Genetic transformation of crop plants: Risks and opportunities for the rural poor

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The world population is increasing at an alarming rate and is expected to increase from 6.5 billion at present to 7.5 billion by 2025. Most of this population lives in the rural areas in the developing countries where poverty, food insecurity and nutritional deficiencies are the major problems. Low crop productivity, limited use of inputs such as fertilizers and pesticides and losses due to biotic and abiotic stress factors are a major constraint to increase production and productivity of crops. With the advent of genetic engineering, it has become possible to clone and insert genes into the crop plants to confer resistance to insect pests and improve the nutritional quality. Genetically transformed crops with Bacillus thuringiensis and herbicide resistance genes have been deployed for cultivation in USA, Canada, China and Australia. However, very little has been done to use this technology for improving crop production in the harsh environments of the tropics, where the need for increasing food production is most urgent. However, there is a need to follow the biosafety regulations and a better presentation of the results to the general public for a rational deployment of the genetically transformed crops for improving the livelihoods of the rural poor.

NEARLY 70% of poor and food-insecure people live in rural areas in the developing countries. Low productivity in agriculture is a major cause of poverty, food insecurity and poor nutrition in low-income developing countries, where agriculture is the driving force for broad-based economic growth and poverty alleviation. Productivity increases in agriculture, led by agricultural research, formed the basis of rapid economic growth and poverty reduction in many countries in Asia, Latin America and North Africa[1]. Therefore, accelerated public investments are needed to facilitate agricultural and rural growth through high-yielding varieties resistant to biotic and abiotic stresses, environment-friendly production technology, availability of reasonably priced inputs in time, strong extension services, dissemination of information, improved infrastructure and markets, primary education, health care and adequate nutrition.

These investments need to be supported by good governance and an environment-friendly policy for sustainable management of natural resources. Advances in crop improvement have led to green revolution becoming one of the scientifically most significant events in human history. Green revolution in wheat helped to surpass in four years the production accomplishments of the past century[2]. Land and water are diminishing resources and there is no option but to increase crop pro ductivity per unit area. There is a need to examine how science can be used to raise biological productivity without associated ecological costs. In countries such as India, farming provides livelihood to nearly 66% of the population and there is concern that expansion of proprietary science may lead to a situation where the technologies of the future remain in the hands of a few multinational companies[2]. There is a genuine fear that the emerging gene revolution, spearheaded by proprietary science, can come under monopolistic control. Therefore, there is an urgent need to take the fruits of gene revolution to the poorer sections of the society. Biotechnological approaches in agriculture and medicine can provide a powerful tool to alleviate poverty and improve the livelihoods of the rural poor. The fate of small farm families in the short-term will depend on precision agriculture, which involves the use of right inputs at the right time. Biotechnology can play an important role in integrated gene management, integrated pest management and efficient post-harvest management.

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Population increase and food security

According to projections by the United Nations, world population will increase by 25% to 7.5 billion in 2020. Nearly 1.2 billion people live in a state of absolute poverty[3] and about 800 million people are food insecure[4]. Food insecurity and malnutrition result in serious public health problems and a lost human potential in developing countries. The major problems faced by the rural poor include: low productivity, food insecurity and poor nutrition.

The availability of land for food production is decreasing over time and such a decrease is expected to be much greater in the developing countries than in developed countries. Mexico, Ecuador, Nigeria and Ethiopia had a per capita cropland availability of 0.25 ha in 1990 compared to below 0.10 ha in Egypt, Kenya, Bangladesh, Vietnam and China. By 2025, per capita cropland availability will be below 0.10 ha in countries such as Peru, Tanzania, Pakistan, Indonesia and the Philippines[5]. Such a decrease in availability of cropland will have major implications for food security, particularly in the developing countries. Grain production has shown a remarkable increase from 1950 to 1980, while a marginal increase was recorded from 1980 to 1990 (Figure 1). Thereafter, the grain production has almost remained static. The rate of increase in food production has decreased to 1% per annum in the 1990s compared to a 3% increase in the 1970s (ref. 6). At times people have limited access to food not because of nonavailability of food, but due to poor purchasing power. After mid-1980s, there has been a slow and steady decline in per capita availability of food grains[7]. In India, the food production is precariously balanced despite a substantial increase in the area under irrigation. By 2001, there is a need to increase the production of pulses from 15 million tonnes in 1995 to 20 million tonnes, milk from 64 to 92 million tonnes and animal foods from 7 to 17 million tonnes. There is a general trend in reduction of number of people facing under-nutrition[8]. The figure is expected to come down from 35% (1969–1971) to 12% in 2010 (ref. 9). By 2010, the number of people facing malnutrition will be 30% in sub-Saharan Africa, 10% in west Asia and north Africa, 6% in east Asia, 12% in south Asia and 7% in Latin America.

The need for developing transgenic crops

One of the practical means of increasing crop production is to minimize the pest-associated losses, which are currently estimated at 14% of the total agricultural production[10]. There are additional costs in the form of pesticides applied for pest control, currently valued at US $10 billion annually. Massive application of pesticides not only leaves harmful residues in the food, but also causes adverse effects on non-target organisms and the environment. Insect pests, diseases and weeds cause an estimated loss of US$ 243.4 billion in eight major field crops (42%), out of total attainable production of US$ 568.7 billion worldwide (Figure 2). Amongst these, insects cause an estimated loss of US$ 90.4 billion, diseases US$ 76.8 billion and weeds US$ 64.0 billion. The actual losses have been estimated at 51% in rice, 37% in wheat, 38% in maize, 41% in potato, 38% in cotton, 32% in soybean, 32% in barley and 29% in coffee. Insect pests and diseases have the potential to cause 52% loss in wheat, 58% in soybean, 59% in maize, 74% in potato, 83% in rice and 84% in cotton[3]. In the five most important crops of the semi-arid tropics (sorghum, pearl millet, pigeonpea, chickpea and groundnut; Figure 3), the biotic and abiotic stress factors have been estimated to cause an estimated loss of US$ 15.74 billion[11].

