tenth of the total cultivated land of 1.5 billion ha in the world. In the 40-year period from 1950 to 1990, area planted to rice increased by over 70%, and mean yield increased by more than 110%, resulting in a tripling of global rice production (IRRI 1997).

8.2.1 IRRI/International Rice Program

The first rice semidwarf, IR8, was released in 1966, 4 years after the first wheat semidwarf in 1962. Tall traditional rice had a biomass of 12 t/ha with a harvest index of 0.3 and yielded 4 t/ha. With the introduction of the semidwarf IR8 in 1966, biomass was increased to 18 t and the concomitant increase in harvest index from 0.30 to 0.45 allowed the semidwarfs to double yield potential from 4 to 8 t (Khush 1990). From 1966 to 1996, 42 improved rice varieties have been released by IRRI. During that 30-year period the annual genetic gain in yield has been 75 kg/ha equivalent to 1%/year (Peng et al 1998). The best yield of the latest varieties is between 9 and 10 t/ha.

Table 19. Area planted (%) to improved varieties of rice

	1970	1983	1990
All LDCs	30	59	74
Asia[a]	12	48	67
China	77	95	100

[a] Excluding China.
Source: Byerlee (1994).

Table 20. Global rice production

Year	Total yield (million t)	Yield (t/ha)
1963	250	2.0
1973	335	2.4
1983	450	3.1
1993	520	3.5

Source: IRRI Rice Almanac (1997).

The data in Table 19 show that adoption rates for improved rice varieties in all LDCs increased from 30% in 1970 to 74% in 1990 (Byerlee 1993). China had higher adoption rates, increasing from 77% in 1970 to 100% in 1990. Benefits from the initial rice varieties of the Green Revolution (Dalrymple 1977) released between 1966 and 1973 have been estimated to increase annual production in 1973 by 7.7 million tons valued at $2.2 billion in 1990 dollars. Following the introduction of high-yield rice semidwarfs in the 1960s, world rice production doubled from 250 million t in 1963 (Table 20) to over 500 million t in 1993 (IRRI 1997). During the same 30-year period, 1963 to 1993, global yield per hectare increased by almost 75% from 2.0 t/ha in 1963 to 3.5 t/ha in 1993.

8.3 Wheat and Rice Summary

In summary, yield increases associated with the introduction of the semidwarf wheat and rice in the 1960s produced a combined wheat/rice increase in production of 16.4 million t in 1973 valued at $4.1 billion in 1990 dollars. This increased production of wheat and rice is estimated to have saved a billion people from famine in the 1960s (El Feki 2000) when many in international development in the 1960s were fearful that triage would be the only outcome. Opportunities for increasing wheat and rice yields in the 21st century will depend on the use of both conventional and biotechnology applications that will focus on

- continued population improvement for abiotic and biotic stresses and quality
- greater nutrient use efficiency
- new ideotypes
- wide crosses
- hybrids
- marker-assisted selection
- transgenic crops that will incorporate both input and output traits

More specifically for **rice**, input traits will include disease and insect resistance, herbicide tolerance, improved hybrid technology based on male sterility/restorer genes, as well as genes for delayed senescence which could result in substantial increases in yield and genes that enhance photosynthetic activity to increase yield potential that is currently constraining increases in productivity. Output traits for rice will include enhanced vitamin A (golden rice), enhanced iron content, and modified starch. (See Table 15 for listing of specific input and output traits for rice likely to be available in the next 5 years).

More specifically for **wheat**, input traits will include resistance to fungal diseases such as *Fusarium* scab, virus diseases such as barley yellow dwarf virus, herbicide tolerance, and possibly hybridization genes. There is also the possibility in the midterm of increasing nitrogen efficiency through the incorporation of the glutamate dehydrogenase (GDH) gene and genes that code for the activity of enzymes such as Rubisco that can enhance photosynthetic activity and productivity. Output traits will focus on various quality aspects related to bread and pasta qualities, as well as some quality related to feed wheat. (See Table 15 for listing of specific input and output traits for wheat likely to be available in the next 5 years).

8.4 Maize Improvement

Despite the fact that almost twice as much area of maize is grown in developing countries compared with industrial countries, production is 300 million t in industrial and only 250 million t in developing countries, for a total global annual production of over 550 million t. Unlike rice and wheat which are mainly consumed as food, maize is used for food and feed, as well as for industrial processing. In industrial countries the majority of maize is used for feed and industrial uses. Maize, however, is an important food staple in many developing countries and is particularly important in sub-Saharan Africa and Central America where it is often the principal food source.

