Agricultural Biotechnology and Poverty:
Can the Potential Be Made a Reality?[1]

by

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The challenge for developing country agriculture in the next 25 years is enormous, particularly if it is not only to satisfy the growing effective demand for food, but also to help reduce poverty and malnutrition, and to do it in an environmentally sustainable fashion. Due to population growth and rising incomes, demand in the developing countries is predicted to increase by 59% for cereals, 60% for roots and tubers, and 120% for meat (Pinstrup-Andersen, Pandya-Lorch, and Rosengrant, 1997). This increased supply cannot come from area expansion since that has already become a minimal source of output growth at a world scale, and has become negative in Asia and Latin America. Neither can it come from any significant expansion in irrigated area due to competition for water with urban demand and rising environmental problems. While it will thus need to come from growth in yields, the growth rate in cereal yields in developing countries has been declining from an annual rate of 2.9% in 1967-82 to 1.8% in 1982-94, which is the rate needed to satisfy the predicted 59% increase in cereals over the next 25 years. The growth in yields cannot consequently be let to fall below this rate in developing countries without increasing the share of food consumption that is imported. With 1.3 billion people in absolute poverty (earning less than $1 per day) and 800 million underfed in the developing countries (World Bank, 1999), agriculture should also have a major role to play in poverty reduction, particularly since three quarters of these poor and underfed live in the rural areas where they derive part if not all of their livelihoods from agriculture as producers or as workers in agriculture and related industries. The real income of poor consumers also importantly depends on the price of food.

If poverty is to fall and the nutritional status of the poor is to improve at the current levels of food dependency, the growth rate in yields will have to increase and these increases will have to occur in part in the fields of poor farmers and will have to generate employment opportunities for the rural poor. Since the growth rate in yields achieved with traditional plant breeding and agronomic practices has been declining, the next phase of yield increases in agriculture will likely have to rely importantly on the new scientific advances offered by biotechnology. Yet, while biotechnology has made impressive progress in the agriculture of some of the more developed countries, it has had little impact in most developing countries, and particularly in the farming systems of the rural poor. The objective of this paper, therefore, is to explore under what conditions could the current biotechnological revolution in agriculture be helpful for reducing poverty in developing countries. Failure to capture this potential would further increase the income gap between developed and developing nations and would be a serious setback in the struggle to reduce poverty.

I. World poverty and the role of agricultural technology: direct and indirect effects

1.1. How do direct and indirect effects differ?

As demonstrated by the experience of the Green Revolution, which led to a doubling or tripling of yields for the major staple foods in the mid-1960s, technological change in agriculture can be a powerful force in reducing poverty. In their review of the social benefits of the Green Revolution, Lipton and Longhurst (1989) enthusiastically concluded that: "Indeed, if social scientists had in 1950 designed a blueprint for a pro-poor agricultural innovation, they would have wanted something very much like the

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Modern Varieties: labor-intensive, risk-reducing, and productive of cheaper, coarser varieties of food staples". The way this aggregate result comes about is, however, a complex phenomenon and there are typically both winners and losers among the poor. Hence, using the technology instrument as part of a strategy for poverty reduction requires careful ex-ante analysis of the nature of technology and typically a set of interventions complementary to the release of technology to maximize beneficial effects and mitigate social costs. Since biotechnology has features distinct from those of the Green Revolution, not just in terms of what it can do in the field but also where it comes from and under what conditions it reaches farmers, it is important to analyze the specific potentials and risks which it offers for poverty reduction if it is to be used effectively for that purpose.

There are two channels through which technological change in agriculture can act on poverty. First, it can help reduce poverty directly by raising the welfare of poor farmers who adopt the technological innovation. Potential benefits can be through increased production for home consumption, more nutritious foods, higher gross revenues from sales deriving both from higher volumes of sales and higher unit value products, lower production costs, lower exposure to yield risks, lower exposure to unhealthy chemicals, and improved natural resource management.

Second, technological change can also help reduce poverty indirectly through the effects which adoption, by both poor and non-poor farmers, has on:

- The price of food for consumers.
- Employment and wage effects in agriculture.
- Employment and wage effects in other sectors of economic activity through production, consumption, and savings linkages with agriculture (Adelman, 1975), lower costs of agricultural raw materials, lower nominal wages for employers (as a consequence of lower food prices), and foreign exchange contributions of agriculture to overall economic growth.

Through the price of food, indirect effects can benefit a broad spectrum of the national poor, including landless farm workers, net food buying small holders, non-agricultural rural poor, and the urban poor for whom food represents a large share of total expenditures. Indirect effects via employment creation are important for landless farm workers, net labor selling small holders, and the rural non-agricultural and urban poor. Hence, the indirect effects of technological change can be very important for poverty reduction not only among urban households, but also in the rural sector among the landless and many of the landed poor.

There has been an active debate among development economists about the relative importance of the indirect and direct effects of technological change in reducing poverty. The problem emerges if the technologies used to achieve these two effects are not the same, implying trade-offs in the allocation of public research budgets or biases in the impact of privately released technologies. If there are tradeoffs, using technology to fight small holder poverty at the cost of a lesser aggregate gain in productivity may lower total poverty reduction. Thus, Alston, Norton, and Pardey (1995) argue that the main benefit of agricultural technology is through greater food availability and a lower price of food. According to them, research should consequently focus on generating the greatest aggregate output gain, while concerns for poverty reduction among small holders should be achieved through other instruments.

When are there trade-offs between direct and indirect effects? Within a given agro-ecological environment, if land is unequally distributed and if there are market failures, institutional gaps, and conditions of access to public goods that vary with farm size, then optimum farming systems will differ across farms. Small farmers will typically prefer farming systems that are more labor intensive and less risky while large farmers would prefer farming systems that are more intensive in capital and they can afford to assume risks. In this case, unless land was equally distributed (countries like Burkina Faso or Taiwan with generalized small holder agriculture), heterogeneity of farming systems prevails and there are typically trade-offs between indirect and direct effects. The more unequally land is distributed and the more market failures are farm size specific, an in Latin America, the sharper the trade-off.

Note that the degree of tradability of commodities benefiting from technological change is key in determining the relative importance of direct and indirect effects. With non-tradables, falling prices extract the net social gains from technological change to the benefit of rural and urban consumers. However, even in an open economy where the price of food is internationally determined, indirect effects are important through the multiple roles of agriculture in economic development. In this case, larger effects may be obtained through technological change in the production of cash crops for exports. Hence, once an economy is open and goods are internationally traded with low transactions costs, technological change in high value crops may have larger indirect effects than production of staples that can be acquired cheaply on the international market. What matters, in this case, is to carefully identify the role of agriculture as a source of aggregate income growth (Winters, de Janvry, Sadoulet, and Stamoulis, 1998) and how aggregate income growth translates into poverty reduction by mechanisms that will generally be other than through the price of food.

1.2. Differential incidence of direct and indirect effects across poor households

As world population is becoming increasingly urbanized, the role of technological change in reducing aggregate poverty correspondingly evolves from direct to indirect effects. Yet, it is striking that the share of rural in total poverty remains so high. As the data in Table 1 show, for the countries with available information, rural poverty accounts on average for 63% of total poverty, reaching 90% or more in populous countries such as China and Bangladesh and 76% in India. This is in part due to the fact that the incidence of rural poverty is much higher than the incidence of urban poverty. On average across countries in Table 1, the incidence of rural poverty is 53% higher than that of urban poverty. It is only in some of the Latin American countries that the urban poor are the majority (e.g., 65% in Mexico, 73% in Brazil, and 89% in Venezuela), stressing the inevitably dominant role of indirect effects in these countries. In the rest of the world, and in many of the Latin American countries as well, the rural sector remains the main reservoir of poverty. Data on extreme poverty would accentuate the relative importance of the rural sector in total poverty even more. Reducing rural poverty should expectedly require both direct and indirect effects. The question which we need address is how much of rural poverty can be attacked via direct versus indirect effects. We turn for this to a characterization of the sources of income for the rural poor.

As the data on sources of income in Table 2 show, even for poor farm households, off-farm incomes (which include agricultural wage income) are a very important source of income, averaging 55% in the countries listed in Table 2. In Nicaragua, households on the 45% smallest farms derive 61% of their income off-farm. In Mexico, in the ejido sector, households on the 57% smallest farmers derive 76% of their income off-farm. In Chile, the 60% poorest farm households derive 67% of their income from off-farm activities. Off-farm incomes are even more important among poor rural households than among poor farm households. As examples, the 60% poorest rural households derive 80% of their income from off-farm activities in El Salvador and 86% in Ecuador. The poorest 50% derive 68% of their income from off-farm activities in Panama and 50% in Pakistan. The average for countries listed in Table 2 is 68%. Hence, indirect effects have to be very important for the rural poor, including the landed poor.

Among off-farm sources of income, wage employment in agriculture tends to be important for the rural poor, both landless and landed, particularly where land is more unequally distributed as in Latin America. Among rural households, the poorest 60% derive 45% of their total income from wage labor in El Salvador and 54% in Ecuador. Hence, for technological change in agriculture to be poverty reducing, employment creation has to be a key feature. Technological change that is massively labor-saving (e.g., mechanization and herbicides) is likely to have adverse effects on rural poverty (The Nuffield Foundation, 1999).

If the farming systems of poor small holders differ from those used in commercial farming, direct effects require technological advances in crops and with traits that concern small holders. Hence, to anticipate what crops and traits should be targeted for direct poverty reduction, we need to characterize the specificity of small holder agriculture by contrast to commercial farming. As producers, these small holders are highly heterogeneous, combining in various forms the following assets (exogenous variables) that determine the scope of their options:

Land assets

Small farm size, lack of reliable water for irrigation, often incomplete property rights (squatters, open access resources, common property resources).

Productive capital assets: low stocks of tools, equipment, and animals.

Human assets

Frequently, large family labor endowments.

Family labor costs advantages as they can avoid moral hazards associated with hired labor and transactions costs on labor markets.

Low human capital endowments, low educational levels.

Institutional assets

Formal credit constraints due to lack of collateralizable assets, but potential access to local credit on the basis of locally shared information and social collateral (family and friends, money lenders, group lending, village banks).

Lack of access to formal insurance (lack of access to local information for formal providers of insurance leads to moral hazards and adverse selection), but potential access to mutual insurance networks (with problems of covariate risks) and pseudo-credit (contingent interest-free loans).

Low access to extension and information.

High transactions costs in accessing markets (resulting in low effective prices when selling products and factors, and high effective prices when buying).

Social assets

Often members of traditional corporate communities, with both advantages (mutual insurance, contingent loans, information sharing, labor exchanges) and disadvantages (conformism, pressures on successful entrepreneurs to share gains). These communities are typically constituted of large numbers of small holders with weak access to outside information, limited infrastructure, and low educational levels, making the introduction of new community rules (such as on biosafety as we shall see later) particularly difficult.

Public goods assets

Often located in regions with poorly developed infrastructure and poorly developed public services. Lack of political clout to access public services.

Regional assets

Often located in marginal lands where soil fertility is low and exposure to risks high.

Often located in small agro-ecological niches with limited supply of technological options (small market size) and low effective demand for technological innovations.

As a consequence of heterogeneous asset positions, small holders tend to have highly diversified patterns of behavior (endogenous variables). For the potential role of technological change in reducing poverty directly, this has several implications:

i) Low income and low liquid asset positions imply high risk aversion and high discount rates in inter-temporal choices.

ii) Because sources of income are multiple (pluricativity), and farming systems diversified, technological change in any one crop will have overall effects on household income that are small.

iii) High heterogeneity implies small domains of application for any technology and the need for a broad array of technological options, making costly the use of technology as a direct instrument for poverty reduction.

Finally, in weighting the relative role of direct and indirect effects in poverty reduction, we need look at the consumption side as well. Many small holders are net buyers of food. Hence, they will benefit from indirect effects through lower food prices created by technological change in the fields of other producers, small and large. A number of others are self-sufficient, and hence unaffected by the fall in price that may be induced by the diffusion of technological change. Data for Nicaragua (Davit et al., 1998), Mexico (de Janvry, Gordillo, and Sadoulet, 1997), and Southeastern Senegal (Goetz, 1992) show the following distribution of households among net buyers, self-sufficient, and net sellers:

Percentage of farm households	Corn Nicaragua	Beans Nicaragua	Corn Mexican ejido	Coarse grains SE Senegal
Net buyers	23	28	27	37
Self-sufficient	30	30	32	19
Net sellers	39	37	28	34
Sellers and buyers	9	5	13	10

As net buyers, 23 to 37% of the farm households in these three countries will benefit from indirect effects of technological change through the price of grains.

1.3. Measuring the relative importance of direct and indirect effects

Quantifying the relative magnitudes of the direct and indirect poverty reduction effects of technological change is quite difficult as these effects are interrelated and depend on both the structure of the economy and the nature of the technological change. Because general equilibrium effects are involved, we use a computable general equilibrium (CGE) model for archetype economies representing poor countries in Sub-Saharan Africa, Asia, and Latin America (Sadoulet and de Janvry, 1992). These archetype economies are not designed to represent an entire region or to be a sample of countries in the region, but rather to characterize a set of countries in the region with similar structural characteristics.[2] The model used in this paper is a standard neoclassical CGE model in which agents respond to relative prices as a result of profit maximizing and utility maximizing behavior in determining levels of production and consumption, and markets reconcile endogenous supply and demand decisions with adjustments in relative prices.

CGE models are homogenous of degree one in all prices and nominal values. Hence they can only solve for relative prices and not for an absolute level of prices. This requires that a numeraire be chosen. Note that the choice of the numeraire does not affect any real value obtained from the simulation, in particular the real income effect of technology, but it does affect the allocation between direct and indirect effects. Technological change in agriculture is expected to induce a decline in agricultural prices relative to non-agricultural prices, in particular because of the increased income and demand for non-tradable sectors of the economy. If at one extreme the numeraire is an index of non-agricultural prices, then the relative price change is read as a decline in the agricultural price, leading to important positive indirect effects on real incomes and probably very low or even negative direct profit effects in the agricultural sector. If, on the other hand, the numeraire is close to the agricultural prices, relative price changes are read as an increase in non-agricultural prices, leading to high direct effect and negative indirect effect. We chose for numeraire the nominal exchange rate, so that all results can be read in dollar terms, and the decomposition that we report in the tables reflects changing prices relative to the dollar price of the commodities.

A second issue with respect to the division between direct and indirect effects, is the allocation of self-employment on farm and homegrown consumption of food. Although self-employment of family labor on farm responds to the external wage when the labor market works, we will consider it as part of the

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[2] The archetypes were built on the basis of aggregate information for a set of low income food importing countries in the three continents, and social structure coming from Social Accounting Matrices from Kenya for the Africa Archetype, Sri Lanka for the Asia archetype, and Ecuador for the Latin America archetype. The Africa archetype represents the following countries: Benin, Burkina Faso, Central African Republic, Ethiopia, Ghana, Guinea, Kenya, Lesotho, Liberia, Madagascar, Mali, Mauritania, Mozambique, Rwanda, Senegal, Sierra Leone, Somalia, Sudan, Tanzania, Togo, and Zaire. The Asia archetype represents: Bangladesh, Sri Lanka, Pakistan, Philippines, Papa New Guinea, China, and India. The Latin America archetype represents: Brazil, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, El Salvador, Guatemala, Honduras, Jamaica, Mexico, Nicaragua, Panama, and Paraguay.

direct effect of technological change on the farm income. Regarding home consumption, assume for a moment that the household is self-sufficient in food, so that production and consumption of the agricultural product are equal. Then a decrease in the agricultural price, which in fact does not affect the welfare of the household, appears as a negative direct effect on agricultural profit and a positive indirect effect from the decline in the consumer price. To avoid this artificial accounting, we therefore impute the change in value of the initial home consumption of own production to the direct effect. Hence only the decline in the value of what is sold by net sellers is counted as a direct loss and only the decline in price of what is purchased by net buyers is counted as an indirect price effect.

In summary, we measure welfare effect by real income, which is nominal income y divided by a household idiosyncratic consumer price P. Nominal income of a given household can be divided into profit income in agriculture and other income:

$$W = \frac{y}{P} \text{ and } y = (p_a^q q_a - x_a) + y_{-a},$$

where p_a^q, q_a, x_a and y_{-a} are the producer price, the production level, the cost of agriculture, and the non-agricultural income of the household, respectively. The three components of the welfare effect of technological change reported below are:

- Direct effect: $\left(p_a^q q_a - x_a\right) - \left(p_a^{qo} q_a^o - x_a^o\right) + \left(p_a^q - p_a^{qo}\right)\min(c_a^o, q_a^o) + (wL - w^o L^o)$
- Indirect income effect: $y_{-a} - y_{-a}^o - (wL - w^o L^o)$
- Indirect price effect: $y\left(1 - \frac{P^o}{P}\right) - \left(p_a^q - p_a^{qo}\right)\min(c_a^o, q_a^o)$

where c_a, w, and L are consumption of agricultural product, wage, and on farm self-employment, and the subscript ^{o} refers to the value of variables before the technological change. The direct effects include the change in agricultural profit, the changing opportunity cost of home consumption of own production, and the change in self-employment on own farm. The indirect income effect comes from changes in nominal income from all sources other than own agricultural production. The indirect price effect comes from the change in prices, excluding the effect through the opportunity cost of home consumption.