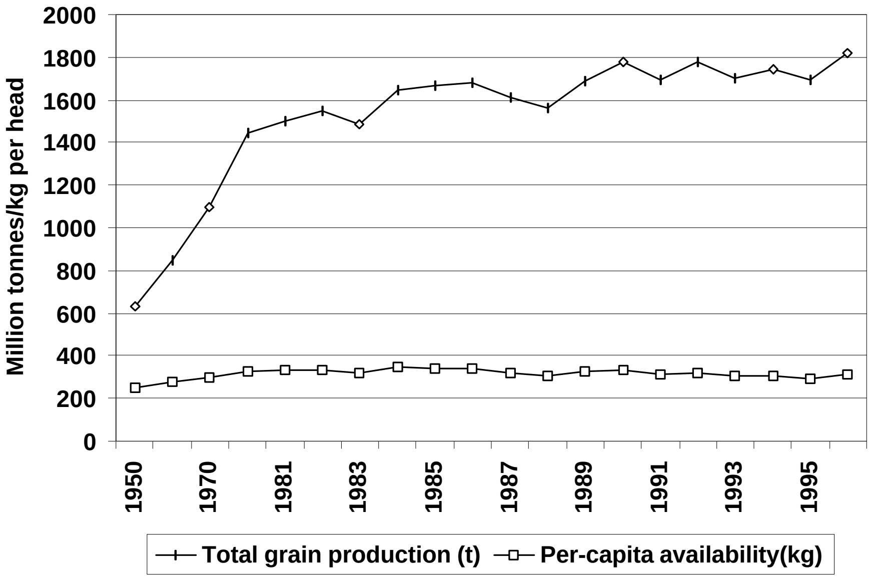

Figure 1. World grain production and per capita availability of grain (1950–1996). Based on data from Engelman and LeRoy[7].

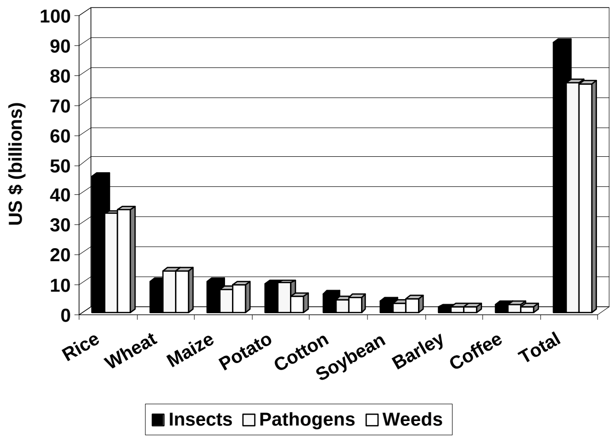

Figure 2. Estimated yield losses due to insects, diseases and weeds in eight major field crops (1988–1990). Based on data from Oerke *et al.*[10].

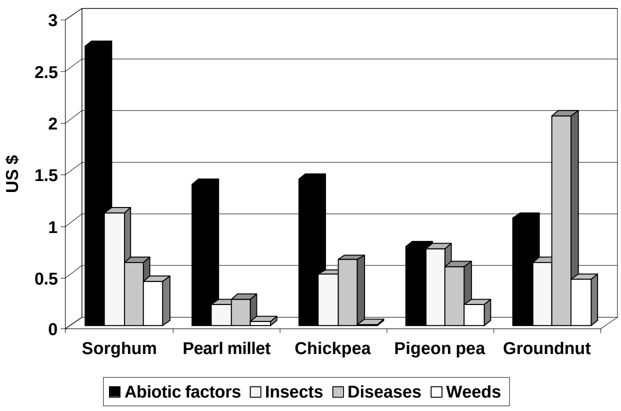

Figure 3. Extent of losses due to abiotic stress factors, insects, diseases and weeds in sorghum, pearl millet, pigeonpea, chickpea and groundnut in the semi-arid tropics. Based on data from ICRISAT[11].

Amongst these, the losses due to insects, diseases and weeds have been estimated to be US$ 3.17, 4.12 and 1.14 billion, respectively. Losses due to biotic stress factors have been estimated to be US$ 8.48 billion. Biotechnological approaches can be used in a rational manner to reduce the pest-associated losses in the harsh environments of the tropics.

Application of pesticides to minimize the losses due to insect pests, diseases and weeds results in adverse effects on the beneficial organisms, leaves pesticide residues in the food and results in environmental pollution. As a result, chemical control of insect pests is under increasing pressure. This has necessitated the use of target-specific compounds with low persistence and an increase in emphasis on integrated pest management. Although the benefits to agriculture from the pesticide use to prevent insect-associated losses cannot be overlooked, there is a greater need to develop alternative or additional technologies, which would allow a rational use of pesticides for sustainable crop production. Integrated pest management has historically placed great hopes on host-plant resistance. However, conventional host-plant resistance to insects involves quantitative traits at several loci and as a result, the progress has been slow and at times difficult to achieve.

Many species of insect pests, plant pathogens and weeds have developed resistance to the currently available pesticides[12]. A large number of insects have also shown resistance to insecticides belonging to different groups and 645 cases of resistance have been documented until 1996. Maximum reports of resistance development pertain to organophosphates (250), followed by synthetic pyrethroids (156), carbamates (154) and others (including chlorinated hydrocarbons) (85). Many species (about 85) of insects have developed resistance to more than two groups of insecticides. Maximum numbers of insects and mites showing resistance to pesticides have been recorded in vegetables (48), followed by those infesting fruit crops (25), cotton (21), cereals (15) and ornamentals (13) (Figure 4). In India, there are several documented cases of development of resistance in insects to insecticides (Table 1). Maximum number of insects showing resistance to insecticides has been recorded in cotton, vegetables and tobacco[12]. *Helicoverpa armigera* (which is the most serious pest on cotton, legumes, vegetables and cereals) has shown resistance to several groups of insecticides in cotton, tomato, chillies, sunflower, groundnut, pigeonpea and chickpea. This has resulted in widespread failure of insect control causing extreme debts, at times even forcing the farmers to commit suicide. The cotton whitefly (*Bemisia tabaci*) has shown resistance to insecticides in cotton, brinjal and okra; while tobacco caterpillar (*Spodoptera litura*) has been found to be resistant to insecticides on cotton, cauliflower, groundnut and tobacco. Green peach and potato aphid (*Myzus persicae*), cotton aphid (*Aphis gossypii*), mustard aphid (*Lipaphis erysimi*) and diamond back moth (*Plutella xylostella)* have also been found to exhibit resistance to insecticides in several crops. Development of resistance to insecticides has necessitated the application of higher dosages of the same pesticide or increased number of pesticide applications. The farmers often resort to insecticide mixtures to minimize the insect damage to crops. This not only increases the cost of pest control, but also results in insecticidal hazards and pollution of the environment. It is in this context that the use of biotechnological techniques to contain the pest damage, both in the developed and the developing countries, becomes all the more important.

