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Agricultural Biotechnology and Poverty Reduction in Low-income Countries

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Summary. — While biotechnology innovation is concentrated in high income, "Tier I" countries, international diffusion of innovations to improve the diet, health, and incomes of the poorest will be largely driven by "Tier II" innovators such as China and Brazil. Adoption of beneficial biotechnologies in "Tier II" and "Tier III" countries will increase as more transgenic versions of conventionally grown varieties become available and as costs decline, which in turn will depend upon regulatory approvals being needed only once for each transformation event and transaction costs for accessing technologies being minimized. Investments in higher education and intellectual property clearinghouse institutions can greatly facilitate technology transfer.

Key words — agriculture, biotechnology, globalization, innovation, poverty, technology transfer

1. INTRODUCTION AND BACKGROUND

Economic history can be read as a testament to the transformative power of technology in relation to the human condition (Rosenberg, 1982). The older part of this testament tells of a progression from hunting to farming to military technologies, while the newer part begins when mechanization and fossil fuels were enlisted for industrial production. Across the entire chronicle, we see the catalyst that technology has been for economic growth, improvement of human welfare, and alleviation of poverty. Using energy-intensive mechanical technologies, we have achieved living standards for hundreds of millions of people around the globe that are beyond the imagination of prior generations (Bresnehan & Gordon, 1997). Yet, despite raising average standards of living, technology has not eliminated poverty.

World Bank (2000) estimated that in 1998, 56% of humanity lived on less than $2 a day and 24% subsisted on less than $1 a day. Detailed analyses of poverty [1] reveal that entry into this status and exit from it are asymmetric, yet share some important characteristics. A primary reason for a household falling into poverty is an adverse health event, [2] including mortality. On the upside, the main determinant of a transition from poverty to non-poverty is (formal and informal) employment. In both cases, health status is critical, directly with respect to downside poverty risk and indirectly in terms of fitness for labor recruitment and productivity.

Biotechnology has the potential to improve living standards in low-income countries. Applications of biotechnology can increase food output, improve nutritional quality, and raise health status. Although it remains an area of controversy, biotechnology has already achieved significant productivity gains and improvement in health status of farm workers (Huang, Hu, Rozelle, & Pray, 2005; Pray, Huang, Hu, & Rozelle, 2002). Somewhat less controversially, genetic biofortification of food crops is poised as a biologically and economically effective approach to widespread alleviation of micronutrient deficiencies (Albrecht, 2002; Bouis, 2004). Less controversially still, biotechnology has certainly begun to alter the landscape of preventative and therapeutic medicine, and additionally it is beginning to enlist food and agriculture in ever more creative ways to prevent and treat disease, including naturally

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derived "functional foods" or "nutraceuticals" (Raskin, Ribnicky, & Komarnytsky, 2002), as well as plant made vaccines and biotherapeutics (Daniell, Streatfield, & Wycoff, 2001).

In this paper, we explore some of the challenges and opportunities that exist for the world's poor to take advantage of applications of the life sciences in agriculture, one of today's most dynamic areas of innovation. This is an enormous topic that has been extensively analyzed and debated in the literatures of multiple fields of scholarship, including development economics, public policy, rural sociology, international agriculture, and others. We endeavor here not to review these wide ranging literatures in any comprehensive fashion, but rather to share a common framework and key insights that have emerged over the years of our own engagement in research on these issues. [3]

2. TECHNOLOGY IN A CONTEMPORARY GLOBAL CONTEXT

History indicates that technological advancement and sustained increases in general living standards go hand in hand (Bresnehan & Gordon, 1997). Just as importantly, today's global income inequality is characterized by disparities in the scope and depth of technological assimilation. International diffusion of technology and sustainable innovation is hindered by three salient factors:

1. *Institutional capacity*—Countries which receive innovation often lack the institutional pre-requisites to facilitate orderly and sustained assimilation of advanced technologies. Among other things, these include legal standards and enforceable property rights, administrative and regulatory capacities to assure safety of new technologies, and both public and private research capacities, including the work of educational and research institutions, extension and public health programs, as well as profit motivated firms seeking to develop and reach new markets.
2. *Financial capacity*—Recipient countries often lack the financial resources necessary to invest in R&D for local innovation or even to capitalize on the adaptation of existing technologies. In the absence of enforceable property rights, it is also difficult to recruit foreign or domestic capital to alleviate this constraint.
3. *Human capital*—Clearly, there are very significant global disparities in average education levels, and these seriously limit the geographic scope of technology development and use.

