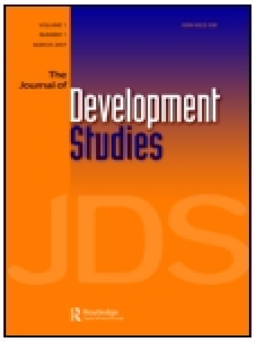

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The Impact of Agricultural Biotechnology on Yields, Risks, and Biodiversity in Low-income Countries

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ABSTRACT *This paper shows that the current generation of transgenic crop varieties has significant potential to improve economic welfare in low-income countries. These varieties might increase crop yields in low-income countries in cases when pesticides have not been used. They will reduce negative health effects of chemicals when they replace them. With low transaction costs, appropriate infrastructure, and access to intellectual property, multiple varieties of transgenics will be introduced. The gain from transgenics will be reduced, and crop biodiversity may be lost when only a small set of varieties is transgenetically modified. The adoption of transgenics will also be affected by risk and credit considerations.*

I. Introduction

Agricultural biotechnology has been introduced primarily to meet market needs of farmers in rich countries; there are concerns that this technology will not be appropriate for, or serve the needs of, farmers in the South. One concern lies with the yield-enhancement potential of agricultural biotechnology, a major priority for new crop varieties in the South, due to the modest yield effects from use of transgenic varieties (TGVs) thus far in the North (Altieri, 2001). Other concerns are that TGVs are introduced by private-sector organisations that tend to offer a limited range of choices and that the introduction of TGVs may accelerate loss of crop biodiversity.

This paper relies on economic logic to analyse the impacts of TGVs on yields and crop biodiversity. To develop our argument, we introduce a framework to analyse adoption of TGVs. Our analysis suggests that the introduction of TGVs may have different yield effects in different countries, reflecting differences in economic and

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climatic conditions, and that *TGVs may actually have significant yield effects in low-income countries.* We use empirical results from China, India, and other countries to support our theoretical predictions. We also show that TGVs play a risk-reducing role, and develop a framework to assess the impacts of pest infestation risks on adoption of TGVs. Finally, we argue that under a range of plausible circumstances, introduction of TGVs may not lead to a reduction in crop biodiversity and, in some cases, may actually lead to its enhancement. Thus, some of the concerns about the limited value of TGVs for low-income countries are misplaced. Moreover, the real challenge is to develop the institutional setup that will allow low-income countries to take advantage of the potential of TGVs.

II. The Yield Effects of TGVs: A Conceptual Approach

Pest-resistant TGVs are the primary types of TGVs that have been introduced and used by farmers. These varieties have been modified primarily through the insertion of *Bt* genes into seeds and hybrids of cotton, corn, soybeans, and so forth. Herbicide-resistant varieties have also been developed, most notably, varieties that tolerate Roundup. Our conceptual analysis considers the various impacts of 'pest reducing' TGVs. This generalisation fits Roundup Ready (RR) varieties, but it is more appropriate when analysing *Bt* varieties. This is a simple version of a model introduced in Ameden et al. (2005); it will show that the same technology may have different impacts in different locations depending on prevailing economic and environmental conditions.

We consider a farm with a fixed amount of land where the farmer can vary the quantity of pesticides used and choose a crop variety to produce an agricultural crop. We assume that the farmer can grow three varieties – a traditional variety, denoted as variety L; a TGV version of this local variety denoted as variety M; and a generic TGV denoted as variety G. The output of the traditional variety is denoted by $Y(L)$, the local TGV by $Y(M)$, and the generic TGV by $Y(G)$. Using the damage-control specification of Lichtenberg and Zilberman (1986), the output of each variety is equal to the potential output ($POTY$) net of pest damage, $Y = POTY * (1 - DAMAGE)$, where potential output is the maximum output produced without pest damage. While the potential output of the traditional and local TGV is assumed to be the same, the potential yield of the generic TGV is assumed to be lower. The variable $DAMAGE$ is the fraction of output damaged by pests. Pest damage depends on the original size of the pest infestation ($NoPest$), the quantity of pesticides applied ($Pesticide$), and whether the crop variety was a TGV. The damage can be expressed as a function (F) of these factors:

$$DAMAGE = F(NoPest, Pesticide, TGV),$$

where TGV is an indicator that assumes a value of 0 for the traditional technology and 1 for TGVs.

The TGVs reduce pest damage substantially. Given initial pest infestation and pesticide application, only a small fraction of the damage that occurs with a traditional variety occurs with a TGV. Figure 1 depicts the relationships in the production process.