The promise of genetic engineering of crops

In addition to widening the pool of useful genes, genetic engineering also allows the use of several desirable

Table 1. Development of insect resistance to insecticides in major field crops in India

	Insect pest		Exhibiting resistance to			
Crop	Common name	Scientific name	Op*	Carb	Pyr	Ch
Cotton	Cotton jassid	*Amrasca biguttula*	x			
	Cotton aphid	*Aphis gossypii*	x			
	Cotton white fly	*Bemisia tabaci*	x			
	Cotton bollworm	*Helicoverpa armigera*	x	x	x	x
	Potato aphid	*Myzus persicae*	x			
	Tobacco leaf caterpillar	*Spodoptera litura*	x	x		
Rice	Rice leaf folder	*Cnaphalocrocis*	x		x	
		medinalis	x		x	
	Leaf folder	*Marasmia patnalis*	x			
Brinjal	Cotton jassid	*A. biguttula*	x			
	Cotton white fly	*B. tabaci*	x			
	Potato aphid	*M. persicae*	x	x	x	
	Brinjal fruit borer	*Leucinodes orbonalis*	x			
Tomato	Cotton bollworm/tomato fruit borer	*H. armigera*	x			
Chillies	Cotton aphid	*A. gosspyii*	x	x	x	
	Cotton bollworm	*H. armigera*	x	x		
	Potato aphid	*M. persicae*	x			
Cabbage	Potato aphid	*M. persicae*	x	x	x	
	Diamond back moth	*Plutella xylostella*	x		x	x
Cauliflower	Diamond back moth	*P. xylostella*	x	x		x
	Tobacco leaf caterpillar	*S. litura*	x			
Okra	Cotton white fly	*B. tabaci*	x		x	x
Sunflower	Cotton bollworm	*H. armigera*	x	x	x	x
Mustard	Mustard aphid	*Lipaphis erysimi*	x	x		
Groundnut	Cotton bollworm	*H. armigera*	x	x	x	x
	Tobacco leaf caterpillar	*S. litura*	x			
Tobacco	Tobacco aphid	*Myzus nicotianae*	x	x		
	Potato aphid	*M. persicae*	x	x	x	x
	Tobacco leaf caterpillar	*S. litura*	x	x	x	
Chickpea	Cotton bollworm/pod borer	*H. armigera*	x	x	x	x
Pigeonpea	Cotton bollworm/pod borer	*H. armigera*	x	x	x	x

*Op, organophosphates; Carb, carbamates; Pyr, pyrethroids; Ch, chlorinated hydrocarbons. Based on data from Rajmohan[12].

genes in a single event and reduces the time to introgress novel genes into elite background. Research on transgenic crops, as is the case with conventional plant breeding and selection by the farmers, aims to selectively alter, add or remove a character of choice in a plant, bearing in mind the regional need and opportunities. It not only offers the possibility of bringing in a desirable character from closely-related plants, but also of adding desirable characteristics from the unrelated species. After the transformation event, the transformed plant becomes a parent for use in conventional breeding programmes.

Development and deployment of transgenic plants in an effective manner will be an important prerequisite for sustainable use of biotechnology for crop improvement. As a result of advances in genetic transformation and gene expression during the last decade[13–15], there has been a rapid progress in using genetic engineering for crop improvement, of which protection of crops against the insects is a major goal. The potential of this

Table 2. Spectrum of activity of proposed insecticidal genes for genetic transformation of crops for protection against different organisms

Insecticidal gene	Insect				Nematodes	Fungi	Mammals
	Lepidoptera	Coleoptera	Hemiptera	Orthoptera			
Serine protease inhibitors*	+	+	–	+	+	+	±
Thiol protease inhibitors*	–	+	–		+		–
Lectins*	+	+	+		+	+	±
a-amylase inhibitors	+	+	–				±
Cholesterol oxidase		+					
Lipoxigenase	+		+				
Acyl-hydrolase		+				+	–
Chitinase*	+					+	+
Polyphenol oxidase	+	+					
Rhibosome inactivating proteins	+	+					
Bt toxins*	+	+	–	–	–	–	
Vegetative insecticidal proteins	+	+					–
Small RNA viruses	+						
Neurotoxins from insects and mites	+	+					+?
Secondary plant metabolites	+	+	+	+	+	+	±

+, Active; –, Inactive; ±, Moderate activity; *, Genes already inserted into crop plants; Based on information from Hilder and Boulter[13], and Sharma *et al.*[15].

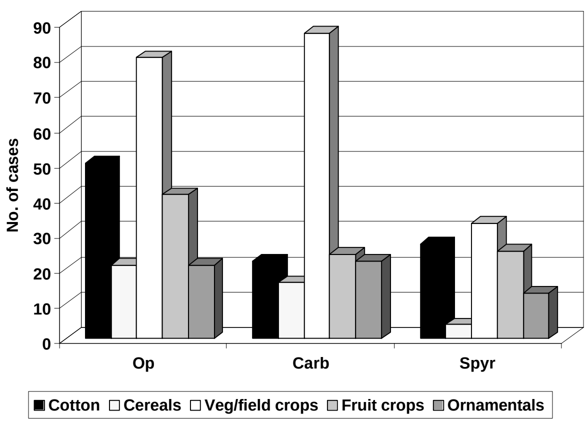

Figure 4. Development of insect resistance to different groups of insecticides (op, organophosphates; carb, carbamates; spyr, synthetic pyrethroides). Based on data from Rajmohan[12].

technology has now been recognized widely. Once efficient protocols for tissue culture and transformation are developed, the production of transgenic plants with different genes is fairly routine[14]. Such protocols have been reported for several crops in the past.