In Table 3, we present the main features of the archetype economies. The three archetypes have similar aggregation schemes. The sectoral aggregation includes three agricultural sectors (export crops, cereals, and other agriculture), food processing, industry, trade-and-services, and administration in the African and Asian archetypes, and two agricultural sectors (export crops and other agriculture), minerals, industry, trade-and-services, and administration in Latin America. The definition of social classes is adapted to the individual contexts. While in Africa rural households are classified in three farm sizes, Asia has a large class of rural landless, and two farm sizes, and Latin America has three farm sizes. As we do not have income distribution within the class and therefore cannot count the number of poor in each class, we define rural poverty as including the two poorest rural classes in Africa and Asia, and only the poorest farm size in Latin America. The urban poor include the low-education urban population in the three archetypes. Poverty levels are thus not comparable from one archetype to another, since they are largely dependent on the aggregation scheme. However, for analyzing changes in poverty as a consequence of technological change, comparisons across experiments and across archetypes are interesting. The Sub-Saharan African economies are remarkable for the large share of agriculture in GDP (47%), and hence the potential aggregate growth effects derived from technological change in agriculture. The share of the three sectors in agricultural value-added are 28% for the export crops, 45% for cereals, and 27% for other agriculture that includes mainly non-tradable livestock. While the export crops sector is highly tradable, the other two are not due to the specificity of these crops. The share of rural households in total household income is high (61%) and the share of poor rural households in total rural income is even higher (65%). Poverty is largely rural, with the share of rural households accounting for 64% of the total income accruing to poor households. For the rural poor, income derived from agriculture is 67% of total income, with the remaining 32% derived from wage earnings. For them, agricultural commodities are a large share (72%) of total consumption. The agricultural sector is smaller in Asia than in Africa, and even smaller in Latin America where it only accounts for 13.6% of GDP. The size of the diversified "other agriculture" sector also increases drastically from the African to the Asian and the Latin American archetype. The share of labor in agricultural value-added is not comparable between the archetypes. Because the casual labor market is very shallow in Africa, family labor has been included as a fixed factor and its contribution accounted for in profit income. By contrast, since labor markets in Asia and Latin America are active, family labor contribution is valued at its opportunity cost on the labor market and accounted for separately. Cereals in Asia are highly tradable, which means that their price is essentially determined by the world price and the exchange rate, and not influenced by domestic production. Although, as mentioned above, poverty levels are not strictly comparable across archetypes, note, however, that Latin American poverty is largely urban, as opposed to what is seen in Asia and Africa. Another important contrast between these economies is the importance of income diversification for rural households with on farm income (including family labor) decreasing from 67% in Africa to 25.6% in Asia, and to a low 16.4% in Latin America. This immediately indicates that direct effects have a substantially lower potential in Asia and Latin America than in Africa. Finally, while in Africa the rural poor spend 72% of their budget on agricultural commodities, this share declines to 40.2% and 13.7% in Asia and Latin America, respectively. This is partly due to the higher income level (in Latin America) and the relative importance of product transformation and hence consumption of goods from the food processing sector rather than agriculture directly. Note that in Africa and Latin America, all consumption of agricultural commodity is home produced, while in Asia, with a large class of landless, the poor only produce 67.3% of their consumption of agricultural commodities. Hence there is no indirect food price effect on the rural poor of Africa and Latin America.

Table 4 reports the impact of different scenarios of technological change simulated in the African archetype. A 10% increase in total factor productivity due to technological change in all crops creates income gains for both urban and rural households. Note that consumer price effects are small and negative for all poor. This comes from the increase in price of non-tradable sectors of the economy that more than compensates for the decrease in food prices (-6%) in consumption baskets. For rural households, the share of income gains that comes from direct effects is 77.1% and from indirect effects 22.9%, with almost half of the direct effect derived from home consumption of production. This imbalanced outcome between direct and indirect effects comes from the peasant structure of the sector. The sectoral distribution of gains from technological change for the poor is 75% captured by the rural poor and 25% by the urban poor. Technological change in agriculture is thus very effective for the rural poor, mainly through direct effects.

Targeting technological change on cereals, which have low tradability, creates a sharper decline in price (-12%). This decline in price is transmitted to the food processing sector (mills and bakeries) which then benefits consumers at large. At the same time, since the cereals sector is a small 13% of the economy, the aggregate effect on GDP is only 2.9% growth. As a result, the urban poor benefit essentially from lower food prices and not from general growth effects. Income gains for the rural poor are almost exclusively captured through benefits in home consumption, since the drastic decline in the price of cereals negatively affects their marketed surplus. The negative price effect on rural income is even sharper when technological change is focused on other crops due to the larger marketable surplus in that sector with low tradability. In this case, it is the urban poor that capture a majority of the income gains (64%), with the rural poor only receiving 36% of the gains.

Finally, we can target technological change on either small or large (or all) farmers through rural development interventions. Targeting technological change on the rural poor gives rise to an aggregate growth effect of similar order of magnitude as an untargeted technological change since they control almost 75% of total agricultural value-added. However, this raises direct effects and decreases indirect effects as prices decline less and employment effects are also less than if large farmers were involved. If technological change is targeted on the large farmers, direct effects on the rural poor are negative. Indirect effects are their only source of real income gains. As a consequence, the urban poor are the main beneficiaries, capturing 68% of the income benefits to the poor. In Africa, rural development interventions to make poor farmers participate to technological change are thus important for rural poverty reduction since indirect effects through large farmers' adoption never compensate for their loss of direct effects if they are excluded.

A selected number of simulations with the Asian and Latin American archetypes are reported in Table 5 to illustrate contrasts brought about by differences in the structure of the economies. An increase in total factor productivity in Asia produces a lower decline in food prices than in the other two regions, largely due to the greater tradability of the agricultural sectors. This decline is not sufficient to compensate for the increase in other prices induced by aggregate growth and hence the indirect price effect on poverty is negative. However, employment effects due to the increase in agricultural production creates strong income gains for the large landless group, so that indirect effects account for 63% of total income effects on the rural poor despite the negative price effect. In Asia, the employment effect of technological change is thus key in reducing rural poverty. For the urban poor, indirect effects on the cost of living are similarly negative and they only benefit from non-agricultural effects brought about by the general growth in the economy. At the aggregate level of all poor, direct effects on poverty only account for 26% of the increase in real income of the poor, while the rural poor capture 72% of all benefits accruing to the poor, which is somewhat lower than their 78% share of poverty. The same technological change in Latin America produces very different outcomes. There, the urban poor capture the bulk of the increase in real income, with 70% of all benefits, which is similar to their share in poverty (73%). Consumer price effects are strongly negative for both the rural and urban poor, driven by an increase in other prices, and employment effects are also stronger than in the other two economies. In the aggregate, indirect effects account for 86% of the total effect on the real income of the poor. In Latin America, with high levels of urbanization and rural poor households highly dependent on off-farm income sources, the indirect effects of technological change are thus largely dominant.

The last two columns of Table 5 illustrate an interesting counterintuitive result whereby poor rural households benefit more from a technological change targeted to non-poor rural households than if it were targeted to themselves. This comes from the fact that: 1) the non-poor represent a large class controlling more than 65% of agricultural production and 2) the rural poor depend for 63% of their income on off-farm labor employment. Hence, despite a larger increase in aggregate consumer price and a negative direct effect on the agricultural income of the rural poor, the aggregate effect on rural poor is larger than if the technology was targeted to their land assets. For the urban poor too, employment effects largely compensate for the negative effect on aggregate price.

We conclude by observing, first, that the relative role of direct and indirect effects depends on the structure of the economy. Direct effects are important in reducing aggregate poverty in an economy that is as agrarian and rural as the African, but less so in Asia which has a large class of rural landless households and even less in Latin America where the poor are largely urban and even the rural poor have highly diversified sources of income with a high share of off-farm incomes. Second, results show that the targeting of technological change across crops and types of households is far from neutral. To maximize direct income benefits, technological change needs to focus on small farmers' crops that are maximally tradable to avoid falling price effects. Targeting the benefits of technological change on small holders mitigates price declines and thus raises direct benefits to them. In Africa, designing technological change for small farmers production systems and assisting their diffusion among small holders through rural development interventions are thus key to aggregate poverty reduction. In the case of Latin America, indirect benefits derived from technological change in the fields of large farmers are greater than direct effects derived directly from a technological change that would target their own farms. In this case, maximizing the aggregate productivity effects of technological change is the best approach to poverty reduction, both rural and urban, vindicating, at the level of social aggregation used in this model, the position of Alston, Norton, and Pardey. Finally, designing technological change for maximum employment creation in agriculture is important for poverty reduction in Asia where the landless account for an important share of total poverty.

1.4. Implications for the role of technology in poverty reduction

We thus conclude by observing that technological change in agriculture can serve as an instrument for poverty reduction, but that the distribution of these gains between direct and indirect effects, and hence across households in poverty, is highly dependent on the structure of the economy, on the structure of poverty, on the focus of technological change by crops and farming systems, on complementary rural development programs to target diffusion on specific social sectors, and on policy interventions in price formation (degree of tradability). How to best use the technology instrument for poverty reduction thus depends on each particular context. We found that employment creation in agriculture, the design of improved small farmer production systems, and aggregate productivity effects will be the dominant instruments for poverty reduction according to particular contexts. In all cases, hence, the optimum balance between these three effects needs to be determined. The allocation of budgets to research, particularly when small holder farming systems differ from those of commercial agriculture and when labor-saving technological options are available, needs to be adjusted to each particular situation.

II. The potential of biotechnology for poverty reduction

The early phase of the Green Revolution (1965-75), consisting in the introduction of semi-dwarf varieties of wheat and rice, fundamentally focused on raising yields of open-pollinated seeds. These varieties were selected to be responsive to high intakes of fertilizers under irrigation. Because they were highly susceptible to pest infestations (Byerlee, 1996), they required extensive spraying of chemicals. Hence, the new varieties were most readily adoptable by farmers located in the best-endowed regions, with good market integration, easy access to credit, and sufficient ability to bear risks. The main poverty reduction effects were thus indirect, through lower staple food prices and higher employment opportunities in agriculture and related activities. Direct effects were small and sometimes negative as prices fell for non-adopters (usually the smaller farmers) and bypassed areas (usually the more marginal areas) (Scobie and Posafa, 1978; Lipton with Longhurst, 1989).

The second phase of the Green Revolution (1975-present) sought to consolidate and extend these yield gains by diversifying research in the pursuit of a wide range of traits desirable for the less well endowed areas and for the small holders. Continued yield gains were sought by increasing the productivity of factor use, rather than applying higher doses of chemicals and water. The number of high yielding varieties of a particular crop was broadened to extend the geographical range of applicability to specific ecosystems and raise spatial genetic diversity. New traits included resistance to pests and diseases and tolerance to stress. This allowed to reduce the variance of yields. Shorter growing season allowed multiple cropping and reduced exposure to risks. The area of applicability was extended toward rainfed and marginal areas. As shown by Byerlee and Moya (1993), diffusion of HYV in rainfed areas caught up with diffusion in irrigated areas. The lag in spring wheat varieties for an 80% rate of adoption between irrigated and rainfed areas was 5 years in Argentina, 13 years in Pakistan, and 15 years in Syria. The range of crops was also widely broadened toward crops suited for marginal environments and consumed by poor people in tropical and semi-tropical environments such as pearl millet, sorghum, and cassava. The quest for traits additional to yield, in particular traits desirable for poor farmers and improved natural resource management, was thus the trademark of the second phase of the Green Revolution. As a consequence, direct effects on poverty reduction were significantly enhanced.

The advent of biotechnology offers the possibility of amplifying these achievements of traditional breeding for three reasons:

(1) Acceleration of the pace of research through use of selectable gene markers, promoters, and new scanning devices.

(2) Cheapening of research due to productivity gains in research.

(3) Broadening of the spectrum of potential products and traits through genetic engineering (recombinant DNA techniques, insertion of genetic materials) of plants and animals: wide crossings (transfers of genes from wild relatives of the crop) and transfers of foreign genes.

Biotechnology offers a range of applications to agriculture that include: (1) plant tissue culture, cellular approaches, and animal reproduction techniques such as artificial insemination; (2) DNA technologies for genetically modified organisms (GMOs); (3) diagnostic kits for identification of plant and animal pathogens; and (4) agroindustrial applications (Byerlee and Gregory, 1999). Applications of biotechnology to animal production such as new vaccines is described in Cunningham (1999).

Making the potential of biotechnology for poverty reduction become a reality requires careful identification of the main features of agbiotech research that can have direct and indirect effects on poverty: what crops, what traits, and for what environments? In what follows, we review the potentials and risks of biotechnology in addressing each of the determinants of poverty in developing countries through indirect and direct effects. Most of the risks come from the fact that biotechnologies, most particularly GMOs, are developed by the private sector in response to demands by developed country producers and consumers. Spread to developing countries of these technologies adequate for a developed economy context may have perverse effects on the poor and the environment.

2.1. Indirect effects

1. Employment creation for landless workers and labor surplus small holders.

Potentials:

- Employment creation if biotech research targets yield increases in labor intensive crops: high value crops, unmechanized crops.
- Expansion of crop production on previously unusable lands through drought, salinity, and aluminum tolerance.
- Crop production in seasons when previously not possible.

Risks:

- Labor-displacing herbicide-tolerant plant varieties (Roundup Ready plants) which allow herbicides to replace hand weeding.
- Production in the MDCs of substitutes for labor-intensive crops previously produced in the LDCs (trade substitution effect): vanilla, sugar, coffee, cocoa.
- Innovations are more input substituting (e.g., biological pest resistance replacing chemicals) than yield increasing (Altieri).

2. Lower food prices for consumers and aggregate growth effects

Potentials

- Lower prices if area and yield increase for the production of staples for poor people, and local demand is inelastic.
- Lower prices if cost reduction and inelastic local demand
- Foreign exchange savings through import substitution in food and bio-farmed industrial inputs

Risks

- Main effect of GMO may be input substitution as opposed to yield increase (Rome meeting GR breeders). Cost reduction would lower prices, but failure to raise yields would prevent rising demand to put upward pressure on prices.

3. Nutrition enhancing for consumers

Potentials

- Nutritional improvements such as high lysine corn (food and feed), polysaturated oils in the tropics, foods with specific therapeutic properties (e.g., foods with fatty acids that approximate cod liver oil)
- Health benefits: pharming treatments for tropical diseases such as malaria vaccine in bananas.

- Reduced exposure to residual pesticides.
- Improved micronutrient content of foods (iron, zinc, vitamin A-enriched crops)
- Improved processing qualities: starch quality and quantity, higher dry matter content.

Risks

- Uncertain consumer risks of bio-insecticides such as Bt.
- Unanticipated allergies or sickness in some population.

2.2. Direct effects

1. Adoption by small holders with low farm assets position (land, water, tools)

Potentials

- Choice of crops: small farmer crops, crops in peasant farming systems, crops with high land intensity, crops with high tradability.
- Scale neutrality of GMO technology.
- Choice of traits in crops: Resource substitution as opposed to resource complementarity with early Green Revolution varieties: HYV required complementary resources in the form of irrigation, good soil, fertilizers, herbicides, and pesticides. GMO allow to substitute for these resource requirements, allowing cost saving and improved yields under low input conditions. Examples: nitrogen fixation symbioses, low nitrogen tolerance, pesticide and fungicide saving through biological resistance.
- GMO can broaden widely the plants benefiting from genetic improvement since transfer barriers no longer exist between species and biological kingdoms. Crop portfolios can be broadened beyond the cereals covered by the Green revolution. Crop types cultivated in PFS can be targeted for improvement, such as cassava, sweet potatoes, beans, lentils, cowpeas, pigeon peas, amaranth, millet, sorghum, quinua, rainfed rice, mangrove rice, etc. Creation of new varieties: hybrid wheat and rice, super rice, super wheat, wide crossings, interspecific rice hybrids.
- Short cycle cereal varieties allowing one more crop per year (land-saving)
- Increased range of GMO varieties and traits enhances the possibility of precision farming and hence greater intensity of land use.
- Choice of traits in animal production: artificial insemination, embryo transfers, new vaccines, animals secreting human pharmaceuticals in their milk.