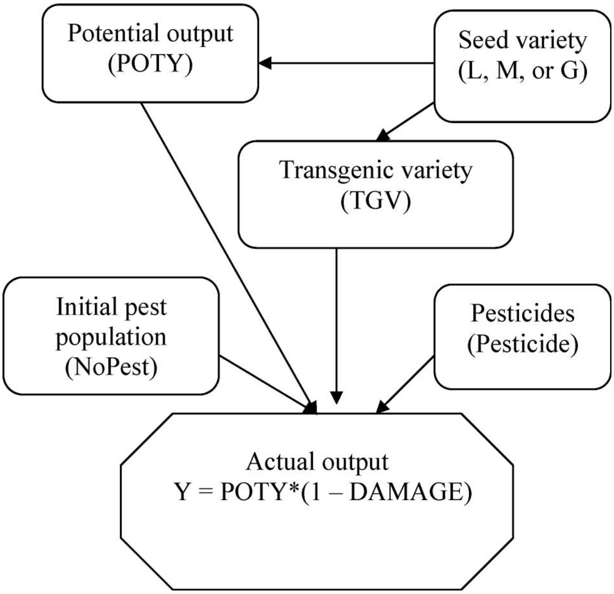

Figure 1. The damage control mechanism

Farmers are assumed to pursue profits, and their gain from application of pesticides is different across varieties. Pesticide application levels are also different across varieties. Therefore, to determine the impact of TGVs on yield given a specific pest infestation level, we must compute the amount of pesticides that would be applied with each variety and assess the yield effect accordingly. The revenue from production is a product of output price (*Yprice*) and output (*Y*).[1] The short-term profits the farmer is assumed to maximise are equal to revenue minus the fixed and variable costs of pesticides. The fixed cost of pesticides, denoted by *Fixpest*, consists of the costs of application equipment and the number of times needed to apply the pesticides. The variable cost of pesticides, denoted by *Pprice*, is the product of the amount of pesticides applied and its price. Thus, operational profits (*OProfits*), which exclude the costs of production and seeds that are used earlier in the season before the arrival of the pests, is the difference between revenues and pesticide costs,

$$Oprofits = Y * Yprice - Pesticide * Pprice - Fixpest.$$

For each variety, the farmer determines whether or not pesticides would be used and, if pesticides are used, how much should be applied. To answer this question, the farmer has to compare maximum short-term profits with no pesticide use and maximum short-term profits with pesticide use. The short-term profits without pesticides is equal to the output price times the yield with untreated pest infestation. The short-term profits, assuming pesticides are used, is the revenues when the pest infestation is treated minus the cost of the pesticides and the fixed costs of application. When pesticides are applied, the optimal level of pesticide use is determined where the incremental gain from increased pesticide use (because of higher yield) is equal to the incremental costs of pesticides.[2] In determining whether or not to apply pesticides, the farmer compares the trade-offs between the extra revenues associated with the damage reduction and the additional cost of the pesticides and their application. Pesticides will be applied if the return from higher yield covers both fixed and variable costs of pesticide applications.

Ameden et al. (2005) show that when pesticides are applied, the quantity applied is likely to increase as the output price or potential output are higher, the damage avoided is more valuable, and the price of the pesticides is lower. Also, pesticide use increases with the size of the initial pest infestation. The likelihood that pesticides are applied (nonzero pesticide) is likely to decline as the fixed costs or the variable costs of pesticides increase. Moreover, the use of pesticides is likely to decrease as TGVs are adopted because the genetic modification reduces pest damage substantially and serves as a substitute for chemical pesticides, reducing their value and productivity.

A very likely outcome is that it is optimal to apply pesticides with the traditional variety and not with the TGVs. Even when pesticides are applied, both with and without TGVs, the adoption of TGVs will reduce pesticide use. The pesticide-saving effect associated with adoption of TGVs is higher the greater is the application level with the traditional variety, and the greater is the efficacy of the TGV in pest control. However, because the potential output of the generic TGV is smaller that the local TGV, fewer chemicals are likely to be applied with the generic TGV, that is,

$$Pesticide\ (L) > Pesticide\ (M) > Pesticide\ (G).$$

Ameden et al. (2005) show analytically that, when a TGV is used instead of the traditional variety, the genetic modification along with the pesticide use will reduce pest damage, resulting in higher yields, and that this effect is likely to be greater in low-income countries. This yield effect depends on the effectiveness of the TGVs and the fixed and variable costs of pesticides. If the fixed and variable costs of pesticide use are low and productivity of pesticides is limited, then the yield effect of TGVs is low. This is likely to be the case in rich countries where pesticides are relatively inexpensive and pesticide-use levels are high, eliminating most pest damage. On the other hand, if pesticide prices and fixed costs of applications are very high relative to output price, as they tend to be in low-income countries, and availability of effective pesticides is severely limited, then pesticide application rates will be low and may even be zero. This, coupled with the humid climates of poor countries (as opposed to the temperate climates of rich countries), is likely to result in much higher initial levels of pest infestations and associated pest damage. Thus, in low-income countries, the introduction of TGVs has significant potential to reduce pest damage and increase yields.