Resistance to insect pests, diseases and herbicides

The first transgenic plants with a gene derived from *Bacillus thuringiensis* (*Bt*) were produced in 1987(refs 16–18). While most of the insect-resistant transgenic plants have been developed by using *Bt d*-endotoxin genes, many studies are underway to use non-*Bt* genes, which interfere with the nutritional requirements of the insects. Such genes include protease inhibitors, chitinases, secondary plant metabolites and lectins (Table 2). Genes conferring resistance to insects have been inserted into crop plants such as maize, cotton, potato, tobacco, rice, broccoli, lettuce, walnuts, apples, alfalfa and soybean[19–21]. The first transgenic crop was grown in 1994 and large-scale cultivation was taken up in 1996 in USA. Since then, there has been a rapid growth in the area under transgenic crops in USA, Canada, Australia, Argentina and China. Successful control of cotton bollworms has been achieved through transgenic cotton[22–24]. Cry-type toxins are effective against the European corn borer[25] and rice stem borers[26–28]. Successful expression of *Bt* genes against the lepidopterous pests has also been obtained in tomato[29], potato[30], brinjal[31], groundnut[32] and chickpea[33].

Several other genes have also been deployed in the crop plants to confer resistance to insects. Transgenic plants expressing trypsin inhibitor gene have been developed in tobacco[34,35], cotton[36] and rice[37]. Transgenic tobacco, maize and rice expressing lectin genes have shown adverse effects against several insect species feeding on these crops[13,15,38,39]. Transgenic tobacco plants expressing chitinase gene have shown increased resistance to lepidopteran insects[40]. Activity of *Bt* can also be increased in combination with tannic acid and proteinase inhibitors[35,41.42].

There will be tremendous benefits to the environment through the deployment of transgenic plants in pest management. Papaya ringspot virus-resistant papaya[43] is being grown in Hawaii since 1996. Deployment of insect-resistant crops has lead to a reduction of 1 million kg of pesticides in USA[44] in 1999 compared to 1998. Rice yellow mottle virus (RYMV), which is difficult to control with conventional approaches, can now be controlled through transgenic rice[45], which would provide insurance for total crop failure. Transgenic papaya with resistance to ringspot virus[46], blight resistant-potatoes[47] and leaf blight-resistant rice[48] are examples of successful control of pests through genetically modified crops. Herbicide-resistant crops can also be used to grow crops without tillage.

At the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), several candidate genes are being evaluated for their biological efficacy against the sorghum shoot fly (*Atherigona soccata)*, spotted stem borer (*Chilo partellus)*, tobacco caterpillar (*S. litura*) and cotton bollworm or legume pod borer (*H. armigera*), which are major crop pests in the semi-arid tropics. Efforts are underway at ICRISAT to insert *Bt*, trypsin inhibitor and lectin genes into sorghum, pigeonpea and chickpea[14].

There has been a rapid increase in area planted to transgenic crops from 1.7 million ha in 1996 to 39.5 million ha in 1999. The value of sales has increased from US$ 0.235 billion in 1996 to US $2.3 billion in 1999. In 1997, transgenic crops were grown in 12 countries and most of the land planted to genetically improved crops was in just five countries (Australia, Canada, Argentina, China and USA), with USA alone accounting for about 80% of the area (Figure 5). Countries other than China included a number of large-scale capital-intensive farms that produce primarily for the industrial country markets. Among the crops produced in these countries are insect-resistant cotton and maize, herbicide-resistant soybean, and tomatoes with a long shelf-life[21]. There has been a rapid increase in the area planted to herbicide- and insect-resistant crops between 1996 and 1997 (Figure 6). Globally, herbicide-resistant soybean, insect-resistant maize and genetically improved cotton account for 85% of all plantings. Both the area planted to genetically improved crops and the value of the harvests grew dramatically between 1995 and 1999 (from less than 1 million ha in 1995 to 40 million ha in 1999)[49,50].

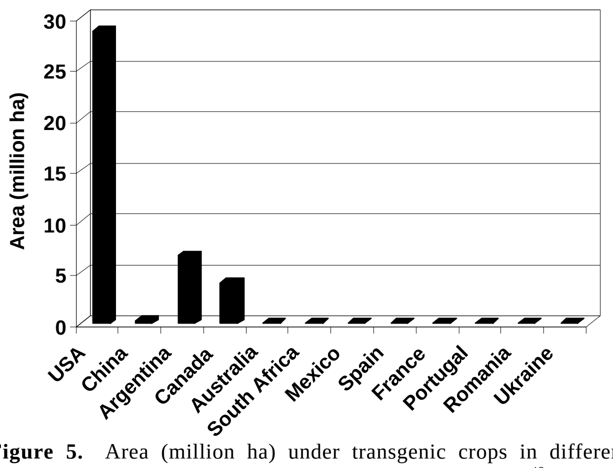

Figure 5. Area (million ha) under transgenic crops in different countries in 1999. Based on data from James and Krattiger[49].

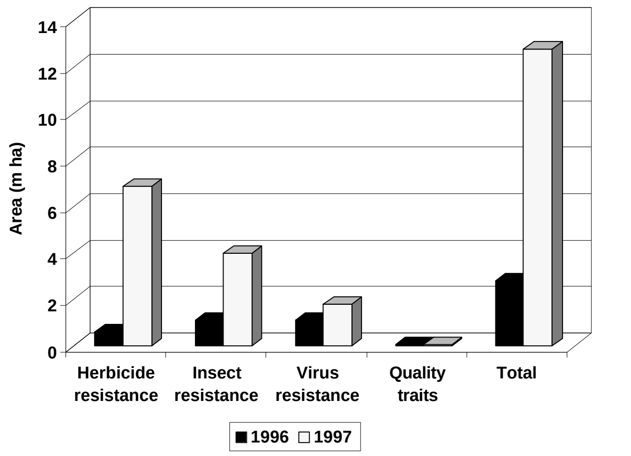

Figure 6. Area (million ha) under transgenic crops with different traits in 1996 and 1997. Based on data from McLaren[21].