Risks

- High fixed transactions costs in accessing GMO.
- If GMO require contract farming (for instance to produce identity preserved crops), economies of scale exist in contracting. Producers associations are needed to reduce these scale effects.
- Non-scale neutral technologies such as Bovine Somatropin (BST) that leads to concentration of production (Cunningham, 1999).

2. Adoption by small holders with low human assets position (education)

Potentials:

- Ease of adoption: special expertise reduced as the technology is in the seed, compared to complex farming systems, production ecology, chemical pest management, or integrated pest management (IPM). Hence, GMO technology substitutes for human capital at the farm level.

Risks

Pest resistance management strategies difficult (e.g., Bt insect reserves) and hard to monitor in smallholding farming.

3. Adoption by small holders with low institutional assets (access to credit, insurance, markets, information) GMO

Potentials

- Resource substitution lowers liquidity requirements. Credit constrained small holders face higher seed costs, but expectedly lower costs of other inputs.
- Possibility of exact reproduction of seeds (apomixis) reduces cost of seeds compared to current hybrids that do not reproduce true.
- Delayed ripening: reduces transactions costs in marketing

Risks

- Human capital requirements are shifted upstream toward the distribution, extension, and regulatory services. Adoption will be limited by failure of these services to perform.
- High transactions costs and economies of scale in accessing information on GMO and implementing biosafety regulations.
- Terminator gene prevents reproduction of seeds, increasing cash costs.

4. Adoption by small holders with low <u>public goods assets</u>

Potentials

- GMO with improved storability: pest resistance to reduce post-harvest losses, longer storage life
- GMO with transactions costs reducing features: improved transportability, extended shelf-life (time between producer and consumer)

Risks

- Often located in regions with poorly developed infrastructure and poorly developed public services.

5. Adoption by small holders with unfavorable <u>regional/environmental assets</u>

Potentials

- Use in marginal lands: GPM for dry land farming, tolerance to acid soils, tolerance to salty soils, tolerance to aluminum toxicity, stress resistance (droughts, frost). Halophytes oilseed plants developed for seawater irrigated agriculture on desert lands.
- Tolerance to soil contaminants.
- Small market niches: significant decline in the cost of doing research and developing new varieties helps shrink the minimum economic size of niches.

Risks

- Low returns to research and failure to invest.

6. Adoption by <u>risk-averse</u> small holders with insurance market failures

Potentials

- Decrease yield variability through improved pest and disease resistance: multigenic tolerance to random attacks of diseases and pests.
- Use of biopesticides, biofungicides, and bioherbicides (e.g., Bt toxin engineered into plants, rice resistance to tungro virus, potato resistance to late blight)
- Drought and stress resistance
- Plant diagnostics: increased speed and ability of farmers to detect and diagnose infestations and crop diseases using biological test kits

2.3. Environmental externalities and health benefits

Potentials

- Reduced environmental externalities due to lower chemical (fertilizers, pesticides, herbicides) use: reduced contamination of groundwater, food supply.
- Reduced farmer exposure to chemicals

- Increased preservation of biodiversity: new genetic traits can be inserted into a broader range of cultivars and local improved varieties compared to traditional breeding.
- Broader genetic diversity in agriculture through use of wide crossings, making available the germplasm of land races and wild relatives with high multigenic resistance, leading to greater genetic diversity of improved varieties.
- Bioremediation of land and water

Risks
- Gene flows into wild relatives: spread to weeds of herbicide tolerance (super weeds).
- Pest resistance to Bt toxins.
- Bt poisoning of beneficial insects.
- Weediness: crops with bio-engineered traits escaping in the wild
- Development of new viruses from virus-containing transgenic crops (Kandall et al., 1997)
- Environmental risks insufficiently studied before release.
- Environmental risks may be greater in smallholder agriculture since biodiversity is greater in peasant farming environments, increasing the potential for undesirable gene flows into nature.
- Biosafety regulations not in place in LDC and difficult to enforce overall and especially among small holders. Costs of meeting regulations too high for small holders.
- Suppression of weeds (herbicide tolerant crops) may reduce the population of beneficient insects and birds that feed on those weeds and their seeds.

2.4. Market and second round effects

Potentials
- Faster diffusion will reduce the differential price penalty on small holders if they adopt later than commercial farmers under conditions of inelastic demand (Scobie and Posada GR effect).
- Precision farming: Biotechnology opens new opportunities for research in designing agricultural production systems for heterogenous conditions and environments. It increases the set of genetic materials available for producers and enables finer adjustments of genetic materials with eco-agronomic conditions. Biotechnology thus enhances the possibility of precision farming, without requiring the most advanced equipment. Increased precision and resource use, as well as efforts to manage heterogeneity, can happen even when the capital base is limited. With reduction in the cost of computing, more information-intensive management practices can be developed for poor farmers. One of the challenges of the CGIAR is explore how biotechnology can be combined with information technologies (GIS) to help the poor in spite of the heterogeneity of their conditions.

Risks
- The ability to stack on traits in seeds through biotechnology is limited. A pesticide study by Dupont suggests that even by the year 2025 chemical pesticides will still be the main means to address pests. Therefore, production system designers have to determine what functions should be covered by genetic manipulation, and how to complement these functions with management practices in agronomy and acroecology.

III. The generation of agbiotech innovations with potential for poverty reduction

The spread of biotechnologically engineered crops in agriculture has been rapid, but only in a few selected countries and crops, and for a small number of attributes (James, 1998; Krattiger, 1998). Total area worldwide is estimated at some 75 million acres, which more than doubled between 1997 and 1998, with 80% of that area is in the United States alone. Developing countries where transgenics are important are China and Argentina, with minor areas planted in Mexico and South Africa. A number of other countries have conducted transgenic crop field trials, including Bolivia, Chile, Costa Rica, Cuba, Egypt, Guatemala, India, Malaysia, Thailand, and Zimbabwe. Yet, only some 10% of the GMO crop field trials were located in developing countries (James, 1998). The main transgenic food crops are soybeans, corn, canola, tomatoes, and potatoes. The main traits pursued through crop field trials on GMOs are herbicide tolerance (54% of the area planted in 1997), insect resistance (31%), virus resistance (14%), and quality traits (less than 1%).

To assess the potential for biotech innovations to reach developing countries and be useful to the poor, we need first identify the patterns of generation and ownership of innovations. We do this by focusing on one example of technological innovation, the development of Bt crops (for a description of the technology and its diffusion in developing countries, see Krattiger, 1997). A systematic search of the U.S. Patent and Trademark Office (USPTO; http://www.uspto.gov/patft/index.html) database for utility and plant patents directly involving insect toxicity of the *Bacillus thuringiensis* (Bt) microorganism yielded 327 utility patents granted as of the end of March 1999. An estimate of Bt utility patent grants for 1999 was made by multiplying first quarter 1999 data by four, projecting a total cumulative stock of 402 Bt utility patents by the end of 1999.

3.1. Bt utility patents by type of innovating institution

To compare the sources and rates of Bt innovation, we have classified the innovating institutions into three broad categories: (1) the public sector, which includes universities, public research institutions, and government agencies; (2) the small-scale private sector, which includes small biotechnology companies and individuals; and (3) the large-scale private or corporate sector, which includes large chemical, pharmaceutical, and seed companies;

Table 6 counts Bt patents by the category of the assignee specified on the front page of the patent. In virtually all cases the assignee of a patent is the institution at which the individual inventor(s) are employed, and therefore the assignee can be considered the innovating institution. Figure 2 shows the absolute number of patents granted on Bt technologies each year to innovators in each of the three broad categories (based on data from the "All" columns in Table 6). Figure 3 gives the same information, but shows the percentages of patents granted on Bt technologies each year to innovators in each of the three broad categories: public, small private, and corporate (based on data from the "% of total" columns in Table 6). In this figure, the "pioneering" patents—those granted up to 1987—are aggregated together.

Over 50 percent of the pioneering Bt patents resulted from public and university research. However, since 1987 Bt patents granted to public and universities have averaged only about 10 percent of the total number of Bt patents each year. In the early nineties the majority of patents was coming from small biotechnology firms, most notably from Mycogen (San Diego, CA), Plant Genetic Systems (Ghent, Belgium), and Ecogen (Langhorne, PA). In the late nineties, as larger corporations have moved decisively into the crop biotechnology business, their share of Bt patents has increased. Fourty-three percent of the Bt patents granted in 1998 were assigned directly to large corporations (*not* counting their subsidiaries).

In total, including our extrapolation for the grants of Bt patents in 1999, , roughly 11 percent of the cumulative stock at the end of 1999 will have come from public and university innovators, 55 percent from small private innovators, and 34 percent from large corporate innovators.

The dynamics of the flow of Bt technology patent grants—differentiated by type of innovating institution—lends support to the conventionally held notion of a public-to-private technology transfer pipeline in agriculture. In the first phase, during the 1970s and early 1980s, a majority of the pioneering upstream patents were granted to public researchers—including the Battelle Institute at the Ohio State University (Columbus, OH), the USDA, and the U.S. Navy—and to universities. The two most influential and most cited Bt patents on record were granted to the University of Washington (Seattle, WA) in 1984.[3]

[3] Researchers who use patents as statistical indicators have found that the number of forward citations that a patent receives (from patents that are issued at later dates) is correlated with the economic value and thus the technological

Then, in a second phase during the late 1980s and early 1990s, Bt technology was picked up and further championed by small biotechnology firms—with the bulk of the influential "middle aged" patents granted to the likes of Mycogen, Plant Genetic Systems, and Ecogen. At that time these firms were risky hi-tech, small businesses largely backed by venture capital.

As Bt technology began to show its commercial potential in the mid-1990s, a third phase of its transfer to private agricultural suppliers began. Large corporations with interests in pesticides and other agricultural inputs began to increase their positions in Bt technology through a dual strategy: (1) they increased their own in-house research of Bt, as reflected by the increasing share of patents granted to these large corporations in the late 90s; and, (2) they began to buy up those small biotechnology firms that held Bt patents[4].

The sequence in patenting can be seen from the average age of patents taken by the different institutions involved. They are as follows:

Public sector and universities	7.4 years
Biotechnology companies and individuals	5.0 years
Large corporations	3.9 years.

3.2. Bt utility patents by type of institution exercising controlling ownership

The three phases of the public-to-private trend is seen clearly in Table 7 which gives the stocks of U.S. utility patents in force for Bt technologies in 1987, 1994, and 1999. In each of these years, the Bt patents that existed and were in force *in that year* are categorized by the type of organization that held controlling ownership of the patent *in that year*.

In Table 7, in order to compare the ultimate ownership and control of Bt technologies, we have classified the institutions into three broad ownership categories that differ somewhat from the innovating categories in Table 6: (1) the Big 6 corporations; (2) the rest of the private sector, which includes other corporations, independent biotechnology companies and individuals; and (3) the public sector, which includes universities, public research institutions, and government agencies.

The special ownership category (the "*Big 6*") was created for those six large corporations which have been actively consolidating major global positions in agricultural biotechnology research capacity, intellectual property, and markets. These six corporations are listed in order of the number of Bt utility patents that they are estimated to control by the end of 1999:

1. Dow (124 patents),
2. Novartis (31 patents),
3. Aventis (21 patents),
4. Monsanto (20 patents),
5. AstraZeneca (11 patents),
6. DuPont (7 patents).

A second broad category consists of "*other private*" owners. This includes other corporations with a presence specifically in Bt technologies but less in other agricultural biotechnologies. The most significant "*other corporations*" are Abbott Laboratories (8 patents), Nissan (5 patents), and Boehringer Mannheim (4

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importance of that patent (Griliches, Hall, and Pakes, 1993; Hall, Jaffe, and Trajtenberg, 1998). The Bt patents in this study were each cited an average of 4 times by March 1999 when we counted. The two 1984 University of Washington patents were cited 72 and 59 times respectively, by far the greatest, suggesting that they represent breakthrough inventions to which everyone else applying for Bt patents have been obligated to refer back.

[4] Dow bought a 46% stake in Mycogen in January 1995, increased that to a controlling stake of 52% in December 1996, and acquired all remaining Mycogen shares in September 1998. AgrEvo, the agricultural joint venture of Hoechst and Schering, bought a controlling interest in Plant Genetic Systems in 1996. (Hoechst, together with AgrEvo, has agreed to merge with Rhone-Poulenc to form a new life sciences corporation, Aventis, by November 1999.)

patents). “Other private” owners also includes “*independent biotech”* firms, those small biotechnology firms that have not been acquired by larger corporations in the year specified. The most significant of those independent in 1999 are Ecogen (18 patents) and AgraQuest (2 patents). Individuals are considered private owners of the patents assigned to them, and thus the “*individuals*” ownership category is the same as the individual innovators category in Table 6. Likewise, all of the patent counts in the third broad category of “*public and university*” ownership consider the assignee institution on the front page of the patent, which is the same as the innovating institution, to be the owner[5].

Figure 4 provides a vivid illustration of the change in structure of ownership of Bt technologies over the years. The stock of 24 Bt patents in force in 1987 consisted largely of the pioneering patents. Half of these were in the public sector, and only 10 percent were in the hands of the parent companies that would eventually become the Big 6 agbiotech corporations. The much larger stock of 151 Bt patents in force in 1994 consisted of all those Bt patents granted between 1977 and 1994. (The life of a US patent 17 years.) In 1994, over 60 percent of the Bt patents were controlled by the burgeoning category of small independent biotechnology firms as they raced to develop the technology. The ownership of the stock of 386 Bt patents projected to be in force by the end of 1999[6] provides contrast that illustrates the third phase of technology transfer. By the end of 1999, the Big 6 are expected to control over 65 percent of the stock of Bt patents, with the entire private sector controlling close to 90 percent. The universities and public institutions will be responsible for only 10 percent of the existing Bt patents.

Figure 5 indicates the mechanism by which the Big 6 so rapidly came to control such a large proportion of Bt technology. Three fourths of the 261 patents controlled by the Big 6 in 1999 are assigned to one or another of the small biotechnology or seed companies which the Big 6 corporations have acquired after 1994. The purchase of the single firm Mycogen by Dow Chemical alone counts for the transfer of some 123 Bt patents. (Mycogen has historically been by far the most prolific patentee of Bt technologies.)

3.3. Bt utility patents by technology types

In the title and abstract on the front page of a U.S. patent, the type of technologies protected by the patent are disclosed in summary form. It is thus possible to trace the history of the development of Bt technologies by scoring these technology disclosures into categories of interest. We have chosen four categories that capture the essential developments of the Bt as an agricultural technology (see Table 8):

1. *Novel Bt strains, toxins, and genes* include new strains of Bt microorganism, new Bt protein toxins (or fragments, or synthetic replicas thereof) characterized and derived from Bt microorganisms, or the Cry genes or gene fragments that code for those protein toxins. These novel Bt disclosures also usually specify which insects a new Bt strain or toxin targets.

2. *Genetic process* disclosures include screening assays useful in discovering new effective Bt strains or toxins, genetic transformation methods or vectors, genetic promotors, and other genes or gene fragments or methods to control gene expression.

3. *Bt insecticidal compounds* are solutions or compounds that include Bt strains, transformed microbial hosts, or protein toxins useful for the control of insect pests. These are usually product inventions that take the form of insecticide sprays. Some of these disclosures are simply for the active ingredient of such a product.

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[5] Information on exclusive licenses or other agreements to transfer rights to a patented technology are not part of the public patent records at the USPTO and are usually not disclosed by the parties involved, as it is considered information of strategic value and importance. Our experience leads us to expect that if such transactions were revealed, the resulting reassignments of rights to technologies would reflect the trend of transfer, including the use of public and university patents by private firms and use of small biotech companies’ patents by the Big 6.
[6] Again, forecasts for patent grants in 1999 are the data for the first quarter multiplied by four. The granting office of the USPTO does not exhibit any patterns of seasonality in granting patents.

4. Disclosures of the *Bt genetic modification of crops* includes methods for transformations of specified crop varieties with Bt genes and modified crop varieties themselves, such that the crop exhibits increased insect resistance.

Table 8 counts the technology disclosures made in the U.S. Bt patents from 1976 through our estimates for 1999. The average number of technology disclosures per patent is 1.65. It is not uncommon for a patent to make disclosures in two or even three of the above categories (but none disclose in all four). Figure 6 illustrates the flow of technology disclosures.