The yield effect of TGVs depends on the specific variety adopted. When a local TGV is adopted, the lower pest damage will result in higher yield ($Y\,(M) > Y\,(L)$). If farmers adopt the generic TGV rather than the local TGV, the damage-reduction effect is countered by the lower potential yield of the generic variety. Thus, the net yield effect of the generic TGV is not clear. The yield effect of generic TGV is positive, $Y\ (G) > Y\ (L)$, only if the damage reduction effect (that is, $POTY\ (L) * DAMAGE\,(L) - \mathrm{POTY}\ (G) * DAMAGE\ (G)$) is greater than the yield loss effect (that is, $POTY\ (L) - POTY\ (G)$).

This analysis is supported by several studies on the impacts of *Bt* cotton. Frisvold and Tronstad (2003) document relatively low yield effects (5 per cent and below) in the United States where pesticide use is widespread. Huang et al. (2002) and Pray et al. (2002) analyse the impacts of adoption of *Bt* cotton in China, where pesticides are highly subsidised. They find only modest increases in yield but drastic reductions in pesticide use associated with improved worker safety. On the other hand, Qaim and Zilberman (2003) find dramatic yield increases in India in 2002. They analyse the results from 157 farms that planted each of the three varieties (a traditional variety, a TGV of the traditional variety, and a generic TGV) on different plots. Qaim and Zilberman (2003) find that the TGVs reduced pesticide use by 67 per cent, the local TGV increased yield on average by 87 per cent, and the generic TGV by 80 per cent. They suggest that the high yield effects were the result of high pest infestations levels in the year of the study and that impacts were smaller in other years. Qaim et al. (2005) show that during the season 2002–03 the estimated yield effect of *Bt* cotton in India was 34 per cent. There was a 50 per cent reduction on insecticide use on *Bt* cotton plots, and it generated $100 of extra profit per hectare (Ha.) relative to conventional cotton. Roy (2003) reports on the adoption of *Bt* cotton in some areas of India and finds that in certain areas, adopters had low yields and suffered losses. She argues that in most of these cases a generic, imported TGV replaced local varieties. Her findings highlight the importance of variety choice on the success of TGVs. Herring's (2003) analysis of TGVs in India strongly demonstrates that there are significant variations in yield effects of TGVs between seasons, and that suggests that current analyses of the impacts of TGVs should be modified to accommodate this randomness.

III. Random Infestation and the Adoption Decision

The literature on adoption and impacts of TGVs has relied heavily on deterministic models, though empirical evidence suggests that pest damage and levels of infestation vary between periods. This is especially apparent in studies of the impacts of biotechnology in India, where the yield effect of TGVs may vary from 30 per cent to 80 per cent due to varying levels of pest infestation. Thus, the pest damage or yield effect of a TGV is not a single number – it is a statistical distribution, and the modeling of adoption choices should be stochastic. In this section, we introduce this modeling approach.

The initial pest infestation (*NoPest*) is a random variable that may assume several values, each value with a certain probability. For simplicity, assume that there are two values: a low infestation level *Ns*, and a high infestation level *Nh*. The probability of the low level is *Ps*, the high level, *Ph* and, since these are probabilities, $Ps + Ph = 1$. The farmer has to make decisions concerning pesticide use (how much to apply) and choice of seeds (or hybrids). The pesticide decision is determined once the pest infestation level is known. However, the seed decision is made earlier in the season, before the pest infestation level is known. Our earlier analysis of the pesticide choice applies to the case with random infestation, but the choice of seed is modified to accommodate the randomness of infestation.

We first assume that the farmer is risk neutral, and the farmer's objective is to maximise expected profits. Each variety has its own expected operational profits, and the farmer selects the variety with the highest level of expected profits. Expected operational profits are:

$$EOProfits = OProfits\ (POTY,\ Ns)\ Ps + OProfits\ (POTY, Nh)\ Ph.$$

Recall that the operational profits for a given state of nature, denoted by *OProfits*, is the difference between revenue and pesticide costs. The revenue depends on *DAMAGE* as determined by initial pest infestation levels.[3] The operational profits are the overall profits minus the fixed cost of production and genetic materials that are used early in the season.

Ameden et al. (2005) show that, for every state of nature, the local TGV has higher operational profits than the other two varieties and, thus, it has the highest expected operational profits. The generic TGV can have higher expected operational profits than the traditional variety in situations where the savings in pesticide costs and damage reduction using the generic TGV are more valuable than the loss of potential output that the use of this variety entails. Under these conditions, the following holds:

$$EOProfits\ (M) > EOProfits\ (G) > EOProfits\ (L).$$

On the other hand, the seeds of the local TGV are likely to be more expensive than the generic TGV seeds which, in turn, cost more than the seeds of the traditional variety, thus:

$$Seedcost\ (M) > Seedcost\ (G) > Seedcost\ (L).$$

The choice of which variety to use involves weighing the trade-offs between expected operational profits and seed costs. High pest damage, high pesticide costs, and relatively low TGV costs will lead to adoption of the TGV technology. The generic TGV is selected instead of the local TGV when the marginal benefit of the pesticide cost savings and lower seed costs from switching to the generic is greater than the value of the marginal yield losses, thus expected profits are higher. For each variety, expected profits are the average operational profits across pest infestations (denoted by *EOProfits*) minus the nonpesticide-related fixed costs of production (denoted by *Prcost*) and seeds (denoted by *Seedcost*):

$$ExProfit = EOProfits - Prcost - Seedcost.$$

The expected profits of the traditional variety are denoted by *ExProfit* (*L*), and the expected profits of two TGVs are denoted by *ExProfit* (*M*) and *ExProfit* (*G*), respectively.