Transgenic plants with insecticidal genes are set to feature prominently in pest management in both developed and the developing world in future. Among the developing countries, China, India, Argentina, Mexico, Brazil, Pakistan and South Africa are vigorously pursuing research on transgenic crops. Entomologists, breeders, molecular biologists and agronomists need to determine how to deploy this technology for pest management and at the same time avoid or reduce possible environmental risks. To achieve these objectives, it is necessary to have an appropriate understanding of the insect biology, behaviour, its response to the insecticidal proteins, temporal and spatial expression of insecticidal proteins in the plants, strategy for resistance management and finally the impact of insecticidal proteins on natural enemies and non-target organisms. Equally important are the issues concerning the transfer of technology to the resource-poor farmers, who will benefit greatly from these events. Biotechnology can be used for genetic transformation of the field crops for imparting resistance to the target insects and diseases, adaptation to different abiotic stress factors and improve the nutritional quality of the produce (Table 3). Such an effort will play a major role in minimizing the insect-associated losses, increase crop production and improve the quality of life for the rural poor.

Improved yield

NORIN 10 genes, introduced into Western wheats in 1950s led to the green revolution in mid-sixties. These genes have now been isolated and they act in exactly the same way when used to transform other crop species[51]. These dwarfing genes can now be deployed in other crop species to increase the productivity of differ-

Table 3. Application of biotechnology to improve yield and quality of major field crops in the tropics

Crop	Area of improvement
Rice	Drought and salinity tolerance Resistance to stem borers, brown hoppers, gall midge and leaf sheath blight Nutritional and table quality of grains Resistance to lodging
Wheat	Yield, quality and adaptation Resistance to rusts and Karnal bunt
Maize	Yield and quality Resistance to lodging and stem borers
Sorghum	Yield and quality and adaptation to drought Resistance to shoot fly, stem borer, midge, head bugs and grain molds
Pearl millet	Yield and adaptation to drought Resistance to downy mildew, stem borers and head miner
Pigeonpea	Adaptation to drought Resistance to pod borers and *Fusarium* wilt
Chickpea	Adaptation to drought and chilling tolerance Resistance to wilt, *Ascochyta* blight and pod borer
Mustard	Yield and adaptation to drought Oil content and quality Resistance to aphids
Groundnut	Yield, oil content and adaptation to drought Resistance to foliar diseases, aflatoxins, leaf miner and *Spodoptera*
Cotton	Yield, fibre quality and oil content Resistance to jassids and bollworms Flushing pattern
Sugarcane	Resistance to stem borers Yield Induction of early maturity
Tobacco	Yield and quality Resistance to aphids, *Spodoptera* and viruses

ent crops. Similarly, photosynthetic rates or other physiological characteristics of plants can be changed to increase the production and productivity of crops.

Tolerance to abiotic stresses

Development of crops to have inbuilt capacity to withstand abiotic stresses would help stabilize the crop production. Plants with an ability to produce more citric acid in roots, are tolerant to aluminium in acid soils[52]. A salt tolerance gene isolated from mangrove (*Avicennia marina*) has been cloned and can be transferred into other crop plants. The *gutD* gene from *Escherichia coli* can also be used to provide salt tolerance[53]. These genes will have a great potential for use in marginal lands.

Nutritional factors

Transgenic rice, with a capacity to produce beta-carotene, can be used to overcome the deficiency of vitamin A[54]. Transgenic rice with elevated levels of iron has been produced using genes involved in the production of an iron-binding protein that facilitates iron availability in human diet[55,56].

Pharmaceuticals and vaccines

Vaccines against infectious diseases of the gastro-intestinal tract have been produced in potatoes and bananas[57]. Anti-cancer antibodies expressed in rice and wheat can be useful in diagnosis and treatment of this disease in future[58]. There is a great potential to increase the yield of medicines derived from plants (e.g. salicylic acid) through the use of transgenic technology.

Transgenic crops and the environment

There are a number of ecological and economic issues that need to be addressed while considering the production and deployment of transgenic crops for insect control[59,60]. The most important consideration is the immediate reduction in the amount of pesticides applied for pest control. The number of pesticide applications on a crop such as cotton varies from 10 to 40 and most of the sprays are directed against the key pests such as *Helicoverpa*. In case the transgenic crops are introduced, the number of pesticide applications is likely to be reduced by two-third to half. Reduction in pesticide application would lead to an increase in the activity of the natural enemies, while some of the minor pests may tend to attain higher pest densities in the absence of sprays applied for the control of major pests. The magnitude of these impacts would depend on the diversity of insect species for which the crop serves as the main host[59].

Genetically modified organisms have a better predictability of trait expression than the conventional breeding methods and the use of transgenes is not conceptually different from that of native genes or organisms modified by conventional technologies[61]. The potential of recombinant technologies allows a greater modification than is possible with the conventional technologies and thus might have a greater bearing on the environment.

In diverse agricultural systems such as those prevailing in the tropics, it would be important to understand the biology and behaviour of all the insect species in an ecosystem so that informed decisions can be made as to which crops to transform and the toxins to be deployed. It is also important to consider the resistance management strategies, economic value and environmental impact of the exotic genes in each crop and whether a crop serves as a source or sink for the insect pests and their natural enemies[62]. Several studies have shown that a *Bt* toxin, which is very effective against one insect species, may be weakly active or ineffective against the other insects[63]. Introduction of transgenic crops with insect resistance is expected to reduce the amount and number of pesticide applications. However, greater research effort is needed to identify insecticide molecules that are more effective in combination with the transgenic crops. Introduction of transgenic crops is likely to bring in a qualitative change in our approach to pest control[59]. The most important issues that need to be addressed while considering the deployment of transgenic crops include: (i) development of resistance, (ii) gene escape into the environment, (iii) effects on nontarget organisms and (iv) biosafety of transgenic food.

Development of resistance

Insect pest populations have a remarkable capacity to develop resistance to insecticides. Over 500 species of insects have developed resistance to insecticides[64]. Several species of insects have shown resistance to *Bt* under laboratory and field conditions[13,60]. *Bt*-resistant insect populations in Lepidoptera, Coleoptera and Diptera have been developed under laboratory conditions[65]. In some insect species, the probability of development of resistance may be very low, e.g. *Ostrinia nubilalis*[66]. Development of resistance to *Bt* may not be a serious issue since the *Bt* and insect pests have co-evolved for millions of years[65,67].