Figure 7 reveals a story that we believe is typical for many agbiotech applications, such as bioinsecticides, biofungicides, bionematocides, biofertilizers, and seed treatments. At the far left of figure 7, the pioneering patents from 1976 through 1986 are aggregated together. Roughly one third of these pioneering patents consist of novel Bt strains, among which are the key breakthrough discoveries. Only two genetic process patents occur among these pioneering patents; these are the two breakthrough 1984 University of Washinton patents mentioned previously. The remaining bulk of pioneering patents was granted for Bt insecticide applications. These initial applications were mostly simple solutions of Bt microorganisms or extracts thereof, used as sprays or innoculants, simple stand-alone products that did not require much biological or genetic sophistication.

Several years under this pattern passed, with a few new genetic process patents being added to the stock of knowledge each year. A new generation of technologies came under patent protection in 1989, with the grant of the first U.S. utility patents for the modification of crops with Bt genes. Throughout the nineties the general trend in Bt technologies has been a gradual decrease in the proportion of stand-alone Bt insecticides and an increase in the proportion of genetic processes and of genetically modified crops. This trend of increasing biotechnological sophistication has occurred during the time that biotech firms and corporations have been most involved in innovation and thus goes hand in hand with the increasing proportion of private control of the patent stock.

3.4. Bt utility patents by frequency of citation, indicating importance and value

Researchers who study patents as economic indicators have found that the number of forward citations that a patent receives (from patents later granted) is correlated with the economic value and technological importance of that patent. Figure 8 plots the number of forward citations that the Bt patents in our sample have received as a function of their age. Clearly, there is a time dependent trend in citations, as a patent which is older has more chance of being cited. However, the likelihood of a patent being cited does drop off after a certain age, as its technology becomes obsolete (Hall, Jaffe, and Trajtenberg, 1998). Table 9 shows that, relative to this trend, Bt patents that originate from different types of innovators do differ significantly in their profile of forward citation frequencies.

Universities and public institutions generate only a few patents and they are cited less on average. However, some university patents receive an inordinately high number of citations: those are the breakthrough fundamental discoveries, such the ones represented in the 1984 University of Washington patents. Interestingly, the biotech company patents and the corporate patents account for most of the citations to these breakthrough university patents. The variance of citations to university and public innovation patents is very high because there are many busts and a few large breaks in fundamental research. Thus, the general behavior of public and university research in Bt may be characterized as "risk taking".

Citations to patents from biotechnology firms and individual innovators are on average greater than the trend, however the variance of these citations is considerably smaller than those of public and university patents. These innovators appear to undertake research programs that are less risky and more valuable on average than those undertaken by public institutions and universities.

Corporate patents are cited least of all, but the variance of their citations is very low. These established companies are interested in more narrow applications of technology which are either not of great interest to others or are competitive substitutes to others' technologies. Companies do not generally take large risks by pursuing general-purpose path-breaking technologies.

3.5. Conclusions

Analyzing the sequence of patents reveals the importance of an active public-sector research system (universities and public research institutions) as the source of fundamental innovations that lead to the development of a vibrant sector of independent biotechnology firms. For developing countries that want to develop their own capacity to innovate or to adapt international technologies to local conditions, development of a strong public sector research system would thus seem to be key. In many countries, an element of structural adjustment has been to undermine the research capacity of universities and to dismantle or shrink the public agricultural research system. This runs contrary to the institutional mechanisms needed to acquire national capacity in biotechnology. In addition, for this public sector research system to spawn biotechnology firms, development mechanisms such as offices of technology transfer attached to universities and public research institutes as well as venture capital must be present. Failure to develop these technology generation linkages will waste public funds invested in research. And for large chemical, pharmaceutical, and seed corporations to acquire the technologies developed by biotech firms through licenses or through mergers and acquisitions, and transform them into marketable products, a reliable system of intellectual property rights need to exist. These are the issues that we discuss in the following sections.

IV. Intellectual property rights in biotechnology and their impact on the poor

Many developing countries currently do not have intellectual property rights legislation for biotechnological innovations or do not enforce them. Does this help gain cheaper access to biotechnological innovations or, to the contrary, does this hamper access to this technology? Since access to biotechnology for developing countries is a pre-condition for access by the poor in these countries, we analyze this issue here.

4.1. Social costs and benefits of patenting genetic processes: what deserves patenting?

There currently is an intense race to patent biotechnology findings of DNA sequences (genomics), their roles and impacts (functional genomics), and biotechnology processes (both fundamental and for the development of new products). The extent to which these findings present novel innovations that deserve patentability is a growing debate. The courts, legislators, and regulators are currently making decisions that will determine the outcome of this debate.

Some argue that issuing patents for genomic findings is unjustified, particularly since these findings identify, in essence, a natural situation and the discovery process has become mechanical (Kiley, 1999, a patent lawyer). Nobelist James Watson, co-discoverer of the DNA structure, recommended that "genes should only be patented rarely, when companies could prove a very specific commercial application" (Berkeley Symposium on "Biotechnology at 25", March 13, 1999). The same concern applies to upstram biomedical research where patenting might hamper downstream product development (Heller and Eisenberg, 1998). It would be more socially beneficial for enterprises to market genetic maps in databases and to receive royalties for a subscription to these databases rather than royalties for discovering the contents of genetic sequences. Product development may be hampered when DNA sequences are patented since obtaining the rights to utilize them is costly and time consuming, particularly under the current system that induces proliferation of fragmented and overlapping intellectual property rights (IPR). Obtaining IPR for basic genomics knowledge may thus become a bottleneck that impedes research for new products and makes it more costly, creating the paradox of patents leading to fewer instead of more useful products. Patenting discoveries in functional genomics and applied biotechnology processes is more legitimate since these patents can induce the development of commercial products. Since developing countries are lagging in the appropriation of patents for genomic findings, they will be differentially hurt by the current rush to patent DNA sequences.

4.2. Market failures for IPR in biotechnology

Even if patenting is limited to functional genomics and biotechnology processes, IPR should be managed in a way that does not impede further research. This requires addressing the following issues.

The structure of IPR does not limit research activities per se nearly as much as how the rights to intellectual property are exercised and traded. IPR processes have existed for many years in electronic, printing, and chemical industries. There, as long as obtaining rights is simple, publicly known, and not prohibitively expensive, further research and development can proceed smoothly. Copyrights in the entertainment industry are very elaborate and involve every level of operation. Yet, the performance of these sectors is not noticeably affected because there are effective mechanisms to document and pay for the use of copyrighted materials. For example, when a disc jockey selects a CD at the radio station, he does not ask for permission from the copyright owner. Instead, he documents his selection of music, the radio station pays a clearinghouse a predetermined sum, and the money is distributed to the copyright owners. The same applies in using copyrighted materials for class readers. If similar market mechanisms are established for biotechnology, perfecting access to information and lowering transactions costs, then IPR considerations may not impede further research. The Cohen-Boyer patent is a good, positive example of patents on fundamental biotechnology processes not limiting further research. This was a key patent in gene splicing, and users could obtain the patent right for a flat fee. This patent generated more than $100 million for the University of California and Stanford University. The availability and reasonable price of this patent were crucial to the evolution of the biotechnology industry. Currently, there are attempts to use U. S. courts to ban attempts by owners to block access to crucial patent processes through bureaucratic roadblocks and extortive pricing (Monsanto-UC corn example).

IPR may not be the only constraint in accessing genomics information in developing countries. Major corporations benefit from having exclusive genomics databases as well as effective search software. There are several avenues to overcome the constraints imposed by IPR. First, research institutions in developing countries may reach an agreement to obtain access to these databases, for example in exchange for sharing the knowledge they generate. Second, access to some of these databases might be purchased on the open market. Third, developing countries and the CGIAR may develop databases and software programs for their own purposes and as international public goods.

The cost of accessing patented materials may be a problem for researchers in developing countries. If markets work, discriminatory prices for IPR should emerge whereby researchers in LDCs pay less than researchers who use intellectual property for commercial applications in lucrative markets. There are many precedents of discriminatory pricing for intellectual property and other products that favor developing countries. Pricing rules could be developed that would be especially favorable to research on subsidence foods for peasants in developing countries. Alternatively, CGIAR or research centers in developing countries may have agreements with international corporations and consortia that control biotechnology IPR to barter this knowledge in exchange for access to bioresources and germplasm in developing countries.

4.3. Advantages and disadvantages of introducing IPR for developing countries

IPR laws and their degree of enforcement vary greatly across countries. If major companies cannot obtain royalties on new seeds, they will concentrate on developing hybrid seeds or open-pollinated seeds laced with terminator genes (when available, see New York Times, 1999). In such a case, multinational corporations may take over local seed production or associate with local seed companies (Mahyco in India owned at 20% by Monsanto) and modify the major hybrid seeds to include genetic manipulation. This could result in an increased market share for major improved varieties and a reduction in the acreage planted in domestic varieties that do not incorporate genetic modifications, leading to erosion of biodiversity.

Seed companies will not invest in LDCs where IPRs are not protected if they cannot produce hybrids or do not have or cannot use terminator genes (as in India). While some multinational companies may thus give up on developing open pollinated seed varieties for LDCs because of IPR considerations, domestic seed producers with sufficient scientific capacity can take advantage of new discoveries elsewhere and, without paying royalties, produce generic materials for domestic markets. The publication of patents by the U.S. Patent and Trademark Office (http://www.uspto.gov/patft/index.html) in fact serves to reveal this information. The example of Bt tobacco in China is probably the first among many cases to come. Cheap and speedy production of generic pharmaceuticals in India responds to this logic (Lanjouw, 1988).

Disregarding IPR laws may make life simpler for some private companies in LDCs, especially those that produce genetic materials for domestically consumed food products. They will take advantage of scientific discoveries and not spend the time and money to obtain licenses and pay royalties. However, in many cases a technology transfer arrangement provides assistance and expertise, in addition to the formal right to utilize an innovation. Lack of formal agreements may prevent private companies from taking advantage of new knowledge because they will not have access to the assistance and informal exchanges that accompany formal technology transfers.

IPR create a market for knowledge by providing a legal basis for technology sales and licensing. The advantages, inconvenients, and potential irrelevance of introducing IPR in LDCs can be summarized as follows (see also Herdt, 1999):

Advantages:

- IPR provide greater incentives to invest in research and development within the country.
- The filing of IPR discloses information to other researchers which they can use to make further advances.
- IPR encourage greater research and development investments in industrialized countries on issues of concern in developing countries, and transfers of knowledge and technologies to developing countries.

Inconvenients:

- IPR shift bargaining power toward producers of knowledge rather than users.
- IPR lead to concentration of the seed industry, allowing to increase the price of new seed varieties. Prices of protected products may be priced beyond the reach of the poor. Market power is, however, limited by the following:
    - i) Monopolistic competition is an effective constraint.
    - ii) New varieties are always in price competition with best current varieties.
    - iii) Principal opportunities for rent seeking are in output-quality-enhanced with specificities (monopsonistic output market).
    - iv) In developing countries, there is often competition from strong public sector seed suppliers.
    - v) Seeds are typically only a small part of growers' production costs.
- Broad patents may discourage follow-on inventions and slow the overall pace of innovation.
- The knowledge gap between industrial and developing countries may increase.
- Industrial-country firms may take advantage of indigenous knowledge and biodiversity without compensation to local communities.

Potential irrelevance (hence lack of introduction):

- Gaining access to privately controlled frontier technologies (under IPR) is a low priority for low-resource agriculture. In this case, lack of access to biotechnology is not a current or potential limiting factor to productivity gains.

4.4. International development agencies and defensive patents: IPR for IPG

The introduction of IPR in seed production is an irreversible process and it is likely to be extended to agronomic innovations as well. For instance, there are discussions among policy specialists in the United States about developing intellectual property rights and patents for crop management practices. In this environment, international organizations concerned with poverty reduction such as the CGIAR are starting to patent their technological innovations (e.g., ILRI vaccines) to prevent their appropriation by commercial users and to keep them in the public domain. While such organizations try to develop reasonable criteria for the use of IPR in biotechnology, the practice of patenting innovations and disseminating patented innovations as international public goods (IPG) or club goods targeted to the poor is yet to be established. Patenting should be one instrument in a strategy of taking advantage of new discoveries and improving access for researchers to patented materials of others through bartering. Other instrument include strategic alliances with private corporations and collaborative efforts with universities and research institutions that will enable CGIAR and NARS scientists to gain access to the best equipment and research techniques.

4.5. Role of networks and partnerships

The value of functional genomic knowledge is increasing all the time as the ability to translate this knowledge into marketable innovations also progresses. The CGIAR can use its extensive seed banks and its experimental plots located throughout the whole world, as well as its privileged working relations with NARIs in developing countries, to obtain funding for collaborative research with corporations and universities. Through these associations, physical data collection and biological experimentation can be done in the LDCs, while multinationals and universities in developed countries will contribute know-how and resources to conduct the research efforts. There may be joint ownership of patents or rights from these partnerships. Innovative contracts to create mutual incentives and fairness in the sharing benefits are yet largely to be explored (see the exploratory contractual arrangements initiated by ISAAA at http://128.253.183.94/ISAAA_WEB.html).

Partnership between private companies and public institutions useful in utilizing biotechnology to help the poor can take a multiplicity of forms. They include partnerships between multinationals and companies with access to genetic materials in LDCs, between multinationals and universities, and between universities in LDCs and universities in developed countries. The development of biotechnology capacities in LDCs can be undertaken collaboratively by agricultural and medical institutions. Many of the laboratory techniques are similar, and some future agbiotechnology applications are likely to be aimed at developing medicinal products. Since such products may require labor intensive production systems and specific climatic conditions, this work needs to be done in LDCs. Biotechnology thus tends to remove barriers between agricultural and nonagricultural activities, and between research located in the more and the less developed countries.

Development of new GMOs involve many components, each of which may have been separately patented. Due to technological complementarities, access to a bundle of intellectual assets is consequently needed to develop GMOs: patents on process technologies for inserting DNA, on genes and gene characteristics of plants, and on elite germplasm lines of major crop varieties (Graff, Rausser, and Small, 1999). If the market for IPR does not work smoothly (due to lack of clear definition of property rights, contract hazards, and high transactions costs in licensing and exchanging technologies), this induces mergers and acquisitions in the private sector, and partnerships and consortia in the public sector and between public and private organizations (Wright, 1998). These institutional arrangements are mechanisms to mitigate market failures due to excessively high (sometimes prohibitive) transactions costs in getting joint access to these intellectual assets. Hence, market failures in IPR induce concentration of suppliers of biotechnologies due to technological complementarities. This is what we observed in Figure 7. It has powerful implications for the sources of biotechnological innovations and the conditions of supply of adoptable products for the developing countries and the rural poor. Gifts are consequently important means of access to biotechnology for the poor. However, the motives of the donor should be clearly revealed and the subsequent conditions in accessing the technology clearly identified.

4.6. Role of empowerment and participation to priority setting

Past examples of technological innovations, eventually developed in good faith with a small holder perspective, that failed to be effective for poverty reduction evidenced the dangers of insufficient participation of small holders in the design of research priorities. Examples include the design of labor-intensive technological packages (e.g., Plan Puebla in Mexico) which small holders had difficulty adopting because they face labor constraints and have positive opportunity costs for their time on labor markets, capital intensive packages that mainly benefited large farmers due to market failures and institutional gaps that selectively affect small farmers, and chemical intensive use of HYVs that created health hazards for uneducated users and killed the fish in rice paddies (Loza, 1999). With biotechnology, the range of crops and varieties that can be modified and the range of traits that can be pursued are greatly amplified, making the need for wise choices increasingly important. Since the circumstances of small holders are, as we have seen, highly heterogeneous, choices need to be made in reference to, and hence based on the information coming from, specific clienteles of small holders. At the same time, participation of small holders to priority setting in the choice of crops, varieties, and traits is made increasingly difficult by the complexity of potentials and risks of the biotech options available. Participation can consequently only be effective if it is based on extensive information campaigns to enable (empower) participants. Biotech capacity must consequently be developed not only at the scientific and policy-making levels, but also broadly in civil society, including among potential poor users. Failure to do this would have three risks. One is that small holders and consumers may oppose GMO technologies based on eventually unfounded fears of adverse consequences. The second is missing the opportunity of capitalizing on small holders' unique informational advantages on local circumstances and their potential contributions to the design of technological packages. The third is that unevenly distributed information on the technical difficulties of biotech options is a powerful source of rising inequalities among farm households.

Empowered participation can happen through a variety of institutional options linked to approaches to extension such as farmers' field schools. National councils on biosafety and bioethics should routinely include representatives of small farmers. Identification of the relative benefits and costs of biotech options should thus be done with a perspective on the transfer of information both to and from potential users. The risk, otherwise, is that advances in biotechnology will bypass the poor and increase the gap in competitiveness between them and large farmers at home and abroad.