8.4.1 Maize Breeding in the USA

In the 70-year period from the mid-1920s to 1990s, farm yields of maize tripled in the USA. In the last 30 years farm-level yields increased from 5 t/ha in 1967 to 8 t/ha in 1997. In a series of experiments featuring 36 of the best hybrids that have been released during the period 1930 to 1991, Duvick (1996) estimated that the annual increase from genetic gain was 74 kg/ha, equivalent to an average annual gain of approximately 1%; it was estimated that approximately half of farm-level gains during the same period were due to genetic gains (Duvick and Cassman 1998). Unlike in wheat and rice, dwarf genes did not result in significant increases in maize yield. Genetic gains achieved in the USA are a result of improvements by breeders and associated with the following traits:

- Heterosis
- Higher planting density (30,000/ha to >80,000/ha)
- Tolerance to abiotic and biotic stresses
- More erect upper leaves and small tassels

- Shorter interval between anthesis and silking
- Increase in grain starch, decrease in % grain protein
- Transgenic *Bt* hybrids in 1996 for control of European corn borer
- Transgenic herbicide-tolerant hybrids in 1997 for improved weed control
- Transgenic hybrids with stacked genes for *Bt* and herbicide tolerance in 1998

Source: Modified from Duvick (1996)

The USA was the first country to commercialize transgenic maize in 1996 (James 1997a) with the introduction of *Bt* maize to control European corn borer. Varieties with herbicide tolerance were commercialized in 1997 and those with stacked genes of *Bt* and herbicide tolerance were commercialized in 1998 (James 1998). The benefits associated with *Bt* maize and herbicide-tolerant maize in the USA in 1996 and 1997 are summarized in Table 21. Following the successful introduction of *Bt* maize in the USA in 1996, six other countries have commercialized the product. In 1999, 11.1 million ha of transgenic maize were grown in the following seven countries, listed in order of area grown: USA, Canada, Argentina, South Africa, Spain, France, and Portugal. Transgenic maize represented 28% of the global area of all transgenic crops commercialized in 1999 having increased from 8.3 million ha in 1998 to 11.1 million ha in 1999—an increase of 2.8 million ha equivalent to 33% between 1998 and 1999. Of the 140 million ha of maize grown worldwide in 1999, 8% of the area (11.1 million ha) was planted with transgenic hybrids.

Table 21. Attributes of transgenic maize commercialized in 1996-99

***Bt* maize**

- Effective and targeted control of the insect pest European corn borer (ECB)
- Reduction of insecticide usage
- Yield increases dependent on infestation level
- Reduced mycotoxins[a] – safer for human and animal consumption

Herbicide-tolerant maize

- Flexible crop management – assigned top priority by growers
- Facilitates conservation tillage – less cultivation saves fuel
- Better weed control
- Better soil and moisture conservation
- Reduction in herbicide usage

[a] Munkvold et al (1999).

Source: Clive James (1999).

Both conventional and biotechnology applications have resulted in significant gains in maize, and both will continue to make vital contributions. Biotechnology traits that will benefit maize in the near term include input traits that will provide control of the very important pest, corn root worm, that is responsible for losses of well over $1 billion per year in the USA alone; control of insect pests that are important in different regions of the world (listed in Table 15); control of the fungal disease caused by *Fusarium* head scab which in turn will decrease the level of mycotoxin; and control of other fungal and virus diseases that are important in the different corn-growing regions of the world. Output traits for maize will become increasingly important and will focus on enhanced feed, industrial and food qualities of maize featuring such products as high lysine corn, high oleic acid, and improved starch, high methionine, and low phytate corn.

In summary, it is evident that past genetic gains from plant breeding in wheat, rice, and maize have been impressive and have made a unique, lifesaving contribution to global food security and the health and welfare of humanity. During the period 1960 to 1990 genetic gains generated an estimated half of total gains (McCalla 1999) that allowed:

- Doubling of global cereal production from 1 to 2 billion t annually
- Per capita food availability to increase 37%
- Real food prices to decrease by 50%

Plant breeders are targeting to increase future productivity from 0.5% to 2.0% per annum. Much progress has been made in wheat and rice through increases in the harvest index, which is now close to the theoretical limit of approximately 60% in both crops. Prospects for shifting yield frontiers with conventional technology are greatest in maize, for which temperate germplasm developed in industrial countries is adaptable to temperate areas in developing countries such as China and Argentina. There are also some opportunities for shifting the yield frontier of wheat with conventional technology but fewer opportunities in rice where there is some evidence to suggest that yield potential may not have increased since the introduction of IR8 in 1966 (Peng et al 1998). Most of the gains to date have been due to conventional technology and nontransgenic biotechnology applications such as tissue culture, and marker-assisted breeding that have already contributed to both maize and rice. However, maize has already benefited from transgenic technology that currently is limited to input traits but that will be significantly extended to include output traits in the near term. The magnitude of current biotechnology investments, particularly that of the private sector, in maize, rice, and wheat, will largely determine the relative contribution that biotechnology will make to increased productivity and nutrition of the three crops in the near term. It is expected that the majority of gains due to biotechnology in the near term will continue to be in maize, reflecting the highest R&D investments, but with opportunities for rice and wheat accelerating rapidly as current and significant investments in functional and applied genomics generate technology that can be applied at the same level.