With these constraints in mind, we find it helpful to summarize national economies within a threefold classification, based on the capacity to internalize and sustain technological innovation:

Tier I. Established innovators, essentially the OECD countries, which have already become technology-intensive economies.

Tier II. Emergent innovators, including China and India, which are in transition and which are overcoming all three types of obstacles listed above, at least in some key sectors.

Tier III. Long term net importers of technology, which are the majority of low-income economies.

Inclusion into one of these tiers is, of course, relative and may in fact vary by technological sector. Countries can be expected to transit between tiers over time. While all countries aspire to join the first group, it is, however, unlikely that many will move from third to first in the short to medium term. For this reason, global technology diffusion can be expected to evolve unevenly, as will its attendant benefits. Institutional arrangements will need to adapt and evolve accordingly. The mechanics of North–South technology diffusion operates very differently, depending upon whether the recipient is a Tier II or Tier III economy, and the mechanics of South–South technology diffusion between Tier II and Tier III economies operate differently still. Policies to facilitate diffusion need to recognize global complexity of innovation sources and absorption capacities and adapt accordingly.

(a) *Technology and poverty*

Technology's effects on poverty are many and complex, but it is helpful to simplify by separating them into direct and indirect effects (de Janvry *et al.*, 2005). Some technologies certainly involve trade-offs in which some effects increase welfare in one sector of the economy or segment of the population (such as urban or farm laborers) while decreasing welfare in another (such as smallholder growers). Also, the effects of technology work within a context of other large forces that affect poverty, including market distortions—such as rigged national markets and international barriers to trade—natural resource constraints—such as water availability and land quality, and weak or missing institutions—such as property rights.

Direct effects of technological innovation on poverty are those that raise the welfare of those poor who adopt a new technology themselves or who are able to gain from increases in the productivity of their own labor. Agricultural households who adopt new technology in their own production activities can benefit from increased production for home consumption, more nutritious foods, higher gross revenues derived both from higher sales volumes and switching to higher value products, lower production costs, lower yield risks, and lower exposure to toxic chemicals. Adoption of new technology can raise worker productivity, and sometimes wages, as well as enhance human capital, improve safety, and make work less onerous. Many of the genetic traits being developed in crop research are labor productivity enhancing in some way, whether through increasing yield or increasing quality. One exception is herbicide tolerance in some systems where it can substitute for labor. [4]

Indirect effects of technological innovation on poverty include growth, efficiency, and price effects. Technology or productivity induced economic growth in related sectors—such as agribusiness, food processing, or bioenergy—and elsewhere in the economy can spill over to rural markets. Improved international competitiveness in the agricultural sector resulting from innovation can provide foreign exchange benefits. Indirect effects through food prices can benefit many poor groups, including landless farm workers, net food-purchasing smallholders, non-agricultural rural poor, and the urban poor for whom food represents a significant share of total expenditures. Indirect effects via employment creation (from increased yields, area expansion into marginal lands, or vertical expansion into downstream agribusiness operations such as livestock or biofuel processing) are important for landless farm workers, net labor supplying smallholders, and the rural non-agricultural and urban poor.

The relative magnitude of the direct and indirect effects of technological change in agriculture on poverty can be quantified through computable general equilibrium (CGE) models. [5] In these models, the direct effects include the change in agricultural profit for adopting smallholders, the changing opportunity cost of home consumption for own production, and the change in self-employment on one's own land. 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.