To understand the implications for the analysis, when pest infestation and damage are randomly distributed, consider the following simple example. Assume that no pesticides are available to fight a particular crop pest, but it can be controlled by a TGV. Suppose that there are two states of nature – no infestation that occurs with probability of 50 per cent and infestation that leads to loss of 50 per cent of the potential output with 50 per cent probability. The yield distribution and expected yield are presented in Table 1 below, for the traditional variety and two TGVs.

Table 1. Yield distributions for various varieties

State of nature	Probability	Yield with traditional variety	Yield with local TGV	Yield with generic TGV
No crop loss	0.5	POTY	POTY	0.95 * POTY
Crop loss	0.5	0.5 * POTY	0.9 * POTY	0.855 * POTY
Expected yield		**0.75 POTY**	**0.95 POTY**	**0.9025 POTY**

Numeral example.

We assume that the TGVs reduce the pest damage by 80 per cent, so that with the local TGVs there is a 50 per cent probability of no damage and 50 per cent probability to have 10 per cent damage ($50\% * 0.2$). We further assume that the generic TGV reduces potential output by 5 per cent. Then with use of the generic TGV, there is a 50 per cent probability of having a 5 per cent yield loss and 50 per cent chance of 14.5 per cent yield loss ($1 - 0.95 * 0.9 = 0.145$).

Let's now assume there are no other costs but seed costs and that seeds of the traditional variety are free. Expected profits for the traditional variety are equal to 75 per cent of the revenue generated by selling the potential output ($0.75 * POTY$), while the expected profits of the local TGV are based on producing 95 per cent of potential output ($0.95 * POTY$). If the price of the TGV seeds is less than $0.2 * POTY$, then the TGV is preferable to the traditional variety even though 50 per cent of the time there is no apparent yield effect of adoption.

The expected profit of the generic variety is derived from $0.9025 * POTY$ minus the seed costs. If the TGV seeds cost more than $0.0475 * POTY$ and the generic seeds cost less than $0.1625 * POYY$, they will be adopted. In this case there will be 50 per cent probability of 5 per cent yield loss relative to the traditional variety, but another 50 per cent probability of yield gain of 71 per cent ($(85.5\% - 50\%)/50\%$). Both local and generic TGVs increase expected yield, but their yield effects relative to the traditional technology vary between seasons. The adoption of the generic TGV may reduce yield in some of the periods, thus judging the technology based on its performance in one period may be misleading.

Impacts of risks are more significant in cases where farmers are risk averse and are concerned not only about the average profits but also about its variability and 'downside events'. Feder et al. (1985) survey a large body of literature showing that adoption behaviour of farmers in low-income countries suggests they are risk averse; this risk aversion is likely to decline with the size of the operation. Risk-averse individuals are ready to pay a premium to reduce the risk they face. The variance of profits is a convenient measure of risk. In our examples above, both TGV technologies increase expected profits and also significantly reduce the variance of profits. For example, the variance of the traditional variety is $0.0625 * POTY^2$ and the variance of the local TGV is $0.0025 * POTY^2$. The adoption of the TGVs divides the variance of profits by 25. Thus, farmers may adopt TGVs because of their positive impact on average profitability and risk-reducing effect.

Other factors may contribute to high yield effects from adoption of TGVs in low-income countries. If lack of access to credit restricts the ability of farmers, especially small farmers, to purchase expensive inputs such as pesticides, then the associated low levels of pesticide use increase the potential yield effect from adopting TGVs. Of course, if credit constraints make it more likely that a generic TGV is adopted rather than a more expensive local TGV, the yield effect will be smaller. Moreover, if farmers' abilities to borrow are severely restricted and TGVs are relatively costly, use of TGVs would be similarly restricted.

Credit availability varies greatly across regions, with poorer farmers located far away from financial centres having a greater difficulty to obtain credit. Thus, while adoption of TGVs is likely to be slow in these areas, our analysis suggests that these areas with severe credit limitations would experience greater yield-increasing effects from adoption.

Combined risk and credit considerations are likely to have a significant impact on farmers' choices. High levels of pesticide use increase farmers' debt-to-income ratio, while low pesticide use could lead to crop failures. For years where pest infestations are suddenly high, or price of output is low, farmers may fail to repay a loan, leading to bankruptcy. Poor farmers without access to credit or institutions for storing wealth cannot address risk effectively by saving. Thus, if TGVs provide a significant risk-reducing effect and are relatively lower in cost compared to pesticides, they are likely to be adopted and be particularly valuable to poorer farmers who are more vulnerable to risk.