8.5 Global Demand for Cereals in 2025—The Plant Breeding Challenge

The most recent data from IFPRI (Rosegrant, personal communication 1999) indicate that in the 30-year period from 1995 to 2025, global demand for cereals will increase by 805 million t from 1.776 billion t in 1995 to 2.581 billion t in 2025 (Table 22). Thus, demand will increase by 45% in 30 years. Eighty-five percent of the deficit of 805 million t (equivalent to 679 million t) will be in developing countries and 15%, equivalent to 126 million t, in industrial countries. It is projected that only 7% of the increased production will come from additional land area leaving 93% to be generated from productivity gains. Thus, the global food security challenge is to increase productivity of cereals at the farm level by 805 million t between 1995 and 2025.

Table 22. Projected world demand (million tons) for cereals[a]

	1995	2025	Deficit
Industrial	704	830	126
Developing	1072	1751	679
World	**1776**	**2581**	**805**

[a] Rice, reported as milled rice (0.65% of paddy).
Source: Rosegrant (1999 personal communication).

The World Bank (McCalla 1999) reports that world grain yields at the farm level increased at an annual rate of 2.1% during the 1980s but fell to <1.0% in the 1990s. There is some evidence that farm yields are plateauing and even declining in some cases in the more intensive rice/wheat production systems in Asia. The situation seems more critical for rice than wheat, with maize the least affected. Intensification leading to yield decline in rice has been associated with increased salinity, waterlogging, various toxicities and biotic stresses. Opportunities for increasing yield through closing the yield gap between experimental and farm yields are available for maize, but judged to be few in the high production rice irrigated areas and only modest in irrigated wheat (Pingali et al 1999), with areas such as the Yaqui Valley in Mexico and the Punjab in India already close to maximum achievable yield.

The annual genetic gain in cereal productivity is currently 1%, or less, per year. Although this falls short of the increase required to meet demand over the next 25 years, increasing annual genetic gains and applying biotechnology to shift the frontiers of yield potential (as defined by Evans and Fischer 1998) offer the best probability of success. Given the performance of plant breeding over the last 30 years and the promise that biotechnology offers, there is reason to be cautiously optimistic that cereal demands in 2025 can be met, provided that three criteria are satisfied:

- Higher priority and increased resources for crop improvement activities by public and private sectors in industrial and developing countries, and where appropriate the establishment of synergistic public-private sector partnerships.

- Commodity prices and orderly markets that will ensure reasonable returns to farmers on their investment and provide the incentive for adopting improved seeds and agronomic practices that can contribute to increased productivity and sustainability; a level international playing field in relation to commodity subsidies is necessary to facilitate equitable competition.

- Adoption of a multiple-thrust global food strategy that will include population control, improved food distribution, and increased crop productivity that will capitalize on the full potential that both conventional and biotechnology applications offer, including the timely approval of improved varieties by regulatory agencies for early and safe adoption by farmers to optimize productivity gains.

If these three criteria are met, there is reasonable probability that technology can increase cereal productivity by 45% by 2025. Of the three cereals, rice probably offers the greatest challenge due to multiple and complex constraints in the highly intensive tropical lowland irrigated production systems in Asia. There are, however, both conventional and biotechnology applications in rice that offer much promise. For example, encouraging progress is being made in developing a new plant type that could increase yield potential from the current 10 t/ha to 12.5 t/ha. Use of these new plant types as parents for hybrid rice could increase productivity, by up to a further 20%, to reach 15 t/ha which would help meet the rice requirements of 2025 (Pingali et al 1999). Rice has benefited much from biotechnology research funded by the Rockefeller Foundation and from the rice genome project, which was to be completed in 2004 but is now expected earlier, possibly in 2002. A team commissioned by the World Bank (Kendall et al 1997), led by the late Nobel Laureate Dr Henry Kendall concluded that transgenic technology can contribute 10 to

25% increase in productivity in rice in the next decade and advocated the appropriate use of biotechnology. Whereas the first generation of biotech “input” agronomic traits contributes to increased productivity, the second generation of “output” quality traits will enhance food nutrition (Mazur et al 1999). With the support of the Rockefeller Foundation and other donors, a gene encoding for beta-carotene/vitamin A has been incorporated in rice. This has the potential to enhance the diets of 400 million people in developing countries suffering from vitamin A deficiency, of whom 180 million are children, and results in 2 million deaths annually (Conway 1999, Nuffield Council 1999). Producing more nutritious food for developing countries is critical because today malnutrition affects 840 million people. The above examples of potential technology in rice offer evidence to support the thesis that there is a reasonable probability that plant breeding can continue to make a significant contribution to productivity that will allow global cereal demands in 2025 to be met.

The most compelling case for biotechnology is its potential contribution to global food security. It is critical that a combined strategy of conventional and biotechnology applications be adopted as the technology component of a global food security initiative. Adoption of such a strategy will allow society to continue to benefit from the vital contribution that plant breeding offers the global population as a result of:

- Continued annual increments in productivity achieved through genetic gains, which will also generate healthier and more nutritious food/feed products.