While biotechnology may offer significant potential for overall poverty reduction, particularly in smallholder agriculture, it may not prevail over the other large forces that keep people in poverty. Within a given agro-ecological region, 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 vary accordingly. It stands to reason that small growers would prefer farming systems that offer greater value-added per unit of land, are capital-saving, and less risky, while large growers prefer farming systems that are labor-saving, and they can afford to assume more risk if they are compensated by higher expected incomes. In such cases, there will exist trade-offs between achieving indirect and direct effects if budget constraints in research requires priority setting, that is, if technology is designed for one system but not for another. The more unequally land is distributed and the more market, institutional, and government failures are farm-size specific, the sharper will be the trade-off. Even when the effects of biotechnological innovation are aligned for poverty alleviation, four important caveats need to be considered (de Janvry *et al.*, 2005).

The first caveat is that other greater sources of income gain should be pursued first when feasible, particularly gains that can be made through improved access to land, improved property rights, investments in irrigation, higher levels of human capital, and access to non-agricultural sources of employment.

The second is that other types of technological advances in agriculture besides those derived from biotechnology may be more appropriate for enhancing smallholder incomes. These are often just simple adaptations of existing results from agricultural research to the needs of smallholders, including improved farming systems, agro-ecological practices, and traditional breeding of crops for the specific and often highly particular contexts where the poor are located. These approaches, however, are often complements and not substitutes to biotechnologies.

The third is that for any kind of technology to be adopted by smallholders, market failures that affect those smallholders may need to be eliminated for adoption to have any meaningful impact. Institutional gaps need to be filled, complementary public goods provided, and policies put into place that do not discriminate against the agricultural sector or poor growers. These would include access to credit, risk management tools such as mutual insurance and safety nets, and lower transactions costs in factor and product markets.

Finally, for technology adoption to result in meaningful poverty reduction, other fundamental dimensions of welfare gain also need to be within reach. These include the basic human needs such as health care and education as well as the more qualitative dimensions of welfare such as empowerment and minority rights.

Hence, to be effectively used for poverty reduction, technology instruments need to be embedded within a comprehensive rural development and poverty reduction strategy for the region concerned that weighs technology alongside other instruments for income gains, carefully discriminates among alternative technological paths, makes the technological innovation accessible to the poor for whom it is intended, and complements income gains with access to the other dimensions of welfare.

3. CHALLENGES AND OPPORTUNITIES FOR AGRICULTURAL BIOTECHNOLOGY

Over the next generation, agriculture faces three primary global challenges:

1. meet growing effective demand for food,
2. reduce poverty and malnutrition,
3. achieve environmental sustainability.

(a) *Meeting demand*

Because of population growth and rising incomes, demand in low-income countries is predicted to increase by 59% for cereals, 60% for roots and tubers, and, importantly, 120% for meat over this period (Pinstrup-Andersen & Pandya-Lorch, 1997). This increased supply obviously cannot come from area expansion, a rapidly diminishing source of output growth globally that has already turned negative in Asia and Latin America. Neither can increased supply come from expansion in irrigation, due to competition for water with urban demand and rising environmental problems associated with drainage, soil salinity, and chemical run-offs. Increased supply will thus need to come from growth in effective yields. The growth rate in cereal yields in low-income countries, however, has declined from an annual rate of 2.9% in 1967–82 to 1.8% in 1982–94, the minimal rate needed to satisfy the predicted 59% increase in demand for cereals over the next 25 years (Pinstrup-Andersen & Pandya-Lorch, 1997). Growth in yields consequently cannot be allowed to fall below this rate. Of course, greater international food trade might increase global welfare because of efficiency gains. For example, higher-income Asian economies have successfully bartered industrial comparative advantage against steeply rising food imports. For poor countries, however, food import dependence can be risky when commodity price cycles are taken into account.