V. Transfer of technology and delivery to small holders of adoptable technologies: the supply side

5.1. Insertion of biotechnological traits into locally useful germplasm for small holders

One of the main differences between pharmaceutical and agricultural innovations in biotechnology is the much greater need to adapt the latter to local conditions, in particular, to insert a desirable trait into local varieties. Even though degrees of similarity vary (as we have seen in analyzing the differential value of IPR across developing countries), direct transfers of seeds from abroad are consequently in general not possible. Currently, local seed companies with in general little or no capacity to engage in biotech work produce many of these varieties, and innumerable farmers reproduce their own seeds. The main challenge faced by major seed companies that want to introduce GMOs into LDC markets is to develop a technology for large-scale, cheap insertion of genetic materials into local seed varieties. Generating this production technology is an area where the companies have the biggest advantage. It should result in the development of machinery and procedures that will become cheaper over time through economies of scale and learning-by-doing.

The production of biotechnology varieties in developing countries will require the development of partnerships between major seeds companies that have the intellectual property rights and trait insertion technology and local seed companies. The following institutional arrangements are likely to emerge:

- Takeovers of local seed companies by major seed companies.
- Contracting, where the local seed companies rent the equipment to improve their own seeds.

- New entry companies buy the appropriate equipment, obtain the intellectual property rights, and generate the seeds for small seed companies. Within the local seed companies, a small subset of firms might expand to handle genetic manipulation.

- Government laboratories provide seeds to farmers. These public facilities could be expanded to conduct genetic manipulations. However, the extra costs and the need to form close alliances with private companies that own both IPR and the technology to modify seeds, may lead government agencies to gradually move away from providing seeds.

The cost of modifying genetic materials is likely to decline over time, and the value of inserted traits is likely to increase as they are perfected. These developments have the potential of being favorable to the rural poor, as long as new varieties that they could adopt reach them. Lower costs of insertion, higher value of traits, and the probable decline in the role of government in the provision of seeds, will induce expansion of commercial seed marketing toward more marginal farmers. Historically, we have seen a tendency for the range of clientele served by the commercial sector to expand toward the poor. In the United States, for example, the Bank of America was revolutionary in providing mortgage credit for the working poor (Time Magazine 100, 1998). The Grameen Bank in Bangladesh introduced major institutional innovations in making credit accessible to the poor (Hossain, 1988). A similar expansion of markets for purchased agricultural inputs, in particular seeds, will need to accompany the diffusion of biotechnology in developing countries if it is to benefit the rural poor. This will require studies to demonstrate the viability of best practices for this purpose and to assist in their design. Input suppliers may need some subsidization or insurance coverage as they expand their activities toward the rural poor. Alternatively, extension services may help peasant farmers form purchasing cooperatives for easier and cheaper access to input markets.

A key question is how to fund the investment in equipment and human capital required to modify seeds. We need to learn more about this. It appears that costs would not preclude establishing plants in large-producing countries such as China, India, and Argentina. The main challenge is to deal with small producing regions. Regional organizations will be important for this purpose, connecting small regions with similar agroecological characteristics.

The additional processing of seeds needed for genetic insertion will reduce some of the difficulties associated with enforcing IPR since few companies will be able to do this. It may be that seed companies will provide the insertion activity very cheaply in order to reduce competition and gain greater control over the supply of seeds. Obviously, seed prices will have to include the cost of processing and, therefore, the genetic manipulation they entail will significantly affect profitability.

Stacking into seeds multiple traits is attractive, particularly to ward pest resistance as with Bt (Federici, 1998), but there is an increasing marginal cost to the number of traits that are inserted in a seed and possible tradeoffs. Hence, which traits to choose for insertion needs to be carefully examined for each particular location and group of users, drawing use of GMOs toward precision farming . For this reason, the biggest challenges posed by used of GMOs are: (1) to determine which trait(s) to insert for each particular location and clientele, and (2) to design production systems that combine most judiciously biotechnology, chemical, and agronomic practices (Zilberman, Yarkin, and Heiman, 1999). Some of the mergers and alliances in the United States, as well as the emergence of production consultants, aim to address these problems.

Institutions in support of delivery of GMO to small holders can be quite varied. In some segments of developing countries, we may see the emergence of intermediaries that provide both materials and managerial consulting. In other cases, we may see contract farming arrangements like those in the United States. In particular, some less sophisticated farmers will receive inputs and instructions from organizations that will buy or receive some of their output. A third alternative is the emergence of cooperatives that will obtain or pay for expertise in the design of production systems for their members. A lot will depend on the evolution of public extension and the methodology it uses for delivery of information. Extension can provide management information directly. It can also train local input manufacturers and dealers in the design of production systems (as it does in the United States) as well as work with farming communities to promote local organizations to acquire expertise and knowledge for system design.

The CGIAR faces the challenge of providing the science and some of the basic training to build the human capital that will enable to design appropriate technologies for various locations and clienteles. This includes the optimization of genetic materials, production practices, and equipment for each such location and clientele. This is the area where we need real interdisciplinary cooperation between economists and agronomists, and where some of the new developments in computer science and information systems will be fundamental. Part of the research the CGIAR and some agrochemical and seed companies do is to use the Geographical Information System (GIS) to identify and link microenvironments with similar agro-ecological conditions into mega-environments of a scale sufficient to generate distinct production systems. Much of the crop breeding in the past was based on the transfer of species among regions with similar conditions. When the much larger combined purchasing power of these similar regions is recognized, increased market size will create greater incentives to develop unique technologies that are appropriate for these regions. This is particularly important for the rural poor who live in a multitude of geographically fragmented agro-ecological niches, each with a minute market size.

5.2. Pricing seeds for developing countries

Increased reliance on commercial seeds by poor farmers may have negative equity effects if the seeds are expensively priced. Not only will the seeds of GMOs be inevitably costlier since they require additional processing, but introduction of IPR or improvement of hybrids instead of open-pollinated varieties will also force producers to buy their seeds annually instead of reproducing them at home. Hence, the cost of seeds and the need for liquidity at the beginning of the season which they require may become major hurdles to diffusion among small holders. Market concentration can enable seed companies to charge monopolistic prices for their seeds. But pricing will be dependent on farmers' ability to pay, so one may expect discriminatory pricing, with poorer farmers being charged lower prices, if markets can be segmented. Without competition or some regulation, intermediaries may soak much of the rent from technological innovations. Therefore, governments need develop mechanisms to monitor seed pricing and encourage competition among producers of GM seeds. It is, however, probable that, at least in large producing areas, several major companies will be competing to provide parallel lines of products and services. It will consequently be important to enable as many companies as possible to have distributorships in developing countries. The problem of increasing the competitiveness of imported goods so the poor benefit from lower prices is not restricted to seeds. Any reforms that enhance competitiveness will, in general, benefit the seed market.

Pricing of farm inputs in developing countries may suffer from lack of competitiveness in distribution channels, e.g., only one company may have a distributorship in a particular country, as well as from increased global concentration of distributors. Introduction of regulatory protocols and of a patent system have perverse effects in that sense. For example, the high cost of acquiring patents and registering new chemicals was a major factor in the consolidation of the agro-chemicals industry. The same will happen with the high cost of registering GMOs and of experimenting, in part due to the necessary biosafety requirements. One reason that multinational corporations absorb start-up companies is that they have a relative advantage and greater capacity to conduct pre-registration testing.

In the pharmaceutical and biotechnology industries, we are seeing the emergence of several major global players that compete among themselves. Generally, they charge monopolistic prices during the patent period. Once the patent runs out, "bottom feeder" companies enter the market and produce products at much lower prices. For example, these companies play a major role in providing pesticides to developing countries such as Mexico. One reason that American companies are pushing for cancellation of older chemicals and harmonization of stricter environmental regulations is to reduce the level of competition from bottom feeders. While not unique to developing countries, these issues are also likely to occur in the seed and biotechnology industries as product cycles mature.

5.3. Marketing of new seeds and biotechnology products

With biotechnology, the range of seed varieties available to farmers has the potential of expanding, and new products that combine genetic manipulation and new management strategies are likely to be introduced. Many of these products may be aimed at market segments that have not purchased seeds before or have purchased relatively little. There are significant challenges in building marketing channels and strategies for these populations. Marketing efforts are needed to overcome market failures, particularly for information, credit, and insurance. Some of these services should be provided by the private sector, but they will have to be complemented by public interventions to raise the range of social incorporation toward poorer households. A key element is establishing a distribution network that includes sales people at different levels. These may include salesmen who work for dealers and approach individual peasants, as well as representatives who work for distributors and who recruit and serve dealers.

Studies on the activities of extension show that it works both directly with farmers and indirectly through training people who become dealers or dealers' salesmen. Extension can conduct relatively objective experiments with new varieties and provide education programs, sometimes with the cooperation of the private sector. Such programs may demonstrate new products. Extension can be a very important source of information regarding conflicting claims and comparisons among products. Because of limited budgets, extension in developing countries is likely to assume more of these indirect roles as opposed to giving hands-on help to farmers. Direct help would be increasingly assumed by dealer representatives and consultants.

Some of the marketing activities conducted by dealers will provide mechanisms to reduce uncertainty regarding the fit and the performance of products for particular regions and types of users. These may include free samples or moneyback guarantees of various kinds. In some cases, when new varieties result in a different type of product (e.g., a fortified grain that may fetch a higher price in the city), the seller of the variety may also engage in a contract to sell part of the output, thus preserving the identity of the product (Kalaitzandonakes and Maltsbarger, 1998). Alternatively, especially when risk aversion and access to liquidity are constraints on potential adopters, seed distributors may make sharecropping arrangements with farmers, where the dealer shares both costs and yields with the farmer. This type of contract is effective to mitigate both risk and credit problems for small holders.

Because of the high fixed costs of developing GMOs and their short life cycle due to the rapid pace of technological progress, seed producers and distributors must recapture costs quickly, implying the need for fast diffusion of the new products. Increased contracting in United States agriculture and in other countries reflects this tendency of sellers to build their own market by assuring potential buyers of an opportunity to sell their product at a reliable price. This is in marked departure from the less pro-active role of producers of traditional seed varieties where the diffusion of innovations is left to the autonomous dynamic of demand. In addition, in the case of new production systems that involve biotechnology and other advanced components, diffusion will be slowed if components are sold and promoted separately. Therefore, we may see contract agreements that offer full service so that, in addition to the sale of the inputs, continuous consultation is provided.

Biotechnology will greatly enhance product differentiation in agriculture. This is especially true for products that embody new traits. Developers of these products may use contracting to accelerate diffusion, to assure product quality through identity preservation, and to gain some monopolistic power in the output market. Companies that have premium genetic and brand-name recognition may choose to control and sometimes slow the diffusion process in order to control the price of the final product. In many cases, a key characteristic of brand names is not related to what is grown but to how it is grown. For example, Gerber Foods has its own varieties that are grown without pesticides. Many products that have these features are labor-intensive and are appropriate for production by small holders in developing countries, like non-traditional vegetable exports in Guatemala and Mexico (Carletto, de Janvry, and

Sadoulet, 1999; Key and Runsten, 1999). The diffusion and introduction of these products is typically associated with a more widespread use of contracting with organized small holders.

Some companies may provide developing countries genetic materials or the infrastructure to facilitate the introduction of new varieties as a gift (e.g., Monsanto's gift of transgenic virus resistant potato varieties to Mexico (Qaim, 1998)). Companies may offer gifts to induce a country with a large potential market to more rapidly put into place IPR legislation and biosafety regulations that will open markets for subsequent sales. They may also provide gifts as part of a strategy in exchange for access to biodiversity, or to initiate potential customers, or to generate goodwill as part of a charitable program (see Krattiger, 1998). Companies may donate certain facilities to a region. For example, a company might donate a laboratory that has the capacity to design production systems or modify genetic materials. But such gifts may also serve to introduce a company product or to obtain data for experimentation that may be useful for the company in other activities.

5.4. Regulatory frameworks

The introduction of biotechnology in developing countries requires government regulations on several fronts. They include biosafety, consumer safety, competition, and enforcement of IPR. Biosafety concerns are related to poverty. Most countries have legitimate concerns about the environmental effects of biotechnology, eventually reaching extreme levels of politicization as in India (ISB News Report, 1999). GM crops may indeed carry additional risks in many developing countries and peasant farming communities because of the high level of biodiversity and presence of wild relatives of the bioengineered crops. Since institutions are by definition weaker in developing countries, achieving effective biosafety regulation calls on the need to develop new approaches adapted to their institutional capacity. In addition, enforcing compulsively regulatory frameworks when there are large numbers of small and poorly informed producers is a definite challenge. For example, management of insect resistance to Bt toxins through allocation of land to insect refuges is difficult to enforce when land is the limiting factor that keeps households in poverty. While less demanding in human capital at the level of farmers than conventional technology, a great advantage in using biotechnology to combat poverty directly, biotechnology is highly intensive in human and institutional capital upstream from the farm, for regulatory purposes in particular. There are several options worth exploring to achieve regulation in spite of this.

One is to make seed producers liable to monitor final users because of the higher degree of sophistication they have and their lesser number compared to farmers. If information circulates effectively, they have the direct incentive to prevent incidents that can cause negative publicity for their products. NGOs can be enlisted to monitor their respect of rules and expose violations. Even this requires sufficient freedom of the press, trustworthy courts, and enforcement of sanctions.

Another is to decentralize the monitoring and enforcement of regulation to the community level. Community-level cooperation has a greater likelihood of success than regulatory agencies since community members have access to local information, while centralized regulatory agencies do not, and community members can use the leverage of social capital (ostracization, social norms, interlinked transactions) to enforce rules while centralized agencies are devoid of instruments if courts are not functional. Central regulatory agencies can engage in random checks and ban the use of GMOs in communities (e.g., through distributors) where violators are found. Community-level cooperation is, however, highly uneven across communities, confining use of this mechanism to situations where cooperation holds or can be fostered (Baland and Platteau, 1996).

Regulatory frameworks will differ across countries since the socially optimum trade-off between risk of and return from GMOs will also differ, with greater willingness to take risks in developing countries than in the more developed countries as the marginal utility of income is higher. Weaker and more uneven capacity to regulate implies the need to promote less risky biotechnologies, at a cost in terms of expected returns. Some innovations are indeed less risky, for instance vaccines and pest resistance through leaf consistency. Evolution toward higher risk-higher return options can proceed as the capacity to implement regulations improves.

Finally, the definition of regulatory procedures is best achieved on a regional basis for small and poor countries. Linking by GIS similar environments allows to achieve economies of scale over geographically dispersed mega-environments in need of similar protective measures.

VI. Adoption of GMOs by small holders: the demand side

We have seen in this paper that a selected subset of GMOs, if properly developed and regulated, has the potential of offering a vast array of new or improved traits for adoption by small holders, ranging from insect and stress resistance to improved nutritional value and environmental friendliness. Given availability for adoption at the level of a particular region, differential diffusion across categories households, in particular poor and non-poor, will depend on the relative desirability of these traits for each particular household and on the specific set of circumstances under which they operate. As an example, we simulate the determinants of adoption of Bt seeds, a biopesticide embedded in corn and in a number of other food crops such as potatoes and soybeans with potential value for small holders in developing countries (Carlson, Marra, and Hubbell, 1997). The question we ask is, in an heterogeneous population of small holders characterized by an array of asset positions and behavioral patterns as discussed in section I of this paper, which of these households will be better placed to adopt and which will be excluded from use of the technology. This in turn will help predict patterns of diffusion and the distribution of direct effects for poverty reduction.

6.1. A household model explaining the adoption of Bt crops

The common feature of all biotechnological improvements in crops is that adoption of desirable traits is shifted from variable or fixed factors to the seed. Transgenic Bt seeds provide crop resistance to very specific pests. Pest management through Bt crops differs from the pesticide-based technology in different aspects: it may provide higher protection than chemicals against specific pests, it provides ex-ante protection relative to the timing of infestations, and it shifts the timing of cost outlays from pesticide costs incurred during the growing seasons to seed costs incurred at the time of planting.

With some crops, Bt seeds offer improved resistance to pests which were previously poorly controlled by traditional methods. This is the case of Bt corn which offers resistance to the European Corn Borer for which no chemical insecticide is effective. In that case, adoption of a Bt seed only offers minor savings on pesticide costs, and the trade-off is between increased protection and higher seed costs. With Bt corn, additional seed costs in the United States are estimated at $40 per acre, insecticide savings at 8¢ per acre, and avoided losses at 4 to 8% of production. The value of these avoided losses clearly depends on the potential yield and on the price of corn, which both vary with location and time (Marra, Carlson, and Hubbell, 1999).