- A land-saving technology which will allow production to be limited to the 1.5 billion ha of global cultivable land where sustainable agriculture can be practiced while saving fragile ecosystems and environments, the in-situ centers of biodiversity, wildlife, and forests for future generations. Currently 13 million ha of forest, which are havens of biodiversity and provide watershed control, are lost every year in developing countries.

- More efficient use of external inputs—substitute and develop alternatives to conventional pesticides, which represent a potential hazard for producers, consumers, and the environment. *Bt* crops alone, deployed on 11.7 million ha in 1999, have already substituted a substantial quantity of insecticides that were applied globally and valued at $7.823 billion in 1998 (Wood McKenzie, personal communication 1999). Much more substitution is possible with genes other than *Bt* that confer resistance to insect pests. Similarly, promising biotechnology applications offer significant savings in nitrogen fertilizer usage by increasing the efficiency of fertilizer use on crops which in turn will reduce additional fertilizer needs and modulate fertilizer runoff into watersheds, aquifers, and coastal waters.

- Increased stability of yield—the annals of history record famines that result from instability of yield due to drought, unfavorable weather patterns, pest infestations, and disease epidemics. Biotechnology offers the best option for reducing the variability in yield due to both abiotic and biotic stresses, especially a complex trait such as drought, which is a pervasive constraint that applies to at least one-third of the 1.5 billion ha of global cultivable land.

Opponents of biotechnology have posed questions about the potential environmental, biosafety, and food safety risk of transgenic crops, to which society has an obligation to respond. Proponents of biotechnology, the scientific community and regulatory bodies, have invested significant resources to generate evidence to assess the pros and cons of biotechnology. There is a substantive body of evidence from North America, where approximately 300 million people have consumed food from transgenic crops for 4 years, that transgenic crops and their derived food and feed products pose no more risk to people and the environment than conventional food (Miller and Conko 2000). The countries of the European Union (EU), however, have invoked the "precautionary principle," claiming that there is insufficient scientific evidence to conclude that there is no risk to consumers from transgenic crops, or the products derived from them. Accordingly, the sovereign states of the EU have prohibited imports of some varieties of transgenic crops and have, by and large, halted the planting of transgenic crops in most member states. In their publication "Precautionary Principle" Stalls Advances in Food Technology, Miller and Conko (2000) conclude that when applied to agricultural and food biotechnology, the precautionary principle focuses solely on the possibility that new products may pose theoretical risks. But this standard ignores the very real existing risks that could be mitigated or eliminated by those products. Applying the precautionary principle in this way often results in increasing, not decreasing, overall risk. For example, they state that if the precautionary principle had been applied decades ago to innovations like polio vaccines and antibiotics, regulators might have prevented occasionally serious, and sometimes fatal, side effects by delaying or denying approval of those products. But that precaution would have come at the expense of millions of lives lost to infectious diseases.

Thus, to date, the evidence presented in support of the adoption of transgenic crops and the consumption of food derived from them, has not convinced the countries of the European Union, which enjoy surplus and relatively inexpensive food and are not prepared to accept the potential risk that may be incurred if they deviate from the status quo. The risk to the poor in developing countries, where 24,000 people a day die from chronic malnutrition (Hunger Site 2000), however, is quite different. The risk is for people suffering from malnutrition in the Third World if industrial countries engage in a process that directly, indirectly, or inadvertently denies or delays them access to biotechnology that can help contribute to alleviation of malnutrition and hunger. Global society must seek equitable solutions that meet the different needs of people and nations and respect differing opinions. Implementing an equitable policy is a challenge in a world where globalization, a web of international protocols (such as the Biosafety Protocol), and international trade are all impacting on the ability of sovereign nations in the developing world to access and use biotechnology in their national food security strategies. The World Trade Organisation (WTO), whose policies and decisions are guided by objective assessments of scientific evidence does not have an advisory body to provide guidance on transgenic products. The establishment of such an advisory body by WTO, as recommended by Miller and Conko, would seem appropriate at this time, particularly to align and rationalize decisions vis-à-vis the Biosafety Protocol where contrary to WTO guidelines, the precautionary principle can be invoked to prohibit the use or transfer of transgenic crops without furnishing scientific evidence to support the case.

The opportunities and constraints associated with public acceptance of transgenic crops are important challenges facing the global community, where agriculture and its related industries, despite modern industrialization, is still one of, if not the, largest industries in the world. Because of our thrice-daily dependency on food, agriculture touches the life of every individual in the global community of over 6 billion. Today, agriculture employs 1.3 billion people and produces $1.3 trillion of produce annually (El Feki 2000). In the USA alone, although farming employs only 1% of the workforce and accounts for <1% of gross domestic product (GDP), the effect of agriculture on the US economy is significant because of its link to many industries. Consequently, in 1996 the US food and fiber system (farming and its related industries) employed 23 million people (17% of the labor force) and accounted for $997.7 billion, equivalent to 13.1% of the $7.6 trillion US GDP in 1996 (Lipton and Manchester 1998). US agricultural exports were valued at $60.4 billion in 1996, equivalent to the produce from almost one-third of US crop acreage. In 1996 US agricultural trade had a surplus of $26.8 billion, whereas nonagricultural trade had a deficit of $235.1 billion.