(b) *Poverty and malnutrition*

The livelihood of the world's poor majority still depends critically on local agricultural profitability. With 1.2 billion people in absolute poverty (World Bank, 2000) and 792 million underfed (FAO, 2004), agriculture has a major role to play in reducing poverty and improving food security (i.e., reducing the probability of succumbing to malnutrition and hunger), particularly since some three quarters of the poor and underfed live in rural areas where they derive part, if not all, of their livelihoods from agriculture as producers or as workers in agriculture and its related industries.

Yet, the real income of the poorest urban consumers continues to depend on the price of food. One way to reconcile these interests is productivity growth in agriculture, reducing costs to make room for rural income without reducing urban real wages by increasing food prices. Since the yield growth rates achieved with conventional plant breeding and agronomic practices have been steadily declining, the next round of yield increases in agriculture will have to rely on the scientific advances offered by biotechnology, precision farming, and production ecology, with most of the gains expected to be derived from the first of these.

(c) *Environmental sustainability*

Environmental and consumer risks that may derive from adoption of genetically modified organisms need to be carefully assessed and regulated. Otherwise biotechnology would lead to an undue risk of setbacks in the already constrained circumstances of the rural poor in low-income countries. While there are certainly legitimate ethical and precautionary concerns regarding the use of some biotechnologies in some contexts, it should be kept in mind that there are also ethical implications to categorically withholding or obstructing the dissemination of an entire class of technology to those for whom it could make a material difference in welfare. Failure to develop and capture the potential of viable agricultural biotechnologies would further increase the gap between North and South and be a setback in the struggle to reduce poverty.

4. FACTORS AFFECTING THE ADOPTION AND EFFECTIVENESS OF BIOTECHNOLOGY IN AGRICULTURE

The term biotechnology refers to a wide array of approaches to applying molecular and cell biology to commercial products and processes. The impact that these developments are able to actually have on poverty depends however upon how effectively the technologies deliver either direct or indirect benefits to the poor. This in turn depends upon the specific characteristics of technologies actually being developed and introduced, those factors that drive the logic of smallholders' adoption decisions, and any other major constraints that could dampen the incentives of developing or using the technology.

(a) *Appropriateness of traits in the R&D pipeline*

Most of the world's existing biotechnology industry is concentrated in high-income countries—particularly the United States—and aims to develop applications that meet demand and solve problems of those with the ability to pay. Just as most investment in medical biotechnology aims to find cures for cancer, diabetes, and cardiac problems while overlooking diseases afflicting only the poor, similarly most investment in agricultural biotechnology seeks solutions for major crops of the North, like cotton, canola, soybeans, and corn while underemphasizing the development of varieties important in the South, such as cassava, cowpea, sorghum, and millet. However, in most cases the very same technology developed for use by high-income adopters—including today's insect resistance and herbicide tolerance traits—can be applied to crop varieties mostly grown by the poor in low-income countries. Other technologies that may not have a viable market in the North, such as the biofortification of crops with micronutrients, can also be applied in low-income countries where micronutrient deficiencies are endemic and debilitating. The key challenge is to mobilize the resources, research, and outreach infrastructures for applications that are relevant to the poor in low-income countries. Biotechnology is not unique in this regard. In many cases, technologies that were developed in the North have been slightly adapted and then reintroduced in the South (Feder *et al.*, 1985).

Pest control is of at least as much concern to farmers in low-income countries, and especially to smallholders, as it is to the farmers of high-income countries. Adaptation of the "cry" genes from *Bacillus thuringiensis* (*Bt*) to impart insect resistance in varieties that can be effectively used by poor smallholders would reduce their exposure to the risks of pest damage and yield loss while not requiring any chemical applications. Most objections raised against *Bt* use in smallholder agriculture is of a secondary or tangential nature: concerns of cost to initially obtain the technology, of the eventual diminishing effectiveness of the technology through buildup of insect resistance to *Bt*, of unrealistic initial expectations of the technology's effects, or of the single transgene crossing out into the broad genetic pool of related landraces. However, none of these objections effectively contradict or obviate the fundamental fact that the trait can indeed be intrinsically helpful to a smallholder, and if planted and managed in a responsible manner can continue to be so almost indefinitely. In addition, a range of additional insect resistance traits beyond today's existing set of commercialized *Bt* genes are actively being explored.