With other crops, such as cotton, Bt seeds offer an alternative means of controlling pests. In that case, the choice is between a more costly seed and pesticide use. With cotton, savings on pesticide are estimated at $20 to $40 per acre depending on location, while additional seed costs are estimated to be $33 per acre (Marra, Carlson, and Hubbell, 1999). How much savings do the Bt seeds allow on pesticides depends on the range of pests that the pesticide treatment was addressing. Transgenic seeds offer resistance to very specific pests, while pesticide treatments can consist in a cocktail of chemicals that control for a wide range of pests. In all cases, pest protection through seeds rather than through pesticide applications brings the timing of expenses forward to the planting season, rather than having them spread over the length of the growing season. This may create problems for poor households with typically tight liquidity constraints.

The model that follows captures the main decisions to be made regarding pest control in the context of a household economy when there are choices to be made regarding the level of use of chemicals and the potential adoption of Bt seeds.

6.1.1. A structural model of technological choice, pest control, and cropping intensity

Production of a single commodity q is written as the product of potential output Q and a pest damage abatement level G (for the specification of damage functions, see Lichtenberg and Zilberman, 1986, and Saha, Shumway, and Havenner, 1997). Potential output, which is output in absence of any loss from pest damage, requires labor L_q, fertilizer F, and land and other productive fixed inputs $\bar{Z}$. Damage abatement is function of the level of pest exposure E. Pest control, which reduces the initial pest infestation $\bar{E}$ to E, requires labor L_g, pesticide P, and human capital HK. The production function can consequently be written:

$$q = Q\left(L_q, F, \bar{Z}; \alpha_T\right) G\left(E\left(L_g, P, HK, \bar{E}; \beta_T\right); \gamma_T\right),$$

where α_T, β_T, and γ_T represent technological parameters, respectively in the potential output, pest exposure, and damage abatement functions. T is an index of a technology among two discrete options, T_0 and T_1.

A simple formalization of the damage abatement function expresses the percentage of potential yield that will be realized as a function of E, the pest population after control:

$$G = e^{-\gamma_T E},$$

with γ_T a parameter of crop damage level for a given exposure to pest (whether this parameter varies with the choice of technology is not yet clear). The initial pest population $\bar{E}$ can be controlled either by the choice of technology or by the application of pesticide:

$$\underbrace{E}_{\text{Pest pop.}} = \underbrace{\bar{E}}_{\substack{\text{Initial} \\ \text{pest pop.}}} \quad \underbrace{\beta_T}_{\substack{\text{Pest pop.} \\ \text{control by} \\ \text{technology T}}} \quad \underbrace{g\left(L_g, P, HK\right)}_{\substack{\text{Pest pop. control by} \\ \text{insecticide}}}.$$

Examples of technological choices that affect the pest population are short season cultivation which reduces the exposure of crops to pests, cultivation under irrigation which may enhance the development of certain pests, and Bt seeds which kill certain species of insects. How small the factor β_T is depends on the choice of technology and on the range and intensity of pests initially in the environment, characterized by $\bar{E}$. In the case of Bt, as each Bt gene is specific to certain pest species, Bt crops may be effective in an environment dominated by one particular insect specie, but not if the range of pests species is wide (Krattiger, 1997).

Insect population control by pesticide is usually less specific, and cocktails of pesticides can be mixed to attack a wide range of pests. The drawback of this non-specificity is that pesticides may kill good pests and predators as well as harmful pests. Pest management with pesticide is very human capital intensive, as it requires the ability to detect pests early, identify them precisely, and know how to treat them with the proper amount of pesticide applied at the right time. Farmer experience in the use of pesticides helps increase the effectiveness of the chemical itself by better choice of dosage, quantity applied, and timing. While in developed countries such tasks as scouting can be purchased from chemical companies as a package, in the context where poor developing country farmers operate, human capital will typically not be available form sources other than family members themselves. We thus consider human capital as a household fixed factor and denote it by $\overline{HK}$. Pesticide use implies a fixed cost C_p for the equipment and the application, and a unit cost p_p for the chemical itself.

The household time endowment $\bar{L}$ is allocated between working on-farm, L^i, and working off-farm, L^o. Farmers can also hire workers L^h assumed to be perfect substitutes to family members. The wage rate obtained on the labor market is w^o, but the potential for moral hazard on the part of hired workers makes their supervision imperative (Eswaran and Kotwal, 1986). We assume that the per unit cost of supervision is a constant per worker, so that there is an effective cost of hired labor $w^h > w^o$ (Sadoulet, de Janvry, and Benjamin, 1998).

In an environment of harsh liquidity constraints for poor households, we divide the year in three periods. The first is the planting season, conceptualized as a short period of time during which there is no source of income but farmers have to incur starting costs such as purchase of seeds if they are to cultivate their land. The second period is the long growing season during which households incur all the other production costs such as purchase of fertilizer, hiring of labor, and pesticides, but also earn cash income from wages if some of their members go on the labor market. Finally, the third period is the harvest season during which farmers cash in the value of the crop. Let C_T be the fixed cost associated with planting under technology T. Typically, start-up cost are low in traditional farming where farmers keep seeds from the previous season, while the annual acquisition of Bt-seeds, especially under enforced IPR regimes (or hybrids or seeds with terminator genes), may represent an entry barrier for some farmers due to liquidity constraints.

Consider a household that is endowed with land and other productive fixed assets $\bar{Z}$, labor $\bar{L}$, human capital $\overline{HK}$, and liquid assets or credit $\overline{M}_0$ and $\overline{M}_1$ at the beginning of the planting and growing seasons, respectively. The household's problem is to choose technology T (Bt or non-Bt seeds), labor allocation, fertilizer use, and pesticide use to maximize expected income earned in both agricultural production and off-farm labor. The household's problem is thus:

$$\underset{\substack{L^i, L^o, L^h,\\ F, P, T}}{\text{Max}} \; pQ\left(L_q, F, \bar{Z}; \alpha_T\right) G\left(E\left(L_g, P, HK, \bar{E}; \beta_T\right); \gamma_T\right) - p_F F - p_p P - w^h L^h + w^o L^o - C_T - C_P 1\{P > 0\},$$

$$\text{s.t.} \quad \begin{aligned} & L^i + L^o \leq \bar{L}, \\ & L^i + L^h = L_q + L_g, \\ & C_T \leq \overline{M}_0, \\ & p_F F + p_p P + w^h L^h + C_p 1\{P > 0\} \leq \overline{M}_1 + \left(\overline{M}_0 - C_T\right) + w^o L^o, \\ & L^i, L^o, L^h, F, \text{ and } P \geq 0, \\ & T = T_0, T_1. \end{aligned}$$

The technical parameters for a technology using traditional seeds and chemicals and a technology using Bt transgenic seeds can be contrasted as follows:

		$T = 0$ Traditional seeds & chemicals	$T = 1$ Bt seeds
Potential yield	α_T	α_0	$\alpha_1 < \alpha_0$
Population control	β_T	β_0	$\beta_1 < \beta_0$
Damage	γ_T	?	?
Initial costs	C_T	low	high

6.1.2. Trade-offs in pest management through the use of Bt seeds

Traditional pest management through the application of pesticides requires time and the purchase of chemicals. In the developing country context, its efficiency greatly depends on the household's endowment in human capital. Its costs include both fixed and variable costs. Where pests are not too abundant, the household has little human capital, and it is under very tight liquidity constraint, it may be optimal not even to fight pests. At higher levels of pest infestation, farmers will apply some pesticide. At even higher levels, they may switch to Bt crops. However, depending on the shape of the damage function and the costs of seeds and chemicals, complete control may or may not be the optimal solution.

What benefits and disadvantages do Bt seeds bring to the farmers? This can be derived from the comparative statics analysis of the solution to the model. The distribution of these benefits and disadvantages across heterogeneous households will determine the pattern of adoption of BMOs.

Relative input costs: Bt seeds are expensive to purchase, particularly if they are not priced competitively, but they offer partial or complete control of pest damage at no extra cost. Compared to the cost of pesticide, it may be either more or less expensive to use Bt depending on the relative prices of seeds and pesticides. If cheap pesticides are available, which may be the case in countries where older and dirtier chemicals such as DDT are still allowed, then traditional pest management may be less expensive than the use of Bt seeds. Similarly, when infestations are not too important and damage control requires relatively little pesticide, using Bt seeds may turn out to be more expensive. Under these circumstances, Bt seeds will not be adopted.

Liquidity constraints: Use of Bt seeds brings forward the liquidity requirements to the beginning of the planting season rather than allowing these costs to be spread over the growing season. Farmers with tight liquidity constraints may not adopt them even if they are profitable.

Potential yield: If the Bt gene is not necessarily implanted in the seed variety that represents the best option for the farmer given his circumstances, the farmer faces a trade-off between a Bt seed with the advantage of better/cheaper control of pest damage against a better traditional variety with no Bt protection. This will typically occur when households are located in small ecological niches that do not attract private investments in the development of Bt seeds. This is captured in the model above by the lower potential yield (the only characteristic of the crop represented in the model) of the Bt technology relative to the traditional seed.

Human capital endowments: Low endowments in human capital reduce the effectiveness of pesticide use and induce adoption of Bt crops. This is one of the features of the Bt technology that makes it particularly attractive for adoption by small holders with typically low human capital endowments.

Level and range of pest infestations: Where pest infestations are quite insect-specific and are either very likely or very intense, ex-ante protection with Bt seeds may be more efficient and cheaper than pesticide use. If infestation are not very frequent, then waiting for the infestation to occur and treating it only if it does, would in expected terms be cheaper. Where infestations come from a wide variety of species, even control of a selected number of species by using Bt seeds will not preclude use of pesticides. As the fixed cost of pesticides must be incurred and with low additional costs (for example for additional chemicals if they can be added to the mix being spread for other diseases), it may not be worthwhile incurring the large costs of adopting Bt seeds.

Poorly controlled pests: In some cases, such as Bt corn, transgenic seeds allow the control of a pest such as the European Corn Borer that was poorly abated by traditional pesticide applications. In this case, Bt seeds offer enhanced protection and they are more likely to be adopted.

Marginal lands: When the use of a transgenic crop brings about an increase in protection against a pest (as opposed to an alternative means of controlling a pest), the value of that pest control clearly depends on the potential yield which is being protected. For example, the reduction of losses equal to 4 to 8% of production, as achieved with Bt corn in the United States, may be quite valuable on high quality land but of little value on marginal land. If poor small holders are located in marginal lands, as is frequently the case, Bt seeds may not have a sufficient payoff to be adopted.

6.1.3. Model extensions

There are a number of additional features that characterize Bt technology and poor small holders in developing countries that need to be added to the above model to improve its predictive power of differential adoption. They include the following:

i) Stochastic damage: Both Bt and chemicals reduce the variability of yields, and hence the cost of risk.

ii) Integrated pest management (IPM): Alternative technologies are chemicals, biological control, and Bt. Bt technology preserves the option of complementary use of chemicals, an option not as easily available with biological control.

iii) Multiple pest infestations: The logic would be to use Bt for the most likely pest infestation and chemicals for the less likely.

iv) Identity-preservation: If Bt crops are labeled to allow consumer choice of non-GM foods (ISB News Report, 1999), the product price becomes endogenous to the choice of technology. Since non-Bt crops would fetch a higher price, adoption of Bt seeds would depend on the balance between lower prices and lower costs.

VII. Summary and Conclusions

7.1. Question raised in this paper

We address the following question: can advances in agricultural biotechnology help reduce poverty in developing countries and under what conditions? Hence, we focus exclusively on the intersection between biotechnology and poverty, not on biotechnology in general, and not on developing country poverty in general.

7.2. Premises to an answer

1. Direct and indirect effects of technology on poverty: Technology can help reduce poverty through both direct (income for adopters) and indirect (food price, wage, and employment) effects. Unless land is very equally distributed across farmers, indirect effects will derive more from technological change in the fields of large farmers than from technological change in the fields of small farmers. If technology (choice of crops, traits, and technological packages) is not the same for large and small farmers, and the generation of technology is costly with a budget constraint, then a trade-off exists in generating direct and indirect effects. Landless rural households and urban households can benefit from indirect effects, both as workers and consumers. Poor farmers can benefit from direct effects. However, many poor farmers also derive benefits from indirect effects. Hence, even if there is a tradeoff in the choice of technology between generating direct and indirect effects, small farmers are not necessarily losers when indirect effects are favored. Direct effects are, however, dominant for food self-sufficient and net food selling small farmers. Maximizing aggregate poverty reduction thus requires careful allocation of funds to research to seek the optimum balance between direct and indirect effects. CGE modeling of regional archetypes suggests that direct effects are dominant in Africa, indirect effects via employment creation in agriculture dominant in Asia, and indirect effects via the price of food dominant in Latin America. The optimum balance between direct and indirect effects needs to be established for every country and region. In poor agrarian regions, seeking technological advances that fit the crop and trait requirements of small farmer production systems is key for poverty reduction. In this case, seeking maximum productivity gains irrespective of farm type is insufficient.

2. Alternative sources of direct poverty reduction in agriculture: Biotechnology offers a huge potential for poverty reduction via technological innovations in small holder agriculture. However, other potentially cheaper and faster sources of income gains have not been exhausted, particularly: (1) Through institutional and policy changes, e.g., greater access to productive assets, improved property rights and contracts in

accessing land, more effective agrarian institutions in support of productivity growth such as microfinance, and policies that do not discriminate against agriculture and poor farmers. (2) Through other technological options such as information intensive management systems with traditional technologies, integrated pest management, and agroecology (Altieri and Hecht, 1990). Because biotechnology can only offer control over a few traits, these alternatives must be seen as complementary to biotechnology as well as options to reduce excessive reliance on one single instrument. To insure that other approaches and other technologies are properly combined with biotechnology, initiatives to promote the use of biotechnology need be embedded in comprehensive rural development and poverty reduction strategies.

3. Scientific uncertainty about biotechnology: The genetic structure of plants, with more that 80,000 genes in a typical crop plant, and the way plants interact with other species in an agroecological system are extraordinarily complex subjects. Information about the implications of genetic manipulation and the associated risks is limited, in part because the subject is so new. Long term effects, in particular, simply cannot be assessed for lack of experience. Highly emotional debates about the development of pest resistance, herbicide resistance, biosafety (gene flows, alteration of eco-systems), and food safety are in part based on irreconcilable vested interests and ethical considerations, but also on imperfect information. Hence, given the complexity of the subject and the primitive state of current knowledge, there is merit to err on the side of conservative and reversible options, particularly in the context of poor farmers with weak ability to absorb negative shocks and to abide to regulations. However, a careful balance needs to be achieved between these risks and the urgency of escaping from poverty.

7.3. What is new and different with agbiotechnology in terms of poverty? Positive analysis

Technological progress in developing country agriculture since the early 1960s can be decomposed into three epochs:

Green Revolution I (1965-1975): The main purpose of research was to achieve rapid increases in yields through HYVs, and success was immense, creating large indirect effects for the poor via declining staple food prices and rising employment in agriculture and related activities. Direct poverty reduction effects were, however, often small or negative (Scobie and Posada, 1978): HYVs were designed for the best areas (irrigation, soil high fertility) and diffused among commercial farmers, sometimes with backlash effects on non-adopting poor farmers through falling prices. GR I also often had negative environmental effects through genetic erosion and chemical run-offs.

Green Revolution II (1975-today): Research was aimed at the broadening of desirable traits to consolidate yield gains and to extend the benefits of the GR to other crops, areas, and types of farmers. This allowed the increase of pest resistance and the diffusion of HYV to rainfed areas. The benefits of the GR were thus extended toward small farmers, enhancing direct effects on poverty. These technological innovations were not able to prevent a steady decline in the growth of yields, reducing the pace of gains through indirect effects on poverty.

Green Revolution III or biotechnological revolution: The main differences from GR II can be summarized as follows:

1. Compared to traditional breeding (GR I and II) where trait identification and variety development were confounded, biotechnology dissociates research on traits (functional genomics) from product development (insertion of genes corresponding to traits into selected varieties). Hence, if information on relevant functional genomics exists and can be accessed through markets, contracts, or as public goods, developing countries can develop improved varieties without the need to engage in fundamental research. This has powerful implications for the division of labor in research between developed and developing countries and the type of capacity building needed in the latter, in this case principally to adapt these technologies to their own needs.

2. The current patenting system allows private appropriation of knowledge on genomics, the basic raw materials of biotech research. There is serious concern that such appropriation creates hurdles for access to the relevant materials for research in developing countries, public sector institutions, and the CGIAR and for downstream product development. Evolution of patent law is, however, still in full progress as it is drawn by case laws more than open national debates (Barton, Lesser, and Watal, 1999).