Unlike industrial countries such as the US and countries of the European Union, with a few exceptions, all developing countries are net importers rather than exporters of food, and where a high percentage of the population employed in agriculture are either small resource-poor farmers practicing subsistence farming or the rural landless who are dependent on agriculture for survival; 70% of the world's 1.3 billion poorest people are rural people. Agricultural employment as a percent of total employment was 80% in developing countries in 1950; it is currently 55%, and is still projected to be 50% in 2010 when the population of developing countries will be approximately 6 billion, equivalent to the global population of today. Improved crops derived from appropriate conventional and biotechnology applications for small resource-poor farmers are vital for increasing productivity and for providing access to more nutritious food in the food-insecure rural areas where the majority of the poverty, hunger, and malnutrition exists. Crops are not only the principal source of food but increased crop productivity provides more employment and acts as the engine of economic growth in rural communities. Producing more food on small subsistence farms has the significant advantage that the inevitable infrastructural constraints associated with transport can, to a large extent, be circumvented because food is produced at the same location where it is needed and consumed.

The foregoing does not by any means imply that biotechnology is a panacea. Biotechnology, like any other technology, has strengths and weaknesses and need to be managed responsibly and effectively. Biotechnology represents one essential link in a long and complex chain that must be in place to develop and deliver more productive crops for small resource-poor farmers. This will require the political will, goodwill, and unfailing support of both the public and private sectors in industrial and developing countries to work together in harmony. Distribution systems and organizations that provide extension advice, and manage microcredit and marketing are critical to success and are currently one of the weakest links in the food security chain.

9. Future Prospects for Transgenic Crops

In the early 1990s many were very skeptical that transgenic crops, more familiarly known as genetically modified (GM) crops, could deliver improved products and make an impact in the near term at the farm level. There was even more skepticism regarding the appropriateness of transgenic crops for the developing world, particularly their ability to meet the needs of small resource-poor farmers. It is encouraging to witness that the early promises of crop biotechnology are meeting expectations of large and small farmers in both industrial and developing countries. In 1999, the global area of the four principal crops of soybean, canola, cotton, and corn totaled 273 million ha, of which 15%, equivalent to 39.9 million ha, was planted with transgenic varieties (Table 23). This is unprecedented and equivalent to more than one and a half times the total land area of the United Kingdom; it comprises 30% of the 72 million ha of soybeans planted globally, 14% of the 25 million ha of canola, 10% of the 34 million ha of cotton, and 8% of the 140 million ha of corn. The fact that millions of farmers in 12 different industrial and developing countries around the world made independent decisions after evaluating the technology following their first plantings of transgenic crops in 1996, after which the area increased by an unprecedented multiple of >23-fold, speaks volumes for the confidence and trust farmers have placed in transgenic crops. In China alone, within a short period of 2 years, over 1.5 million small farmers, growing an average of 0.15 ha of *Bt* cotton, have embraced the technology after witnessing first hand in their own fields the significant and multiple benefits it can deliver.

Global area planted to transgenic crops is expected to continue to grow but will start to plateau in 2000 reflecting the unprecedented high adoption rates to date and the high percentage of principal crops already planted to transgenics in the USA, Argentina, and Canada. In 2000, Argentina is expected to modestly expand the area of transgenic crops, with Brazil, subject to regulatory approval and market demand, possibly growing transgenic crops officially for the first time in 2000. China is expected to expand its transgenic crop area of *Bt* cotton, with growth and diversification

Table 23. Transgenic crop area as % of global area of principal crops (million hectares), 1999

Crop	Global area	Transgenic crop area	Transgenic area as % of global area
Soybean	72	21.6	30
Canola	25	3.4	14
Cotton	34	3.7	10
Corn	140	11.1	8
Others	-	0.1	-
Total	**273**	**39.9**	**15**

Source: Clive James (1999).

continuing in South Africa and Eastern European countries. India has transgenic *Bt* cotton that is ready for commercialization pending final approval by the government. The major issues that will modulate adoption in 2000 will be public acceptance, which drives market demand, regulation, and commodity prices. These three issues and labeling of foods derived from genetically modified crops will continue to be dominant factors that will impact on commercial planting of transgenic crops and consumption of genetically modified derived foods in countries of the European Union.

As expansion of transgenic crops continues, a shift will occur from the current generation of "input" agronomic traits to the next generation of "output" quality traits, which will result in improved and specialized nutritional food and feed products that will satisfy a high-value-added market; this will be a stimulus to de-commoditize grain and oil seed markets. This shift will significantly affect the value of the global transgenic crop market and also broaden the beneficiary profile from growers to processors and consumers. Food products derived from transgenic crops that are healthier and more nutritious could in turn have important implications for public acceptance, particularly in Europe where the debate on transgenic crops continues.