Adaptations of herbicide tolerance can be similarly helpful to the poor, both as a yield increasing and as a labor substituting technology, although the labor substitution effect may hurt some. The technology requires a farmer to purchase and use herbicide specific to the seeds; however, the net cost of herbicide plus seed minus reduced labor can in many cases be less than the cost of labor for tillage and weeding alone without the technology. Thus it may be gainful for anyone who is themselves cultivating land and has a sufficiently high opportunity cost on any time spent in labor to control weeds. Competition among technologies should drive down costs and increase availability. Already at least 10 different selective herbicides can be tolerated by plants when given the appropriate transgene, some of them being generic, low cost, widely available herbicides. The poor who may be hurt by this technology are those unskilled laborers who have very low opportunity cost of time, that is, no other comparable source of income given the loss of weeding work. Given these trade-offs, however, the net effect on poverty is an empirical question.

In addition to pest control traits, biotechnology can be employed to improve other agronomic characteristics of crops in ways that can benefit smallholders and food purchasers. Transgenes are being investigated that help plants to combat pervasive problems of disease caused by biological pathogens ranging from viruses, to bacteria, to nematodes, to fungi. Transgenic solutions are also being developed to provide tolerance to the physical conditions of drought and freezing (indeed plants die less due to cold than due to the fact that freezing deprives them of the needed moisture), salinity and other soil toxins such as aluminum and heavy metals. Crops with such traits will require less irrigation and will provide more reliable yields under marginal conditions.

Biofortification has the potential to help alleviate malnutrition through the nutritional enhancement of foods. These include innovations such as pro-vitamin A biofortified rice currently in development, but extend across a broad range of macronutrients (proteins, oils, and carbohydrates), micronutrients (vitamins and minerals), and other functional plant components (isoflavones, resveratrol, etc.). Even when able to maintain sufficient calories, many of the poor are not able to afford the more nutritional, non-staple foods like fresh vegetables, meats, and dairy products, and are thus unable to consistently get minimal levels of essential amino acids or micronutrients. Such dietary imbalance or micronutrient deficiencies, described as “hidden hunger” (Bouis, 2004), can lead to a range of health problems and decreased productivity, undermining the ability to maintain subsistence-level production of food or income from other employment and, if severe enough, initiating the negative cycle of malnutrition and poverty. While many options are available and have been tried for micronutrient fortification, the biotechnological approach promises to be the most economical and practical in many situations (Albrecht, 2002).

Another class of biotechnological innovation aims to improve the input-use efficiency of agricultural products. A set of characteristics—including increased digestibility of plant fibers, balanced amino acids, increased energy content, and increased bioavailability of minerals such as phosphorus—promises to increase the feed conversion efficiency of grains and forages by several percentage points. This could improve the economics of livestock and dairy production while still lowering food price on meats and dairy, protein sources for urban consumers. Improved oil and protein contents for industrial or food processing use of crop outputs may provide opportunities for some growers to specialize in quality-differentiated crops grown at a premium. Longer shelf life and reduced bruising traits in fresh fruits and vegetables can improve durability and decrease wastage during transport and storage, increasing availability and decreasing prices of these micronutrient rich foods in urban locations and off season in low-income countries. The entire range of input-use efficiency gains can create value that can be shared between growers, processors, and consumers, simultaneously allowing higher prices at the farm gate for quality-differentiated output and lower prices in the market place for consumer products such as meat and dairy products, fresh produce, or packaged foods.