3. Genetic engineering increases widely the range of potential new traits for resistance to pests, tolerance to stress, improved food quality, and environmental sustainability. Some of these traits are favorable to the poor while others offer risks. Hence, who sets priorities for research on traits is key in determining the impact of biotechnological innovations on poverty.

4. Biotech allows an increase in the range of varieties of a crop to which new traits can be applied. Hence, the benefits of research on trait improvement that were confined to major varieties under GR II have greater potential to be extended to varieties used in peasant farming systems and in niche farming. This offers the potential of better serving small holders and preserving biodiversity.

5. Biotech allows reduction in the cost and increase in the speed of delivery of new varieties. It also changes the structure of research costs: it increases the costs of fundamental research, but lowers the costs of product development. At the same time, biotechnological research is complementary to traditional breeding since the new traits need to be inserted into the best possible local varieties in order to deliver the myriad of other traits that cannot be controlled by gene transfer.

6. The current state of knowledge in biotech processes only allows the stacking of a few traits by gene transfer. Hence, the question of which functions are to be achieved by gene transfers and which by traditional means (chemical pest management, integrated pest management, agroecology, etc.) needs to be assessed for each particular set of circumstances. Use of biotechnology in precision farming requires the ability to assemble these technological packages for each particular agroecological and social-institutional environment, opening the need for a new approach to farm management science.

6. By embodying traits in the seed, biotechnology changes the structure of costs for farmers from variable costs (insecticides) to fixed costs (seeds with biopesticides). While the acquired traits can be beneficial in expected value, this has several implications for poor farmers: partial and sequential adoption of pest control is prevented, fixed costs are increased, beginning-of-season liquidity requirements are raised, and risks are enhanced as seed expenditures are committed.

7. Biotechnolgy takes breeding science into unchartered territories. Hence, the need for regulation of environmental and food safety effects is enhanced, increasing the role of the public sector in defining rules and of local communities in monitoring and enforcing them. Regulation poses a set of specific problems for implementation in developing countries and among large numbers of poor small holders.

8. While GR I and GR II research generated public goods, agbiotech research is largely in the private domain, with appropriability of profits anchored in IPRs. Consequently, current agbiotech innovations are largely private goods, developed for use in the North (non-food crops particularly feed and fiber, labor-saving and capital-intensive methods, consumer quality enhanced crops, and substitutes for crops imported from developing countries), and controlled by a small number of multinational corporations with no particular concern for poverty reduction objectives but with the possibility of being enlisted for poverty reduction if a source of profits. There currently are important gaps that need to be filled to make biotech innovations relevant for poverty reduction in developing countries: research on staple foods for tropical and semi-tropical environments, labor intensive technologies, and traits for peasant farming systems. Institutional mechanisms need to be devised to fill these research gaps, including defining the new role of the public sector and the CGIAR.

9. Analysis of the source of patents in agbiotechnolgy shows the sequential role of the public sector, biotechnology firms, and the corporate sector in the patenting of research. Effective linkages between these institutions is thus important for research to yield useful products.

10. A large number of technologies are involved in the development of a final product, and ownership over these technologies are often scattered over a number of institutions. Concentration of patent ownership in the corporate sector through acquisitions and mergers evidences these technological complementarities in product development and existence of serious market failures in the acquisition of property rights over the technologies involved in product development.

11. With some 75% of world investment in agbiotech research coming from the private sector, the public sector and the CGIAR are increasingly seeking to develop research partnerships with the private sector. Design of these partnerships is complex since the objectives of partners are at odds: the private sector pursues profits, while the public sector and the CGIAR are pursuing the delivery of public goods.

12. By offering "smart seeds" (e.g., plants that self-protect with biopesticides or can adapt to stress), human capital requirements at the level of users are reduced compared to use of chemicals or of integrated pest management, a feature favorable to diffusion among poor smallholders. However, human capital requirements are pushed upstream toward the institutions developing and delivering adoptable packages containing GMOs and managing regulatory frameworks.

13. Since biodiversity is the raw material for agbiotech research, and much of the relevant biodiversity is located in developing countries and peasant farming communities, access to biodiversity can potentially be used as a source of leverage for bartering access to the products of agbiotech innovations.

14. At the same time, releasing genetically-engineered crops in developing countries that are centers of origin and diversity of these crops (such as maize in Mexico, wheat in the Middle East, and potatoes in Peru) creates higher risks of gene flows in nature and weediness. The need for strict biosafety regulations is consequently greater precisely where they are more difficult to implement, calling for innovative approaches in institutional design.

7.4. Main conclusions: normative analysis

1. Overall conclusion: the role of institutional innovations

Agricultural biotechnology has great promise for poverty reduction, both through direct and indirect effects, with flexibility to strike differential balances between these two sets of effects to reduce aggregate poverty according to country characteristics. Failing to capture this potential offered by agbiotech would be both a serious missed opportunity in the struggle against poverty and a risk that the competitiveness of smallholders in developing countries be further weakened relative to that of other producers and other countries. However, meeting the institutional requirements for this promise to become a reality is highly demanding. Hence, the effort will fail or succeed not so much depending on ability to progress in biological sciences as on the ability to put in place the necessary institutions for the generation, transfer, delivery, and adoption of biotechnological innovations favorable to poverty reduction. Since weak institutional development is an integral feature of under-development, and a pro-poor bias in these institutions is notably lacking, this poses particular difficulties in achieving success that need to be pro-actively addressed.

2. Generation of biotechnological innovations

Institutional requirements to secure the generation of biotechnologically modified crops and animals with traits favorable to poverty reduction should include the following:

i) An IPR regime that does not hamper further fundamental research and downstream product development, particularly for public institutions, international organizations such as the CGIAR, and NGOs that have a concern for the poor. Questioning the features of current patent systems and guiding their future evolution should thus be an integral part of efforts to maximize the role of biotechnology for poverty reduction.

ii) Development of efficient markets for the trading of patented materials. An open system of access to biotechnologies and genetic information that links public and private sectors, and North and South is thus essential.

iii) IPR regimes that recognize the legitimate ownership rights of traditional farming communities over biological resources and give them leverage in gaining access to the private products of biotechnology. Experimentation with innovative contracts to reconcile farmers ownership rights over biodiversity and bio-prospecting (UNEP, 1998).

iv) Development of the capacity of the national academic and public sectors to engage in fundamental research complementary to that of the North, to test alternative technological options, to adopt technology to their own needs, and to engage in product development. Definition of capacity thus depends on the particular balance between these functions. This should be pursued on a regional basis for small and poor countries.

v) Participation of poor producers in the setting of priorities for applied research and product development, particularly regarding choice of crops, traits, and farming systems. Effective participation requires pro-active information campaigns to empower the poor.

vi) Promotion of cooperative arrangements (partnerships, consortia, contract research) bringing together corporate, non-profit, public, and international institutions for the development of biotech products favorable to poverty reduction. Experimentation to identify best practice for these arrangements is needed (ISAAA, 1997).

vii) Coordination of private sector initiatives toward market expansion among smallholders, allowing them to overcome the commons problem typical of such investments.

viii) Enhanced public sector and CGIAR research budgets to work on crops and traits not addressed by private sector research that are important for the rural poor. Declining real budgets for the CGIAR should thus be an issue of concern if the potential of biotechnology for the poor is to be captured.

ix) Institutions to link public and CGIAR research to private sector product development through offices of technology transfer attached to universities and public research institutes, venture capital for the financing of agbiotech companies, and institutions for the fair and effective enforcement of property rights.

x) Use of defensive patents on CGIAR and public sector research innovations that have high potential for poverty reduction with the purpose of keeping them expressedly in the public domain. Due to costs and legal complexities, patents will likely be taken in joint ventures with the private sector. Identification of best practices for such contracts is urgently needed.

3. Transfer of technologies and the delivery of products

Institutions to link the results of research to the delivery of products adoptable by developing country farmers and particularly small holders include the following:

i) Public and non-profit sector roles in the insertion of new traits in poor farmer crops and varieties with insufficient market size to provide private sector initiatives. Assembly of idiosyncratic technological packages combining traits controlled by gene insertion with functions delivered by other approaches such as chemical pest management, IPM, and agroecology.

ii) Development of a regulatory framework for biosafety and consumer protection that corresponds to each country's preferences for risk and expected income gains, which change with stages of development.

iii) Decentralization of the monitoring and enforcement of biosafety regulations to the community level, based on community-level cooperation and verification by central agencies.

iv) Development of institutional mechanisms (such as labeling) and production contracts for identity-preservation of improved small-farmer products.

v) Discriminatory pricing of genetically modified seeds if market segmentation between poor and non-poor is possible.

vi) Subsidies to marketing strategies that promote adoption of new technologies favorable to poverty reduction.

vii) Incentives to insert new traits into a wide range of alternative varieties, allowing better adaptation to local conditions and preservation of biodiversity.

viii) Promotion of the private sector to deliver integrated services to small holders using GMOs and modern inputs.

4. Adoption by small holders

Institutions to reduce poverty among smallholders by supporting adoption of favorable technologies include:

i) Organization of credit schemes to face higher and earlier liquidity requirements in the purchase of seeds with improved trait content that are protected by IPRs, and potentially subject to non-competitive pricing.

ii) Insurance and risk sharing mechanisms to absorb higher risks associated with committed seed expenses and higher cash outlays.

iii) Promotion of grassroots organizations such as service cooperatives in support of contract farming with smallholders for the acquisition of information on GMOs, access to modern inputs, and production of improved agricultural products.

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Table 1. Importance of rural poverty in total poverty

	Year	Rural Po %	Urban Po %	Total Po %	Rural population % of total	% of total poverty that is rural
Middle East						
Yemen Rep	1992	19	19	19	83	84
Morocco	1991	18	8	13	53	73
Algeria	1995	30	15	23	51	68
Tunisia	1990	22	9	14	41	63
South Asia						
Nepal	1995	44	23	42	90	95
Bangladesh	1995	40	14	36	84	93
China	1995	9	2	7	64	90
Sri Lanka	1991	38	28	35	71	77
India	1994	37	31	35	73	76
Pakistan	1991	37	28	34	67	73
Mongolia	1995	33	39	36	41	37
South-East Asia						
Vietnam	1993	57	26	51	80	90
Lao PDR	1993	53	24	46	76	88
Thailand	1992	16	10	13	55	65
Indonesia	1990	14	17	15	68	64
Philippines	1991	71	39	54	47	62
Central Asia						
Kyrgyz Rep	1993	48	29	40	58	70
Africa						
Lesotho	1993	54	28	49	82	90
Guinea-Bissau	1991	61	24	49	67	84
Kenya	1992	46	29	42	74	82
Sierra Leone	1989	76	53	68	65	73
Zambia	1991	88	46	68	52	68
Ghana	1992	34	27	31	62	68
Nigeria	1992	36	30	34	62	66
Cameroon	1984	32	44	40	37	30
Latin America						
Dom Rep	1992	30	11	21	51	74
Colombia	1992	31	8	18	42	74
Nicaragua	1993	76	32	50	42	63
Ecuador	1994	47	25	35	45	61
Honduras	1992	46	56	50	60	55
El Salvador	1992	56	43	48	41	48
Paraguay	1991	29	20	22	24	31
Latin America (data from CEPAL)						
Panama	1994	41	25	32	45	58
Costa Rica	1994	23	18	21	51	57
Honduras	1994	76	70	73	53	55
Peru	1994	68	42	50	28	39
Mexico	1994	47	29	34	25	35
Brazil	1993	51	39	42	22	27
Chile	1994	26	24	24	14	15
Venezuela	1994	48	32	33	8	11
Simple average, all countries		43	28	36	54	63

Sources: World Bank, World Development Indicators; and CEPAL, Social Panorama, 1996

Table 2. Importance of off-farm income for the rural poor

Country	Percentage of households	% share of off-farm income in total household income	% share of wage income in total household income	Source
Farm households				
Nicaragua	45% smallest farms	61		B. Davis et al. (1998)
Mexico (ejido)	57% smallest farms	76		de Janvry et al. (1997)
Panama	73% smallest farms	61		World Bank, LSMS (1998)
Chile	60% poorest	67		Lopez and Valdes (1997)
Paraguay	66% poorest	19		Lopez and Valdes (1997)
Pakistan	71% smallest farms	47		IFPRI Pakistan survey, 1986-89
Simple average		55		
Rural households				
El Salvador	60% poorest	80	45	Lopez and Valdes (1997)
Ecuador	60% poorest	86	54	ECV (1995)
Panama	50% poorest	68		World Bank, LSMS (1998)
Burkina Faso, Sahelian	All	57	2	Reardon et al. (1988)
Burkina Faso, Sudanian	All	65	26	Reardon et al. (1988)
Pakistan	50% poorest	50		IFPRI Pakistan survey, 1986-89
Simple average		68		

Table 3. Characteristics of the regional archetypes

	Africa	Asia	Latin America
Share of agriculture in GDP	47.4	32.0	13.6
Sectoral shares in agriculture			
Export crops	28.0	24.9	33.2
Cereals	45.2	27.7	
Other ag.	26.8	47.4	66.8
Share of labor in ag.value-added	10.4	48.1	45.3
Substitutability domestic/foreign commodities			
Export crops[1]	1.2	1.2	0.8
Cereals[2]	0.3	30	
Other agriculture[2]	0.5	3.0	1.2
Household income shares			
Share of rural households in total household income	61.1	69.8	24.3
Share of urban households in total household income	38.9	30.2	75.7
Share of poor rural households in total rural income	65.7	82.9	58.0
Share of poor urban households in total urban income	59.3	55.2	49.8
Share of poor rural households in total poor households income	63.5	77.7	27.2
Rural poor			
Share of on farm agricultural income in total household income	67.3	25.6	16.4
Share of off-farm labor income in total household income	31.6	41.4	63.2
Share of non-ag. self-employment and other income in total household income	1.1	33.0	20.4
Share of agricultural commodities in total consumption	71.9	40.2	13.7
Share of agricultural consumption produced at home	100.0	67.3	100.0
Urban poor			
Share of agricultural commodities in total expenditures	43.5	33.2	9.0

[1] Elasticity of substitution in CET export-domestic market allocation.

[2] Elasticity of substitution in CES import aggregate.

Table 4. Direct and indirect effects of technological changes on the real income of the poor, African arch

	10% increase in total factor productivity			10% increase in land productivity		
	All crops	Cereals	Other ag.	All farmers	Poor farmers†	Non-poor farmers†
Aggregate effects (growth rates)						
Real GDP	6.8	2.9	2.0	6.8	5.1	1.7
Agricultural production	10.0	3.9	2.8	10.0	7.8	2.2
Food price	-6.0	-12.0	-1.2	-6.3	-3.9	-2.7
Urban poor ($ per capita)						
Direct effect	0.0	0.0	0.0	0.0	0.0	0.0
Indirect nominal income effect	2.2	-0.4	-0.4	2.4	1.9	0.5
Consumer price effect	0.0	1.2	1.2	0.0	-0.1	0.2
Total real income effect	2.2	0.9	0.8	2.4	1.8	0.7
Rural poor ($ per capita)						
Direct effect	5.0	2.4	-0.1	4.5	4.8	-0.2
Indirect nominal income effect	1.6	-0.1	-0.1	2.0	1.5	0.4
Consumer price effect	-0.1	1.0	0.7	0.0	-0.2	0.1
Total real income effect	6.5	3.4	0.4	6.4	6.2	0.3
Share of direct effect (%)	77.1	72.0	-30.1	69.8	77.9	-61.1
Share of indirect effect (%)	22.9	28.0	130.1	30.2	22.1	161.1
All poor ($ per capita)						
Direct effect	5.0	2.4	-0.1	4.5	4.8	-0.2
Indirect nominal income effect	3.8	-0.4	-0.4	4.4	3.4	0.9
Consumer price effect	-0.1	2.2	1.8	0.0	-0.3	0.3
Total real income effect	8.7	4.3	1.2	8.9	8.0	1.0
Share of direct effect (%)	57.7	57.1	-10.7	50.6	60.6	-19.5
Share of indirect effect (%)	42.3	42.9	110.7	49.4	39.4	119.5
Share of rural poor (%)	74.8	79.3	35.5	72.5	77.8	31.9
Share of urban poor (%)	25.2	20.7	64.5	27.5	22.2	68.1

Note: Direct effects include home consumption and self-employment on farm.
† Poor farmers include small and medium farmers. Non-poor farmers include the large farmers.