The pace of biotechnology-driven consolidations in industry, which is a concern to some, was slower in 1999 than in the previous 3 years, although there were many alliances in the area of plant genomics that will continue to be of pivotal importance. The large multinationals with investments in seeds, crop biotechnology, and crop protection have reviewed their future plans. Some corporations have already initiated restructuring, and are planning spin-offs and mergers, which have resulted in more focus and may affect the scope and scale of planned delivery of new products.

The global seed industry will continue to play an important role by providing superior and healthy seed that contributes to increased crop productivity and stability. It is critically important that the public sector and international development institutions in both industrial and developing countries invest in the new technologies to ensure equitable access and benefits from the enormous potential that transgenic crops offer in terms of increased productivity, more nutritious food, and global food security.

In the global village of tomorrow, if we are to use limited resources in the most effective way, we will have to practice comparative advantage and define appropriate roles for the public and private sector. Governments must implement regulatory programs that inspire public confidence and exert leadership in communicating information and knowledge to the public on transgenic crops so that society is well informed and engaged in a dialog about the impact of the technology on the environment, food safety, sustainability, and global food security. Societies in food-surplus industrial countries must ensure that access to biotechnology of developing countries is not denied or delayed, because the most compelling case for biotechnology is its potential contribution to global food security and alleviation of hunger in the Third World where 24,000 people die every day from chronic malnutrition (Hunger Site 2000). It is vital that the public sector and the private sector forge partnerships that will allow the comparative advantages of both parties to be optimized to achieve the mutual objective of global food security. The seed industry has comparative advantages in two important areas. The first is its extensive and effective global plant breeding activities that harness both conventional and biotechnology applications to increase the productivity and nutrition of food crops. The second is the operation of effective seed distribution systems that remain one of, if not the weakest, link in food production chains in developing countries. The value and importance of superior seed is evident irrespective of whether it incorporates conventional or biotechnology improvements, because superior seed is essential for producing improved crop varieties that are, and will continue to be, the most cost-effective, environmentally safe, and sustainable way to ensure global food security in future. Superior seed, incorporating improved transgenic traits, can be a very powerful tool for alleviating poverty because not only can it contribute to the sustenance of the rural poor (Wambugu 1999), but the value of superior seed is known, trusted, and accepted by hundreds of millions of farmers throughout the world.

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Appendix

Appendix Table 1A. 1998 seed exports worldwide, by crop (US$ millions)

Crops	Seed exports
Maize	530
Herbage crops	427
Potato	400
Beet	308
Wheat	75
Other agricultural crops	590
Horticultural crops	1,115
Total	**3,445**

Source: FIS (1998).

Appendix Table 2A. 1998 export of seeds, major exporting countries (US$ millions)

Country	Agricultural seeds	Horticultural seeds	Total
USA	500	200	700
Netherlands	420	200	620
France	432	100	532
Denmark	150	40	190
Germany	150	35	185
Belgium	111	n.a.	111
Italy	73	30	103
Canada	n.a.	n.a.	100
Chile	50	25	75
Argentina	43	1	44
Total	2,330	1,115	3,445

Source: FIS (1998).

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by

Clive James
Chair, ISAAA Board of Directors

Global area of transgenic crops, 1996 to 1999
(million hectares/acres)

	Hectares (million)	Acres (million)
1996	1.7	4.3
1997	11.0	27.5
1998	27.8	69.5
1999	**39.9**	**98.6**

Increase of 44%, 12.1 million hectares or 29.1 million acres between 1998 and 1999

Source: Clive James (1999).

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Contents

This publication is the fourth in a series of *ISAAA Briefs*, which characterize the global adoption of commercialized transgenic crops. A global database for the period 1996 to 1999 is presented and 1999 data is analyzed globally, and by country, crop, and trait. Data on the global status of transgenic crops are complemented with commentaries on relevant key topics including the value of the global transgenic seed market; a review of acquisitions, mergers, and alliances in the biotechnology industry including those related to genomics; an overview of the commercial seed industry: status of transgenic crops in selected developing countries of Asia; future traits in biotechnology; an assessment of the contribution of conventional and biotechnology applications to past and future plant breeding activities in the major staples of wheat, rice, and maize and the impact on global food security; and future prospects for transgenic crops in 2000 and beyond.

In the early 1990s many were very skeptical that transgenic crops, more familiarly known as genetically modified (GM) crops, could deliver improved products and make an impact in the near term at the farm level. There was even more skepticism regarding the appropriateness of transgenic crops for the developing world, particularly their ability to meet the needs of small resource-poor farmers. It is encouraging to witness that the early promises of crop biotechnology are meeting expectations of large and small farmers in both industrial and developing countries. In 1999, the global area of the four principal crops of soybean, canola, cotton, and corn totaled 273 million ha, of which 15%, equivalent to 39.9 million ha, was planted with transgenic varieties. These 39.9 million ha of transgenic crops grown globally are unprecedented, and equivalent to more than one and a half times the total land area of the United Kingdom; they comprise 30% of the 72 million ha of soybeans planted globally, 14% of the 25 million ha of canola, 10% of the 34 million ha of cotton, and 8% of the 140 million ha of corn. The fact that millions of farmers in 12 different industrial and developing countries around the world made independent decisions after evaluating the technology following their first plantings of transgenic crops in 1996, after which the area increased by an unprecedented multiple of more than 23-fold, speaks volumes for the confidence and trust farmers have placed in transgenic crops. In China alone, within a short period of 2 years, over 1.5 million small resource-poor farmers growing an average of 0.15 ha of *Bt* cotton, have embraced the technology after witnessing first hand in their own fields the significant and multiple benefits it can deliver.