Our analysis thus far argues that the concern about potentially low yield effects of TGVs in low-income countries is misplaced. While TGVs may have relatively low yield effects in high-income countries with high use levels of effective pesticides, their yield-increasing potential is high in low-income countries that are subject to high pest infestation levels and do not have effective pest-control strategies. We also saw that yield effects vary randomly, and adoption of TGVs can serve as an insurance mechanism, the impacts of which vary over time. Our analysis suggests that the impact of the TGVs depends on whether a local or a generic TGV is adopted. Adoption of a local TGV will have a higher yield effect, and will help to address another concern – the impact of TGVs on biodiversity, as discussed below.

IV. Biodiversity and the Adoption of TGVs

The practice of using principles of genetics to guide plant breeding is about 100 years old. Selective breeding techniques have been very successful in generating new varieties including the 'Green Revolution' varieties that significantly enhanced agricultural productivity. However, the varieties generated by selective breeding were a distinct genetic departure from traditional varieties. The newer techniques of biotechnology generate new varieties by slightly altering existing varieties, modifying one or two genes, while maintaining the bulk of the original genetic materials. Thus, the impact of biotechnology on crop biodiversity will be slight when the TGVs that are introduced are mainly modified local varieties. However, if a single generic TGV is widely adopted, replacing many varieties, then losses in crop diversity may be significant. Although we do not develop a formal measure of biodiversity, we assume that an increase in the adoption of the generic TGV and, in particular, the replacement of traditional varieties with the generic TGV, represents a loss of crop diversity.

The model and results of Qaim et al. (2005), combined with the results we derived earlier, will be used to identify factors that will lead to wide-scale adoption of generic versus local TGVs. Qaim et al. consider the case of a country where farmers use a large number of local varieties. These are not necessarily landraces, but varieties that were developed through selective breeding to fit local conditions. Here we will investigate analytically the conditions that will lead to adoption of local and generic TGVs in various regions, where adoption is measured by the relative acreage grown with the traditional variety and the local and generic TGVs within each region. Threshold models (see Feder et al., 1985) provide a useful framework to analyse adoption choices and are used here. They assume that farmers in each region are diverse in terms of their human capital, quality of land, and so forth. Farmers are assumed to pursue profits, sometimes adjusted for dynamics and uncertainty considerations. The heterogeneity of farmers may result in differences in their adoption choices. The threshold models reveal the critical (threshold) value of parameters of heterogeneity that separate farmers according to their adoption decisions. These threshold levels are dynamic, changing over time in response to such processes as learning by doing.

As we argued earlier, a farmer will compare the expected gain resulting from the yield effect and pesticide cost reduction of TGVs with the extra costs of the seeds when choosing a crop variety for a specific field. Qaim et al. (2005) identify several patterns of adoption when the heterogeneity of land quality within a region results in differences in potential output. The gains from adoption of TGVs are likely to increase with higher land qualities, and the relative gain from adoption of local TGVs relative to generic TGVs increases with land quality. The local TGVs will be fully adopted and may even lead to expansion of utilised lands to lands that were not farmed with the traditional technology. If at the worst quality land the gain from adoption of the technology is higher than the extra cost needed to pay for the local TGV seeds, then the more it will be adopted. When the local TGV is relatively expensive and the generic TGV is more affordable, partial or full adoption of the generic TGV is more likely.

Thus, the crop biodiversity losses due to the introduction of TGVs are mild when the cost of seeds of local TGVs is low in a large number of regions. This will lead to full or partial adoption of local TGVs in those regions. However, if the price of local TGV seeds is relatively high in most regions, while the generic TGV seeds are relatively cheap and are fully adopted in many regions, the crop biodiversity losses are likely to be substantial.

Several factors will determine the prices of local and generic TGVs and, thus, affect adoption and biodiversity:

1. *The strength of the crop-breeding sector*. In countries with the appropriate scientific infrastructure, such as the United States and China, transgenic modification of crop varieties is done routinely. In some low-income countries, the capacity of the plant-breeding sector is limited, which restricts the number of local varieties that can be modified. In these situations the introduction of TGVs may require reliance on the importation of generic TGV seeds.
2. *Regulatory process and requirements for TGVs*. The cost of developing and introducing new TGV seeds is likely to increase substantially the more restrictive and the less clearly defined the registration requirements are for new TGVs. The introduction of TGVs can be curtailed when the regulatory process is very restrictive. If the regulators are very strict with new local varieties, it may lead to

the importation of generic varieties, which may lead to significant reduction of crop biodiversity.