Gene escape into the environment

The introgression of transgenes into the wild relatives of plants is a potential concern[68–70]. Genes from plants engineered for herbicide resistance could cross over to other plants, creating super weeds. However, there are no records of a plant becoming a weed as a result of plant breeding[71]. Interspecific hybridization is a common process, but hybrids are rare, and most are sterile and there is very little chance of gene introgression into the wild relatives[72]. The possibility of movement of chloroplast from oilseed rape into wild relatives is very low[73]. The antibiotic gene used as a marker to select for gene transfer may lead to resistance in pathogens infecting human beings. However, methods have been developed for removing selectable marker genes after selection of the transgenics[74,75]. Under laboratory conditions[76], plasmid transfer between *B. thuringiensis* subsp. *tenebrionis* and *B. thuringiensis* subsp. *kurstali* HD 1 (resistant to streptomycin) strains occurs at a frequency of 10^{-2}. However, no plasmid transfer has been observed in soil release experiments. A study conducted by the National Academy of Sciences, USA[77] has concluded that: (i) there is no evidence of hazards associated with DNA techniques; (ii) the risks, if any, are similar to those with conventional breeding techniques; (iii) the risks involved are related to nature of the organism rather than the process; and (iv) there is a need for a planned introduction of the modified organisms into the environment.

Effects on non-target organisms

There are no significant effects of transgenic crops on the honey bees[78,79]. Trypsin endopeptidase inhibitor, bovine pancreatic trypsin inhibitor and soybean trypsin inhibitor have been found to be toxic to adult honey bees at 1% weight : volume in sugar solution[80]. A few of the known predators are specialists on one insect and hence the population of the generalist predators would be maintained on the other insect species in nature[62]. Within-field impact may be greater for parasitoids, which feed only one insect species. The populations of such natural enemies can only be maintained on the nontransgenic crops or other hosts of the target pest. The effect of transgenic crops on the abundance of natural enemies should be compared with the nontransgenic fields of the same crop where the natural enemies would be virtually absent because of heavy pesticide application. No major differences have been observed in the abundance of predators between the transgenic and nontransgenic crops[35,81,82]. However, two spotted ladybirds (*Adalia bipunctata*) fed for 12 days on peach–potato aphids (*Myzus persicae*) colonizing transgenic potatoes expressing lectin gene from *Galanthus nivalis* in leaves have shown a decrease in fecundity, egg viability and longevity[83]. Increased levels of parasitism by *Campoletis sonorensis* have been observed on the transgenic plants compared to the nontransgenic plants[84].

Biosafety of transgenic food

The deployment of *Bt* toxin proteins in transgenic plants does not pose a health risk as the *Bt* toxins are rapidly degraded by the stomach juices of vertebrates. Rats fed on purified cowpea trypsin inhibitor have shown a moderate reduction in weight gain[85]. Level of *G. nivalis* lectin expression that provides insecticidal protection for plants did not reduce the growth of young rats, but showed a negligible effect on weight and length of the small intestine[86]. Therefore, careful thought should be given while considering the deployment of transgenes.

Strategies for resistance management and deployment of transgenic plants

Deployment of transgenic plants should be based on the overall philosophy of integrated pest management and should consider not only gene construct, but alternate mortality factors, reduction of selection pressure and monitor populations for resistance development to design more effective management strategies[59]. This is particularly important when considering food security in the developing world. To increase the effectiveness and usefulness of transgenic plants, it is important to develop a strategy[60] to minimize the rate of development of resistance in insect populations to the target genes through: (i) resistance management; (ii) gene deployment and gene pyramiding; (iii) regulation of gene expression; (iv) development of synthetics; (v) destruction of carryover population and alternate hosts; and (vi) adoption of integrated pest management strategies from the beginning.

Potential benefits of genetically transformed plants

There are many potential benefits of biotechnology for the rural poor in developing countries. Biotechnology may help achieve the productivity gains needed to feed the growing global population. It can help impart resistance to insect pests, diseases and abiotic stress factors, improve the nutritional value and enhance the durability of products during harvesting and storage. New crop varieties and biocontrol agents will reduce the reliance on synthetic pesticides and thus reduce farmers' crop protection costs, benefiting both the environment and public health. Research on genetic modification to achieve appropriate weed control will increase farm incomes and reduce the time farmers need to spend on weeding. Biotechnology would also offer cost-effective solutions to micronutrient malnutrition, such as vitamin A and iron.

Research in biotechnology on increasing the efficiency of utilizing the farm input could lead to the development of crops that use water more efficiently and extract phosphate from the soil more effectively. The development of cereal plants capable of capturing nitrogen from the air could contribute greatly to plant nutrition, helping the poor farmers, who often cannot afford fertilizers. By increasing the crop productivity, agricultural biotechnology could help reduce the need to cultivate new lands and conserve biodiversity. Productivity gains could have the same poverty-reducing impact as the green revolution, if appropriate policies are put into place. There is a need to focus on crops relevant to small farmers and poor consumers in the developing countries.

There will be considerable reduction in insect damage through the deployment of transgenic crops. Transgenic maize containing *Cry 1A(b)* gene reduces the stem borer (*Diatraea* spp.) leaf feeding by 76% (ref. 87). However, this *Bt* toxin is largely ineffective against the fall armyworm, *Spodoptera frugiperda*. Transgenic cotton with *Bt* gene causes 94 and 91% reduction in damage in flowers and bolls, respectively. The reduction in insect damage in the transgenic crop results in 39% gain in cotton-seed yield[22]. Analysis of the economic benefits generated by the use of herbicide-tolerant soybean seed in USA has shown that Monsanto received 22%, while seed companies gained 9% of the benefit. Consumers of soybean and soybean products in the United States and other countries shared 21% of the total benefit, while the farmers obtained 48% of the profits[88]. So far, development of crops has focused largely on the crops and cropping environments of North America. There is an urgent need to use biotechnological techniques to increase the productivity potential of crops that play a major role in the life of the rural poor in the developing countries. In addition to the reduction in losses due to insect pests, the development and deployment of transgenic plants with insecticidal genes will also lead to: (i) a major reduction in insecticide sprays; (ii) reduced exposure of farm labour and nontarget organisms to pesticides; (iii) increased activity of natural enemies; (iv) reduced amounts of pesticide residues in the food and food products; and (v) a safer environment to live.