Table 5. Direct and indirect effects of technological changes on real income of the poor, Asian and Latin American archetypes

	Asia	Latin America		
	10% increase in TFP in all crops	10% increase in TFP in all crops	10% increase in land productivity	
			Poor households†	Non-poor households†
Aggregate effects (growth rates)				
Real GDP	5.1	3.7	1.1	2.8
Agricultural production	8.7	7.9	2.2	5.8
Food price	-2.0	-6.5	-2.0	-5.2
Urban poor ($ per capita)				
Direct effect	0.0	1.9	1.4	-0.5
Indirect nominal income effect	3.9	33.3	10.5	27.8
Consumer price effect	-0.9	-12.3	-3.2	-8.7
Total real income effect	3.0	23.0	8.7	18.6
Rural poor ($ per capita)				
Direct effect	2.8	2.6	1.7	-1.1
Indirect nominal income effect	8.2	14.1	3.3	12.4
Consumer price effect	-3.3	-6.9	-1.9	-5.0
Total real income effect	7.6	9.8	3.1	6.4
Share of direct effect (%)	36.5	26.9	53.4	-17.1
Share of indirect effect (%)	63.5	73.1	46.6	117.1
All poor ($ per capita)				
Direct effect	2.8	4.5	3.0	-1.6
Indirect nominal income effect	12.0	47.4	13.8	40.2
Consumer price effect	-4.2	-19.1	-5.1	-13.7
Total real income effect	10.6	32.8	11.8	25.0
Share of direct effect (%)	26.3	13.7	25.6	-6.4
Share of indirect effect (%)	73.7	86.3	74.4	106.4
Share of rural poor (%)	71.8	29.9	26.3	25.5
Share of urban poor (%)	28.2	70.1	73.7	74.5

Note: Direct effects include home consumption and self-employment on farm.
† Poor households include small farmers and the urban poor.
Non-poor households include medium and large farmers and the urban non-poor.

Table 6. U.S. Patents on Bt technologies, by type of innovating institution

	University and public institutions				Biotech firms and individuals				Corporate sector					Total
Year	All	% of total	University	Public institution	All	% of total	Small biotech.	Individuals	All	% of total	Chemical	Pharma.	Seed	
1976	0	0%	0	0	2	40%	2	0	3	60%	0	3	0	**5**
1977	0	0%	0	0	0	0%	0	0	1	100%	0	1	0	**1**
1978	0	0%	0	0	1	100%	1	0	0	0%	0	0	0	**1**
1979	1	50%	0	1	1	50%	1	0	0	0%	0	0	0	**2**
1980	3	100%	0	3	0	0%	0	0	0	0%	0	0	0	**3**
1981	3	100%	0	3	0	0%	0	0	0	0%	0	0	0	**3**
1982	2	100%	0	2	0	0%	0	0	0	0%	0	0	0	**2**
1983	0	---	0	0	0	---	0	0	0	---	0	0	0	**0**
1984	2	100%	2	0	0	0%	0	0	0	0%	0	0	0	**2**
1985	0	---	0	0	0	---	0	0	0	---	0	0	0	**0**
1986	1	100%	1	0	0	0%	0	0	0	0%	0	0	0	**1**
1987	0	0%	0	0	3	75%	3	0	1	25%	0	1	0	**4**
1988	0	0%	0	0	2	67%	2	0	1	33%	0	1	0	**3**
1989	1	8%	0	1	7	54%	7	0	5	38%	0	4	1	**13**
1990	2	15%	0	2	9	69%	9	0	2	15%	1	1	0	**13**
1991	1	5%	1	0	16	84%	14	2	2	11%	2	0	0	**19**
1992	2	11%	1	1	17	89%	17	0	0	0%	0	0	0	**19**
1993	0	0%	0	0	26	74%	24	2	9	26%	6	2	1	**35**
1994	4	13%	1	3	24	75%	23	1	4	13%	1	3	0	**32**
1995	1	4%	0	1	20	83%	20	0	3	13%	2	1	0	**24**
1996	3	9%	2	1	17	52%	17	0	13	39%	8	2	3	**33**
1997	4	15%	4	0	17	63%	17	0	6	22%	2	4	0	**27**
1998	9	15%	6	3	25	42%	25	0	26	43%	10	15	1	**60**
1999 est[1]	8	8%	8	0	36	36%	36	0	56	56%	4	44	8	**100**
Total[2]	**47**	**12%**	**26**	**21**	**223**	**55%**	**218**	**5**	**132**	**33%**	**36**	**82**	**14**	**402**
76-86 avg.	1.1	60%			0.4	20%			0.4	20%				1.8
87-95 avg.	1.2	7%			13.8	77%			3.0	17%				18.0
96-99 avg.	6.0	11%			23.8	43%			25.3	46%				55.0

[1] 99 est. is first quarter 1999 data multiplied by four.
[2] Totals include 1999 estimates.

Fig. 2. Annual flow of Bt patents granted by type of innovator

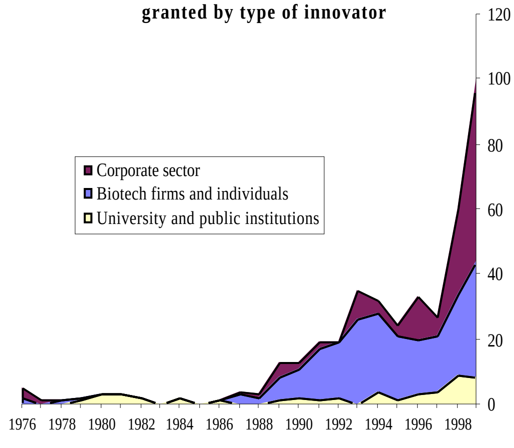
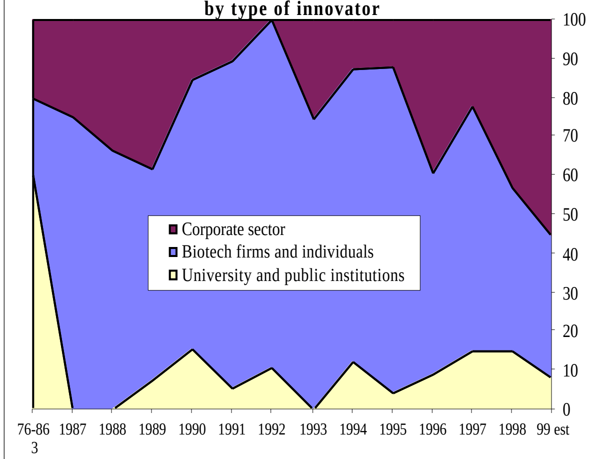


Fig. 3. Annual proportions of Bt patents granted by type of innovator



[3] Data for years 76-86 aggregated to show proportions of pioneering patents

Table 7. Stocks of U.S. patents in force on Bt technologies by controlling ownership in selected years

Year	Big 6[1]	Other Private: All	Other Private: Other corporate	Other Private: Independent biotech.	Other Private: Individual	Public and University: All	Public and University: University	Public and University: Public institution	Total
Stock in 87[2]	3	9	3	6	0	12	3	9	**24**
Stock in 94[3]	13	116	16	95	5	22	6	16	**151**
Stock in 99[3,4]	261	87	41	41	5	38	25	13	**386**

[1] Big 6 are Dow, Novartis, Aventis, Monsanto, AstraZeneca, DuPont and their subsidiaries
[2] Patents granted between 1976 and 1987
[3] Patents granted over previous 17 years
[4] Full-year 1999 estimates included; are first quarter 1999 data multiplied by four.

Fig. 4. Proportions of ownership of the stock of Bt patents in force in 1987, 1994, and 1999

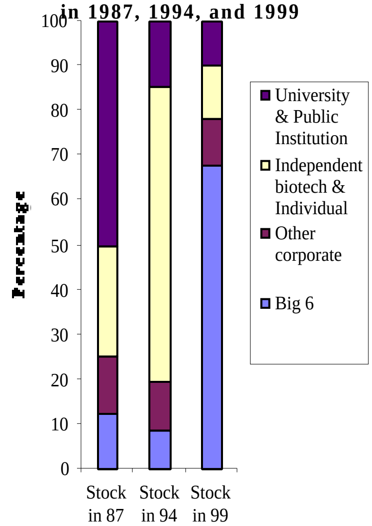


Fig. 5. Source of patents controlled by the Big 6 firms in 1987, 1994, and 1999

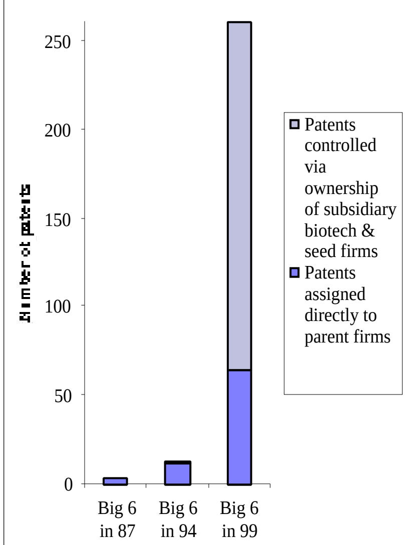


Table 8. Flow of technology disclosures in Bt patents granted 1976-1999

Year	Novel Bt strains, toxins, genes		Genetic Processes		Bt Insecticidal Compounds		Bt Modification of Crops		**Total Disclosures**	Total Patents	Average disclosures per patent
	Disclosures	% of total	Disclosures	% of total	Disclosures	% of total	Disclosures	% of total			
1976	4	44%	0	0%	5	56%	0	0%	**9**	5	1.80
1977	1	50%	0	0%	1	50%	0	0%	**2**	1	2.00
1978	0	0%	0	0%	1	100%	0	0%	**1**	1	1.00
1979	1	33%	0	0%	2	67%	0	0%	**3**	2	1.50
1980	2	40%	0	0%	3	60%	0	0%	**5**	3	1.67
1981	1	25%	0	0%	3	75%	0	0%	**4**	3	1.33
1982	0	0%	0	0%	2	100%	0	0%	**2**	2	1.00
1983	0	---	0	---	0	---	0	---	**0**	0	---
1984	0	0%	2	50%	2	50%	0	0%	**4**	2	2.00
1985	0	---	0	---	0	---	0	---	**0**	0	---
1986	1	50%	0	0%	1	50%	0	0%	**2**	1	2.00
1987	2	29%	1	14%	4	57%	0	0%	**7**	4	1.75
1988	3	60%	0	0%	2	40%	0	0%	**5**	3	1.67
1989	10	50%	1	5%	8	40%	1	5%	**20**	13	1.54
1990	12	41%	5	17%	12	41%	0	0%	**29**	13	2.23
1991	18	50%	4	11%	13	36%	1	3%	**36**	19	1.89
1992	18	55%	2	6%	13	39%	0	0%	**33**	19	1.74
1993	32	58%	6	11%	15	27%	2	4%	**55**	35	1.57
1994	27	60%	4	9%	12	27%	2	4%	**45**	32	1.41
1995	23	61%	6	16%	7	18%	2	5%	**38**	24	1.58
1996	28	53%	11	21%	9	17%	5	9%	**53**	33	1.61
1997	22	50%	8	18%	9	20%	5	11%	**44**	27	1.63
1998	50	48%	21	20%	26	25%	7	7%	**104**	60	1.73
1999 est.[1]	80	49%	40	24%	24	15%	20	12%	**164**	100	1.64
Total[2]	**335**	**50%**	**111**	**17%**	**174**	**26%**	**45**	**7%**	**665**	**402**	**1.65**
76-86 avg.	0.91	31%	0.18	6%	1.82	63%	0.00	0%	2.91	1.82	1.59
87-95 avg.	16.11	54%	3.22	11%	9.56	32%	0.89	3%	29.78	18.00	1.71
96-99 avg.	45.00	49%	20.00	22%	17.00	19%	9.25	10%	91.25	55.00	1.65

[1] 99 est. is first quarter 1999 data multiplied by four.

[2] Totals include 1999 estimates.

Fig. 6. Flow of new Bt technology disclosures in patents granted 1976-1999

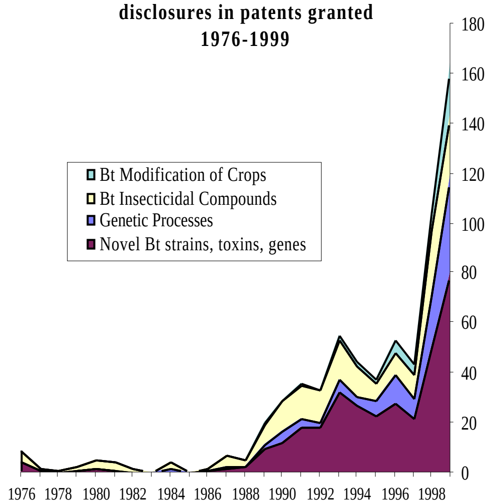
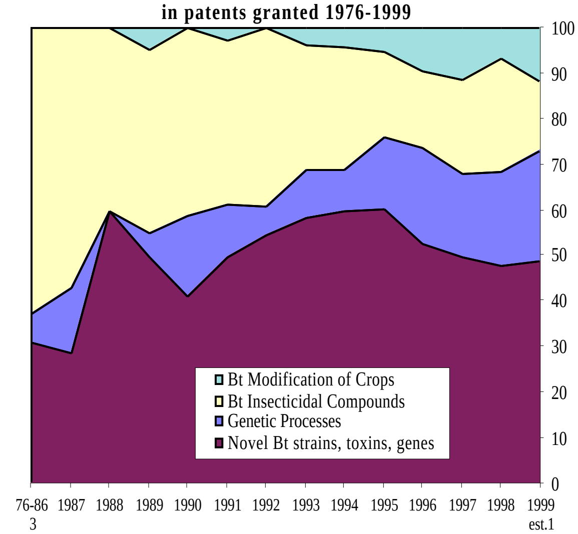


Fig. 7. Proportions of new Bt technology disclosures in patents granted 1976-1999



[3] Data for years 76-86 aggregated to show proportions of pioneering patents

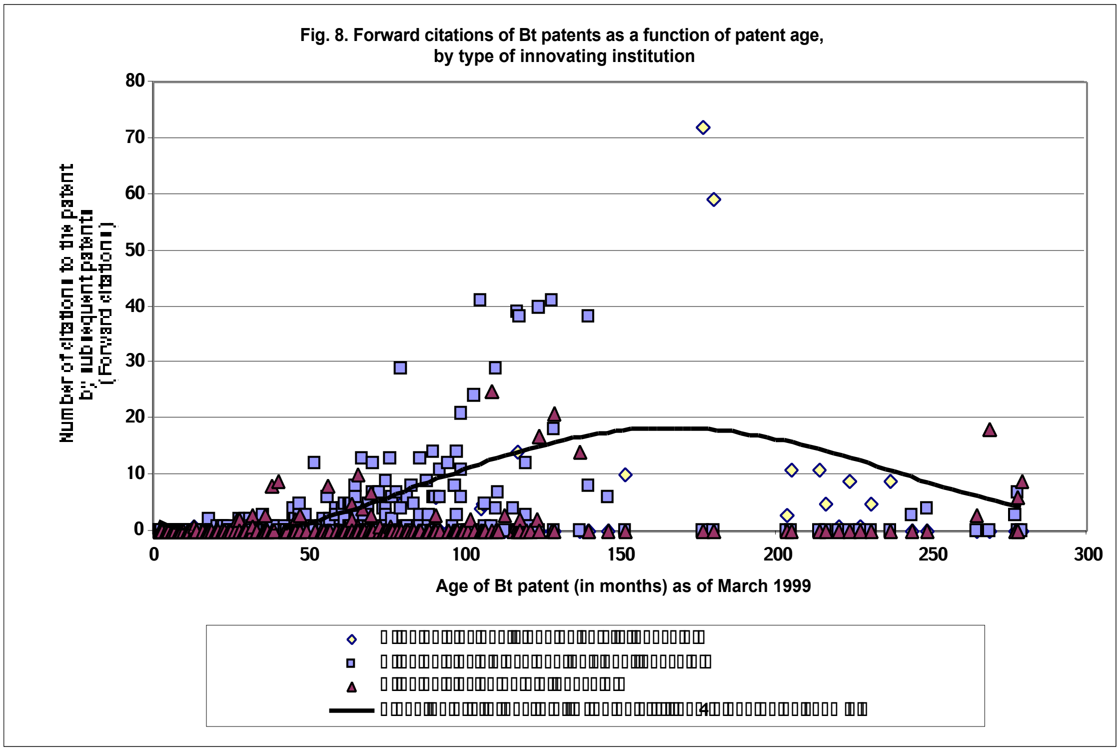


Table 9. Deviation of patent citations from trendline, by type of innovator

	Public and university	Biotech and individual	Corporate	Ovarall
Average Deviation	-0.22	0.22	-0.37	0.00
Variance of Deviations	137.32	38.06	18.14	44.64