3. *Institutional arrangements for TGV seed development and marketing*. Qaim et al. (2005) consider two types of institutional arrangements to establish seed prices: Under the first, the public sector develops TGVs while a competitive seed company distributes them and, under the second, monopolies develop and sell TGVs. The first arrangement has been used to introduce new varieties developed using selective breeding in many low-income countries. The Consultative Group on International Agricultural Research (CGIAR) and the national agricultural research services (NARs) develop new genetic materials, and small seed companies sell them to farmers. The second arrangement is more consistent with the reality of agricultural biotechnology in the North, where large multinational corporations with significant monopolistic power have developed and introduced TGVs. The seed price or technology fee charged by monopolies is larger than the price under competition. Thus, Qaim et al. (2005) predict that there will be greater adoption of TGVs when the seed industry is competitive and that more local TGVs will be introduced. Thus, development and introduction of new TGVs by the public sector and marketing through competitive sellers will benefit biodiversity. Note, however, this requires that the public sector has the expertise and skills to produce new TGVs. In most cases the public sector does not have the know-how and capacity to introduce TGVs, and reliance on the private sector may lead to less costly TGVs.
4. *Transaction cost in seed markets and intellectual property rights (IPRs)*. When the private companies consider introduction of TGVs to a country, their strategy may vary according to cost of transaction and the ability to enforce IPRs. One approach they may pursue is to either import TGVs from other countries or to own or control companies that sell a subset of the local seed varieties and offer a small number of TGVs. An alternative approach is to sell the rights to transgenetically modify local varieties to existing seed companies and charge a royalty (technology fee). The second strategy, which is likely to result in more crop biodiversity preservation, is more likely to be pursued as the cost of negotiation decreases and as IPRs are easier to enforce. A broad range of local varieties may be genetically modified and sold cheaply if the local public sector has the required capacity and is not concerned about IPRs.

Our analysis suggests the emergence of several adoption patterns of agricultural biotechnology that vary in their impact on crop biodiversity. In a country like the United States, with a well-developed seed sector and relatively low transaction costs, local TGVs will be widely introduced, even with private sector distribution. Monopolistic pricing, however, will result in partial adoption of biotechnology in many regions and continued plantings of traditional varieties. The restrictive regulatory environment will result in minimal adoption of TGVs in Europe. The significant capacity of the seed sector, the competitive nature of the seed industry, and relatively low regulatory burden is likely to result in a high number of local TGVs in a country like China. However, in Africa, where the local capacity of transgenic modification is very limited, there may be a higher likelihood of importing generic TGVs, and crop biodiversity will suffer. One of the policy challenges is to develop infrastructure at the local level in Africa so that modification of TGVs will not be so difficult and expensive.

The data presented in Qaim et al. (2005) support our general results. They show that thousands of varieties have been modified in the United States, and the acreage per modified variety in some crops is smaller than in other countries. This may reflect the relative low transaction and modification costs in the United States. Low acreage per variety may reflect a high technology fee that results in partial adoption. In the 2001–02 season, more than 1100 varieties of RR soybeans were planted in the US, with about 20,000 ha. on average for each variety. More than 700 varieties of *Bt* corn were planted, each variety on 10,000 ha., on average. In Argentina, 45 varieties of RR soybeans were planted on 10 million ha., with 200,000 ha. per variety. A total of 700,000 ha. of *Bt* corn were planted, with 15 varieties, so 45,000 ha. were planted per variety. In the case of *Bt* cotton, the United States has 19 varieties grown on 2 million ha., while China, with its public sector development of TGVs and subsidised seed sector, has 22 varieties on 1.5 million ha. Our conceptual analysis and empirical examples are consistent with the results in Ammann (2004), who reviews studies on the impacts of the introduction of TGVs in soybeans and cotton in the United States, and finds that genetic uniformity of crop varieties has decreased by 28 per cent during the period of introduction of TGVs in the United States. The evidence suggests that introduction of TGVs around the millennium did not have significant effect on genetic uniformity.

Both our conceptual analysis and data suggest that the introduction of TGVs will not necessarily lead to loss of biodiversity and significant reduction in the number of varieties grown. The introduction of TGVs may actually increase the number of distinct varieties, narrowly defined, when the technological, economic, and regulatory conditions lead to genetic modification of most traditional varieties and when the TGVs are not fully adopted. On the other hand, limited capacity to genetically modify local varieties may affect biodiversity negatively, as it may lead to the adoption of a small number of TGVs (sometimes imported) on lands that were grown with a larger number of local varieties. Strengthening the capacity of the seed sectors in low-income countries and introducing simple mechanisms to allow developers of TGVs easy access to local varieties will increase the biodiversity of TGVs. The preservation of crop biodiversity can also be enhanced by financial incentives, since the biotechnology choices of the individual farmers and the private sector companies that affect biodiversity are economic choices. The public sector and donors concerned about the preservation of local varieties may cover some of the costs associated with development or introduction of local TGVs that would not have been introduced otherwise. Environmental services payment may be introduced to subsidise farmers to grow local varieties instead of generic TGVs.