Between 1996 and 1999, 12 countries, 8 industrial and 4 developing, have contributed to more than a 20-fold (23.5) increase in the global area of transgenic crops. Adoption rates for transgenic crops are unprecedented and are the highest for any new technologies by agricultural industry standards. High adoption rates reflect grower satisfaction with the products that offer significant benefits ranging from more convenient and flexible crop management, higher productivity and/or net returns/hectare, and a safer environment through decreased use of conventional pesticides, which collectively contribute to a more sustainable agriculture. The major changes in area and global share of transgenic crops for the respective countries, crops and traits, between 1998 and 1999 were related to the following factors:

- In 1999, the global area of transgenic crops increased by 44%, or 12.1 million ha, to 39.9 million ha, from 27.8 million ha in 1998. Seven transgenic crops were grown commercially in 12 countries in 1999, three of which, Portugal, Romania, and Ukraine, grew transgenic crops for the first time.
- The four principal countries that grew the majority of transgenic crops in 1999 were USA, 28.7 million ha (72% of the global area); Argentina, 6.7 million ha (17%); Canada, 4.0 million ha (10%); China, 0.3 million ha (1%); the balance was grown in Australia, South Africa, Mexico, Spain, France, Portugal, Romania, and Ukraine.
- Growth in area of transgenic crops between 1998 and 1999 in industrial countries continued to be significant and 3.5 times greater than in developing countries (9.4 million ha versus 2.7 million ha).
- In terms of crops, soybean contributed the most (59%) to global growth of transgenic crops, equivalent to 7.1 million ha between 1998 and 1999, followed by corn at 23% (2.8 million ha), cotton at 10% (1.2 million ha), and canola at 8% (1 million ha).
- There were three noteworthy developments in terms of traits; herbicide tolerance contributed the most (69% or 8.3 million ha) to global growth between 1998 and 1999; the stacked genes of insect resistance and herbicide tolerance in both corn and cotton contributed 21% equivalent to 2.6 million ha; and insect resistance increased by 1.2 million ha in 1999 representing 10% of global area growth.
- Of the four major transgenic crops grown in 12 countries in 1999, the two principal crops of soybean and corn represented 54% and 28%, respectively, for a total of 82% of the global transgenic area, with the remaining 18% shared equally between cotton (9%) and canola (9%).
- In 1999, herbicide-tolerant soybean was the most dominant transgenic crop (54% of global transgenic area, compared with 52% in 1998), followed by insect-resistant corn (19% compared with 24% in 1998), herbicide-tolerant canola (9%), *Bt*/herbicide-tolerant corn (5%), herbicide-tolerant cotton (4%), herbicide-tolerant corn (4%), *Bt* cotton (3%), and *Bt*/herbicide-tolerant cotton (2%).
- The four major factors that influenced the change in absolute area of transgenic crops between 1998 and 1999 and the relative global share of different countries, crops, and traits were: first, the substantial increase of 4.8 million ha in herbicide-tolerant soybean in the USA (from 10.2 million ha in 1998 to 15.0 million ha in 1999, equivalent to 50% of the 30.0 million ha US national soybean crop in 1999), coupled with an increase of 2.1 million ha in herbicide-tolerant soybean in Argentina (from 4.3 million ha in 1998 to an estimated 6.4 million ha in 1999, equivalent to approximately 90% of the 7.0 million ha of Argentina's national soybean crop in 1999); second, the significant increase of 2.2 million ha of transgenic corn (insect-resistant, *Bt*/herbicide-tolerant, and herbicide-tolerant) in the USA from 8.1 million ha in 1998 to 10.3 million ha in 1999, equivalent to 33% of the 31.4 million ha of US national corn crop in 1999; third, the increase of 1.0 million ha of herbicide-tolerant canola in Canada from 2.4 million ha in 1998 to 3.4 million ha in 1999, equivalent to 62% of the 5.5 million ha of the Canadian canola crop in 1999; and fourth, the 1.0 million ha increase in transgenic cotton in the USA, from 2.2 million ha in 1998 to 3.2 million ha in 1999 (equivalent to 55% of the 5.9 million ha of the US national cotton crop in 1999). The 3.2 million ha of transgenic cotton in 1999 comprised 1.5 million ha of herbicide-tolerant cotton with the balance of 1.7 million ha equally divided between *Bt* cotton and cotton with the stacked gene of *Bt*/herbicide tolerance.