Host plant resistance (HPR) through the conventional breeding approaches and the transgenic crops reduces the need to apply pesticides and thus is compatible with other components of pest management in an integrated pest management programme. Pesticides are highly toxic to the natural enemies, pollinators and other non-target organisms and result in adverse effects on the environment. Conventional HPR slows down the rate of increase of pest populations and exposes the pests for prolonged periods to the natural enemies[89]. The introduction of transgenic plants brings in a new system of HPR into play, which has a potential to influence the tritrophic interactions[87]. The specificity of *Bt* is such that it was expected to have no direct effects on the natural enemies, although indirect effects such as those from the sick and sub-optimal prey would be expected. Preliminary studies have indicated that there is no adverse effect of transgenic plants on the performance of the natural enemies. However, in-depth studies need to be carried out to characterize their impact on biological control agents in the laboratory involving artificial diets and then in the field involving transgenic plants. The use of insect prediction models can further help in understanding the impact of transgenic plants on the activity and effectiveness of natural enemies in controlling insect pests in conjunction with the transgenic crops.

Limitations

Transgenics are not a panacea for solving all the pest problems. There are some genuine or perceived concerns. The major limitations of transgenic plants are:

- Secondary pests are not controlled in the absence of sprays for the major pests.
- Need to control the secondary pests through chemical sprays will kill the natural enemies and thus offset one of the advantages of transgenic crops.
- Proximity to sprayed fields and insect migration may reduce the benefits of transgenic crops.
- Development of resistance in insect populations may limit the usefulness of transgenic crops.

There is a considerable debate about the risks such as development of resistance in insect pests to *Bt* toxins, harmful effects on beneficial insects and cross-pollination of wild and weedy plants with the novel gene. The evidence on these issues is still inconclusive and warrants careful monitoring before the transgenic crops are deployed on a large scale. The biggest risk of modern biotechnology for developing countries is that technological development may bypass poor farmers because of a lack of enlightened adaptation. It is not that biotechnology is irrelevant, but research needs to focus on the problems of small farmers in developing countries. Private sector research is unlikely to give priority to such crops, given the lack of future profits. Without a stronger public sector role, a form of scientific apartheid may develop, in which cutting-edge science becomes exclusively oriented towards industrial countries and large-scale farming[90]. Successful adoption of green revolution technologies depended largely on access to water, fertilizers and pesticides[2]. As a result, inequality between well-endowed and resource-poor farmers increased because of the properties of the technology itself. Excessive and improper use of chemical inputs also led to adverse environmental impact. A major ethical concern is that genetic engineering and life patents accelerate the reduction of plants, animals and micro-organisms to mere commercial commodities. Therefore, all agricultural activities that constitute human intervention into natural systems and processes need to be assessed carefully.

Regulations for production and release of transgenic plants

The permission for release of modified organisms is given after the risk assessment by the individual countries. Some initiatives have already been taken in this direction by NAS in USA[91] and OECD[92]. International organizations such as UNIDO, UNEP, FAO and WHO have published a voluntary code of conduct for release of organisms into the environment[93].

Regulations for handling and release of genetically modified plants in India

The Department of Biotechnology (DBT), Ministry of Science and Technology, Government of India, has formulated guidelines in 1986 for the release of rDNA in 1990 under the Environmental Protection Act[94]. These include institutional biosafety committees to monitor the research activities at the institute level, review committee on genetic manipulation functioning in the DBT and genetic engineering approval committee of the Ministry of Environment and Forests, that has the authority to permit large-scale use of transgenics at the commercial level. The DBT has set up the rDNA committee to prepare modified draft of guidelines from time to time on the basis of current scientific information and from the experience gained locally and outside the country. In general, the biosafety guidelines deal with the definition of rDNA, classification of pathogenic micro-organisms, containment facilities, biosafety levels, rDNA research activities, large-scale experiments, release of transgenics, import and shipment of rDNA and its products and quality of biological materials produced through rDNA technology.

Risk assessment for the deployment of transgenic plants

There is need for a thorough investigation regarding the fate of modified organisms in the environment and their interaction with the wild relatives and the nontarget organisms[59]. Genetically engineered crops can play an important role in pest management and reduce the amount of pesticide applied for pest control, thus leading to reduction of pesticide residues in food and resulting in conservation of the environment[60]. Therefore, it may be important to go beyond the immediate considerations of their influence on the environment. Production and release of transgenic plants should be based on experience and there is a need to streamline and harmonize the regulatory requirements for deployment of genetically engineered micro-organisms and plants for pest management. The promise of biotechnology for increasing the production and productivity of crops for sustainable crop production has been dimmed by the intrinsic safety of the transgenic organisms and evolution of resistant strains of insects. Social and environmental groups have raised a hue and cry about the real/conjectural effects on the nontarget organisms[30]. In the developed countries, biotechnology is seen to be of strategic importance for increasing the share of world market. However, there are serious concerns about the introduction of this technology in several countries.

The focus of biosafety regulations should be on safety, quality and efficacy[95]. Data required for risk assessment include (i) organization and the people involved; (ii) DNA donor, the receiving species, and the transgenic plant; (iii) target environment and the conditions of release; (iv) transgenic plant and environment interaction; and (v) monitoring, control and waste treatment.

General information includes the institution and the people involved in development and the people/ organizations to be responsible for field containment, monitoring and waste treatment. DNA donor and receiving species include complete information about the donor and the receiving species. Information is also needed on the vector and antibiotic or herbicide resistance genes used as a marker. The receiving plant species forms the baseline with which the transgenic plant should be compared. The risk to the environment includes harmful effects on the beneficial nontarget organisms. It is important to describe the invasiveness of the transgenic plant in the wild habitat, ability to propagate sexually/asexually, possibility of transferring the transgene to the same or related species or to micro-organisms and the consequences of gene transfer. Once the transgenic plants are released into the environment, there is a free movement of pollen, seed and the plants outside the immediate environment of release. It is important to monitor the transgenes in the environment after the release and the efficiency with which it is possible to destroy the plant material. Detection of the transgenic plants and the transgene in the nontarget species can be done by visual markers (e.g. *b*-glucorinidase) or a selectable marker (e.g. antibiotic resistance or molecular analysis, e.g. PCR and Southern hybridization). The following issues need to be addressed while considering the deployment of transgenic plants:

- Care should be taken that the release of transgenic plants does not give rise to new pest problems or emergence of new biotypes of the target pest and whether the transgenic technology possess greater risk than the traditional alternatives[96,97].
- In case of gene transfer to the wild relatives, will it lead to expansion of the niche of the species and result in suppression of diversity in the surrounding areas?
- Will the introduction of transgenic plant result in an increase in the land use for agriculture, where agriculture could not be practised earlier, i.e. bringing valuable natural ecosystem under agriculture?