V. Conclusions and Extensions

This paper addresses two of the primary concerns about the value of using the current generation of TGVs in low-income countries. First, we show that adoption of these TGVs might substantially increase crop yields in low-income countries in spite of low yield effects in rich countries. The different impacts of the technology across locations result from differences in the initial pest control strategies. When

TGVs replace effective pesticides, their impact on yields is limited. However, their value is enhanced where pesticides are not used or have limited impacts. There is evidence that in some low-income countries (for example, China), TGVs reduce pesticide use and, thus, improve worker safety and reduce economic and environmental costs. In other countries (South Africa), they improve yields, and in India they do both. Furthermore, the randomness of the pest infestation leads to varying yield effects over time and, thus, TGVs are also a very valuable source of financial insurance for farmers. The risk-reducing effect of TGVs may benefit mostly farmers who are more vulnerable and who have higher aversion to risk. These tend to be smaller farms and, since TGVs do not have economies of scale, they may hold much promise for the poorer farmers in low-income countries, unlike other modern technologies.

We use a conceptual model to show that TGVs have significant yield-increasing and risk-reducing potential in poor nations. Specifically, where pesticide prices and fixed costs of application are very high relative to output prices, reduced pesticide application rates and warm humid climates produce have high pest-infestation levels; the introduction of TGVs then has significant potential to reduce pest damage and increase yields. Moreover, in areas with great variation in pest damage and pest infestation levels between seasons, farmers may adopt TGVs because of their positive impact on average profitability and risk-reducing effect, especially poorer farmers who have limited access to credit and are thus more vulnerable to risk.

The second concern we address is potential loss of crop biodiversity when TGVs are adopted; we show that adoption of TGVs does not necessarily lead to crop biodiversity loss. We argue that the introduction of transgenic crops is less likely to reduce crop biodiversity in regions with strong seed sectors having fewer barriers to access local seed varieties. The preservation of crop biodiversity can be enhanced by incentives that lead to partial adoption of TGVs and by policies and regulations that provide favourable conditions to introduce local TGVs. Thus, the introduction of TGVs to low-income countries in Africa and other regions should be accompanied by expansion of capacity of the local seed sector.

While the paper shows that the two major concerns about introducing TGVs to low-income countries can be addressed, decision-making concerning use of the technology in poor counties should not be based on ability to address all objections raised by critics of the technology. Instead it should be based on weighing benefits, costs, and risks imposed by the technology, taking into account the likely outcomes if the technology is not introduced (see National Research Council, 2000). The analysis in this paper provides a starting point for qualitative assessment of the plusses and minuses associated with introducing TGVs to low-income countries.

Agricultural systems are heterogeneous and subject to ecologic and socioeconomic variability. Adoption is a complex process that requires availability of superior products appropriate for specific locations, a supportive regulatory economic system, and an effective system for dissemination. Therefore, the diffusion of new TGVs will be limited to locations where they can make a positive difference and where the institutional conditions make them acceptable. Nevertheless, whenever they are adopted, the introduction of TGVs is likely to improve the well-being of adopters as a result of reduction in pesticides and risk-bearing cost, and increase in yield. Adoption of the technology will also benefit its providers, as some may be shareholders of agribusiness firms, but others are local dealers and distributors. The increase in yield may benefit consumers of TGV crops, but nonadopters may lose, as the price of their output will decline. Nevertheless, the overall 'market effects' (impacts on consumers and producers) of supply-enhancing technologies are positive (Qaim et al., 2005).

Due to the scale neutrality of TGVs, their basic economics do not favour larger farms. Risk considerations make them especially beneficial to smaller producers who have fewer options to reduce vulnerability to risk than do larger farmers (Just and Zilberman, 1988). There may be credit and other access constraints that have to be removed before small producers can fully benefit from TGVs.

Since food products absorb a relatively larger share of poor families' income, the yield effects of TGVs and the resulting lower prices will be relatively more beneficial to poorer consumers. Our analysis, thus far, suggests that the introduction of TGVs will improve the overall market surplus and will likely have positive distributional impacts, in the sense that relative gain to poorer individuals is likely to be greater. The recent results of Anderson (2005) and Evenson (2005) suggest significant potential of economic welfare gains to low-income countries from the introduction of existing TGVs. The extent that this potential will be realised depends on implementation of policies and on institutions that aim to enhance adoption. Even though the estimated gains are impressive, they only make a small dent in world poverty, and the existing TGVs are only a small part of a broader effort needed to enhance human welfare.

Evidence suggests that under a broad set of circumstances, the adoption of TGVs will likely lead to significant gains in human and environmental health. The work of Huang et al. (2002) for cotton in China and the findings on rice (Huang et al., 2005) suggest that adoption of pest-controlling TGVs will lead to reduction in pesticide use in some cases, and thus reduced environmental contamination and improved worker safety. The adoption of herbicide-resistant varieties will enhance adoption of low- and no-tillage techniques and reduce buildup of carbon storage and soil erosion. The yield effect of TGVs will also allow food demands to be met, utilise smaller amounts of land, and reduce the incentives to deforestation and conversion of wildlands to farming.