- The combined effect of the above four factors resulted in a global area of transgenic crops in 1999 that was 12.1 million ha greater and 44% more than 1998; this is a significant year-on-year increase considering the high percentage of principal crops planted to transgenics in 1998. Commercialized transgenic crops were grown for the second year in two countries of the European Union (30,000 ha of *Bt* maize in Spain and 1,000 ha of *Bt* maize in France) with Portugal growing more than 1,000 ha of *Bt* maize for the first time in 1999. Two countries in Eastern Europe grew transgenic crops for the first time; Romania grew introductory areas of herbicide-tolerant soybean (14,250 ha) and planted <1,000 ha of *Bt* potatoes. Ukraine also grew *Bt* potatoes (<1,000 ha) for the first time. An unverified small area of *Bt* maize in Germany and an introductory area of herbicide-tolerant corn in Bulgaria were not included in the global database.

The value of the global market for transgenic seed has grown rapidly from $1 million in 1995 to $152 million in 1996, $851 million in 1997, $1,959 million in 1998, and an estimated $2.7-3 billion in 1999. Global area planted to transgenic crops is expected to continue to grow but will start to plateau in 2000 reflecting the unprecedented high adoption rates to date and the high percentage of principal crops already planted to transgenics in the USA, Argentina, and Canada. In 2000, Argentina is expected to modestly expand the area of transgenic crops, with Brazil, subject to regulatory approval and market demand, possibly growing transgenic crops officially for the first time. China is expected to expand its transgenic area of *Bt* cotton, with growth and diversification continuing in South Africa and Eastern European countries. India has transgenic *Bt* cotton that is ready for commercialization pending final approval by the Government of India. The major issues that will modulate adoption in 2000 will be public acceptance, which drives market demand, regulation, and commodity prices. These three issues and labeling of foods derived from genetically modified crops will continue to be dominant factors that will impact on commercial planting of transgenic crops and consumption of genetically modified derived foods in countries of the European Union.

As expansion of transgenic crops continues, a shift will occur from the current generation of "input" agronomic traits to the next generation of "output" quality traits. This will result in improved and specialized nutritional food and feed products that will satisfy a high-value-added market, and will be a stimulus to de-commoditize grain and oil seed markets. This shift will significantly affect the value of the global transgenic crop market and also broaden the beneficiary profile from growers to processors and consumers. Food products derived from transgenic crops that are healthier and more nutritious could in turn have important implications for public acceptance, particularly in Europe where the debate about transgenic crops continues.

The R&D pipeline is full of new and novel products with input and output traits that can be commercialized in the midterm. Plant breeding activities in the cereal staples—wheat, rice and maize—have made enormous contributions to global food security. It is critical that a combined strategy of conventional and biotechnology applications be adopted as the technology component of a global food security initiative that also addresses other critical issues including population control and improved distribution. With the adoption of such a strategy, society will continue to benefit from the vital contribution that plant breeding offers the global population and global cereal demands of 2025 can be met. Biotechnology can play a critical role in achieving food security in Asia where 50% of the 1.3 billion poor people in the world reside. China assigns high priority and a strategic value to biotechnology and was the first country in the world to commercialize transgenic crops in the early 1990s. The experience of China, where more than 1.5 million small farmers benefit from *Bt* cotton, would be useful to share with other countries in the region.

The pace of biotechnology-driven consolidations in industry, which is a concern to some, was slower in 1999 than in the previous 3 years, although there were many alliances in the area of plant genomics that will continue to be of pivotal importance. The large multinationals with investments in seeds, crop biotechnology, and crop protection have reviewed future plans. Some corporations have already initiated restructuring, and are planning spin-offs and mergers, which have resulted in more focus. This may affect the scope and scale of planned delivery of new products. It is critically important that the public sector and international development institutions in both industrial and developing countries invest in the new technologies to ensure equitable access and benefits from the enormous potential that transgenic crops offer in terms of increased productivity, more nutritious food, and global food security. Governments must implement regulatory programs that inspire public confidence and exert leadership in communicating information and knowledge on transgenic crops to the public, so that society is well informed and can engage in a dialog about the impact of the technology on the environment, food safety, sustainability, and global food security. The most compelling case for biotechnology is its potential contribution to global food security and the alleviation of hunger in the Third World where 24,000 people die every day from chronic malnutrition. It is vital that the public sector and the private sector forge partnerships that will allow the comparative advantages of both parties to be optimized to achieve the mutual objective of global food security. The value and importance of superior seed is evident irrespective of whether it incorporates conventional or biotechnology improvements, because superior seed is essential for producing improved crop varieties that are, and will continue to be, the most cost-effective, environmentally safe and sustainable way to ensure global food security in future. Superior seed, incorporating improved transgenic traits, can be a very powerful tool for alleviating poverty because not only can it contribute to the sustenance of the rural poor, but the value of superior seed is known, trusted and accepted by hundreds of millions of farmers throughout the world.

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