The risk assessment should be standardized for the plants new to the environment. Most nations already have procedures for development and release of new crop varieties. Although these procedures were primarily based on agronomic performance, the same can be used as a model for a more formal risk assessment to investigate the potential environmental impact of transgenic plants. In world agriculture, if the developing countries have to benefit from the transgenic technology, it is important to promote capacity building and risk management including: (i) scientific and technical team research; (ii) strengthen the infrastructure; (iii) monitor short- and long-term effects of transgenic plants; and (v) develop simple techniques to distinguish transgenic and nontransgenic plants.

Socio-economic issues and biotechnology

Genetic homogeneity enhances genetic vulnerability to biotic and abiotic stresses. Biotechnology companies are therefore recommending resistance management strategies, such as growing 30 to 40% non-*Bt* corn with *Bt*-corn. This has serious implications for the livelihood of small and marginal farmers operating with institutional credit. If transgenic crops are affected by serious diseases as a result of the breakdown of resistance, there will be a catastrophic effect on the lives of poor farmers. The companies will have to agree to compensate them for the crop loss. This problem could become even more serious if companies incorporate genetic use restriction mechanisms, popularly known as ‘terminator gene’ in the new crop varieties. Farmers will have to purchase the new seeds each year. The other dimension is equity in benefit sharing between biotechnologists and the primary conservers of genetic resources and the holders of traditional knowledge. The primary conservers have so far remained poor, while those who use their knowledge (for example, the medicinal properties of plants) and material have become rich. This has resulted in accusations of biopiracy. It is time that molecular biologists and others find ways to implement genuine biopartnerships with the holders of indigenous knowledge and traditional conservers of genetic variability, based on principles of ethics and equity in benefit sharing. Unless research and development efforts on transgenics are based on principles of bio-ethics, there will be serious public concerns about the ultimate nutritional, social, ecological and economic consequences of replacing local varieties with a few, new genetically improved crop varieties. Bulk of modern agricultural biotechnology research is undertaken by the private sector, which protects intellectual property rights (IPR) through patents that extend beyond the first release of transgenic crops. Farmers, therefore, cannot legally plant or sell the seed of patented cultivars without the consent of the patent holder. However, monitoring and enforcing contracts that prohibit large numbers of small farmers from using the crops they produce as seed would be expensive and difficult.

Public perceptions about biotechnology are not based on fact and there is a tendency to over-emphasize the risks to gain public attention[59]. Also there is a risk of modern science bypassing the needs of rural poor as a result of the patenting regime adopted by the multinational companies and the negative role played by the environmental groups. Research in progressive biotechnology should be integrated with appropriate policies and conventional breeding. The benefits and the risks associated with the use of biotechnology to increase agricultural production need to be presented to the general public in a balanced manner and concern for moral and ethical issues of relevance to different societies need to be addressed. Public trust in the application of biotechnology for increasing and stabilizing agricultural production needs to be improved to use modern science for the benefit of the rural poor.

Future outlook

The use of crop protection traits through transgenics will continue to expand in future and gene pyramiding will become very common, which may be related to genetic transformation with two or more genes against the same trait or different traits. There will be considerable emphasis on agronomic traits such as fertilizer-use efficiency, stress tolerance, photosynthetic efficiency and grain yield and quality. This approach of controlling insect pests and diseases would offer the advantage of allowing some degree of selection for specificity effects, so that pests, and not the beneficial organisms are targeted. Research on agricultural biotechnology can contribute to food security in developing countries provided it focuses on the needs of poor farmers and consumers. It is also important that biotechnology be viewed as a component of comprehensive poverty alleviation and it needs to go hand in hand with investment programme in agricultural growth. Public sector research, particularly through partnerships between the International Agricultural Research Centres (IARCs) and National Agricultural Research Systems (NARS), is essential for ensuring that molecular biology-based science serves the needs of the rural poor. It is important that internationally-accepted biosafety standards and local regulatory capacity be strengthened within developing countries. Open debate about the issues involved is essential to present the benefits and the risks associated with the deployment of transgenic crops to the general public in a balanced manner. If appropriate steps are not taken, modern biotechnology could bypass poor people and opportunities for reducing poverty, food insecurity and malnutrition will be missed. Hence, it is important to undertake urgent steps to use biotechnology for improving the livelihood of the rural poor.

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Indian rice varieties released in countries around the world

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In India, rice is grown under diverse ecosystems as rainfed uplands, rainfed shallow, semideep and deepwater lowlands, irrigated lands and hills. These are the major rice ecosystems found the world over. The model cooperative all-India coordinated rice-testing programme evolved at Hyderabad during 1965 helped the country to reach and sustain self-sufficiency in rice from 1977. The International Rice Research Institute at the Philippines built a global rice-testing programme in 1975 based on the successful AICRIP model. Other countries have also benefited through release and commercial exploitation of India-bred rice varieties.

IN India rice is cultivated in 42 million hectares (mha) under four major ecosystems, viz. irrigated (19 mha), rainfed lowland (14 mha), flood prone (3 mha) and rainfed upland (6 mha) ecosystems. Rice ecosystems in India represent 24% of irrigated areas, 34% of rainfed lowlands, 26% of flood-prone areas and 37% of rainfed uplands cultivated to rice in the entire world[1]. No other country in the world has such diversity in rice ecosystems. Therefore, Indian rice research programme is the principal moving force in the world.

All-India Coordinated Rice Improvement Project (AICRIP)[2] was started in 1965 at Hyderabad under Indian Council of Agricultural Research to usher in green revolution. The coordinated variety improvement and testing programme covers 52 cooperating centres in addition to 51 voluntary centres in different agro-climate regions in the country. This programme helps to exchange and evaluate breeding material quickly across the country.

The aim of AICRIP programme is to improve yielding ability, increase efficiency in the use of external inputs and incorporate resistance to biotic and abiotic stresses. The multilocational testing of breeding stock developed at different research centres is organized by AICRIP. The evaluation of genotype x environment interactions in different ecosystems has been the rationale for the multidisciplinary approach to rice improvement research. Depending on genotype sensitivity to photoperiod, three to four years are needed to identify a promising superior genotype based on data from the

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