However, these environmental benefits need to be compared to presumed environmental costs. We show that crop biodiversity losses may be substantial only when the institutional and economic setups lead to broad-scale adoption of generic varieties; moreover, these losses can be reduced by policy intervention. Other environmental problems that may emerge from the adoption of TGVs include gene flows to wild varieties and damage to nontarget species. While the gene-flow problem has been recognised by scientists for some time, Gilligan et al. (2003) and Ammann (2004) argue that it is not persistent, and Ammann's survey of the literature does not reveal cases where TGVs have caused substantial damage. Of course, lack of damage thus far is no assurance of the future; monitoring of possible side effects of TGVs should be pursued. With this said, it is likely that the economic, social, and environmental benefits of TGVs in low-income countries outweigh their costs, and there is a strong case for their application in the poorer nations.

VI. Policy Challenges

The primary policy challenge is to develop policies and mechanisms that will harness the potential of biotechnology to benefit the poor in low-income countries. These products may include pest-resistant and herbicide-resistant varieties of crops such as cassava, manioc, and varieties of rice and maize that are appropriate for low-income countries. The range of biotechnology applications has to be expanded to address constraints that affect farmers in poor countries: drought-resistant and salt-tolerant varieties as well as varieties that will nutritionally enrich staple foods.

Private companies control much of the development and distribution of biotechnology in rich countries, but it is unlikely that they will sufficiently invest in products that target the poor in low-income countries. Instead, the development of these products should be carried out mainly by the public sector, continuing the pattern that emerged during the Green Revolution (Evenson and Gollin, 2003). However, this will require investment in research infrastructure in low-income countries, as well as creative arrangements that will allow transfer of knowledge and minimise barriers and costs of accessing new knowledge on development of new varieties. New organisations that aim to reduce the cost of IPRs for agricultural biotechnology for poor countries are taking initial steps in the right direction (Atkinson et al., 2003).

Another challenge is to develop a regulatory process that will maintain a high degree of safety, yet would not impose excessive regulations on developers of new technology. Reduction of redundancy in regulation and establishment of regional regulatory organisations that take advantage of economies of scale will increase the resources available for product development.

A further challenge is to address restrictions on credit availability. The literature suggests that limited access to credit may slow or reduce adoption of agricultural biotechnology by poor farmers owning small farms. Thus, institutional policies that both reduce the cost of credit and increase its availability are needed. For example, instalment plans that require payment of biotechnology 'fees' on a season-by-season basis for farmers utilising transgenic seeds, rather than significant up-front fees, will improve adoption substantially for poor farmers. Alternatively, if the price of seeds is sufficiently low and credit channels are expanded, small farms that did not adopt chemical pesticides will adopt biotechnology seeds.

While creative credit solutions may be effective for commercially viable farms, further solutions are needed for the poorest subsistence farmers, such as price discrimination structures specifically aimed at alleviating poverty. Seed companies could be assured access to commercial seed markets in one area in return for offering seeds at or below cost to poor farmers in other areas. Of course, introduction of credit and pricing policies will require monitoring of farmer behaviour and markets as well as an effective enforcement system. Extension services and the public sector will be challenged to cooperate with the private sector to introduce such mechanisms.

While we argue that biotechnology holds significant promise for low-income countries and that our biggest challenge is effectively introducing it to benefit the poor, we have to recognise the ecological uncertainties and support research and monitoring activities that assess the impact of biotechnology on the environment.

We need to trigger mechanisms for adaptive learning to enhance productivity of biotechnology and, thus, detect its limitations through monitoring. Furthermore, continued support for basic research and reduction of IPRs and regulatory barriers will likely lead to improved varieties with beneficial traits. Biotechnology is in its infancy. Thus far, we have seen several applications that have been very effective for a small number of crops. Overall, though, the impact of biotechnology on agriculture has been modest. Yet, the success thus far is an indicator of promise and potential that has to be utilised through both research and institutional design.

While we emphasise the value and potential of biotechnology for agriculture in low-income countries, we also recognise that the value of complementary approaches. Biotechnology can complement strategies based on improved precision in farm management or empowerment of farmers through augmentation of human capital and collective action. Thus, biotechnology is an important element of an emerging farming strategy, but it has to be integrated with other approaches to enhance productivity, alleviate poverty, and improve environmental quality in low-income countries.

Notes

1. For this analysis, we assume output price is net of harvesting costs.
2. At the optimal pesticide use level, the value of the marginal benefits of pest damage reduction is equal to the price of the pesticides.
3. Recall from the first section that $DAMAGE = \mathrm{F}\ (NoPest,\ Pesticide,\ TGV)$ and in this case, *NoPest* can take on the values *Ns* or *Nh*. Also, $Oprofits = Y * Yprice - \mathrm{Pesticide} * Pprice - Fixpest$ and $Y = POTY * (1 - DAMAGE)$. Thus, operational profits depend on initial pest infestation levels and the potential yield of the variety, holding other variables constant.

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