Biotechnology also has longer term potential to employ agricultural resources and labor in the production of new biomaterials, for use in energy, industry, and medicine. While these applications are further off, and issues of the proper management and regulation of such technologies are still much debated, R&D is well under way in both public and private laboratories for utilizing the biosynthetic pathway of plants to generate a range of higher value products (Daniell *et al.*, 2001). Highly fermentable carbohydrates or high energy oils can make crops into more efficient bioenergy feedstocks. Expression of specific enzymes by plants can provide high value industrial and analytic supplies. Expression of specific viral and bacterial antigens enables low cost manufacture of vaccines by plants. In fact, a wide range of biotherapeutics could be manufactured in plants. While important and sometimes costly precautions need to be taken to assure containment of such transgenic plants to prevent contamination of conventional food supplies, such high-tech biomanufacturing based largely on an agricultural resource base could still be much less capital intensive than conventional biomanufacturing and very much within the capacity of both Tier II and Tier III countries: an opportunity for technological leapfrogging and more broadly based economic growth.

Finally, biotechnology can be employed to directly address many intractable or costly environmental problems. Biotechnology can contribute to environmental quality through reduced use of some of the more noxious agrochemicals, as well as through applications such as enhanced bacterial waste treatment or composting, phytoremediation, and the utilization of biomass as an energy resource.

(b) *The determinants of adoption*

An important feature of agricultural biotechnology is that new varieties are obtained by making just a slight (and quite precise) modification to the genetic content of existing varieties, while new varieties obtained through conventional breeding may be substantially different than traditional varieties. Therefore, it is possible in principal to modify each existing variety being cultivated today, and the adoption of biotechnology would thus allow the preservation of the existing crop biodiversity in modified form. This insight has received too little attention in the popular debate on links between biotechnology, biodiversity, and the environment.

The extent to which it will happen depends on the economics, property rights, and regulation of biotechnology. An analysis by Ameden *et al.* (2005) considers the case where a grower already using a conventional variety is presented with the choice of adopting a transgenic pest-controlling variety (a variety that has been genetically modified using the tools of biotechnology to include a transgene that confers the pest control trait).

Consider an individual grower with a conventionally bred local variety L whose yield is Y_L,

$$Y_L = (1 - D)Y_P,$$

where Y_P denotes potential yield and D is an index of pest damage between zero and unity. If the grower can use pesticides X to limit damage and faces prices p_L for the sale of output and p_X for the purchase of pesticide, then his profit from growing and spraying the local variety takes the form

$$\Pi_L = p_L Y_L - p_X X = p_L(1 - D)Y_P - p_X X.$$

If, on the other hand, the same grower were to adopt a pest resistant transgenic variety, the profits would take the form

$$\Pi_G = p_G Y_G - p_S S_G = (p_G - p_S s)Y_G,$$

where profits and output prices are analogous and S denotes quantity of transgenic seeds purchased. Finally, we assume that seeds are a fixed proportion of yield ($s = S_G/Y_G$, the isoprofit boundary, is linear).

In the static case, we assume that growers are fully informed and risk neutral, so the adoption decision partitions the space of varietal yields as shown in Figure 1.

The vertical intercept is pesticide cost per unit of average revenue. The slope of the adoption partition is the ratio of marginal profitability of the transgenic variety to marginal revenue on gross (before pest damage) output of the local variety. Clearly, pest resistance confers a yield advantage on the transgenic variety. It should be noted, however, that transgenic varieties generally will have lower gross yields than conventionally bred local varieties, so the slope and intercept of the adoption partition become empirically relevant. Even if we assume risk neutrality and equal prices for both varieties, pesticide efficacy (D) and the cost of the transgenic variety seed (p_S) will be essential determinants of the adoption decision.

Adoption of a pest-controlling transgenic variety will thus tend to reduce pest damage and pesticides application. The impact of its adoption is, however, a random variable because of the randomness of pest damage, and the yield gain from adoption is likely to be higher in periods of high infestation. If the transgenic is based on a generic variety, adoption may actually lead to lower yield in periods of low infestation. If growers are risk averse, they will adopt the transgenic if expected utility of income of the transgenic variety exceeds that of the traditional variety. In making the adoption decision, the gains associated with the change in the yield distribution and reduction in pesticides costs are compared to the extra

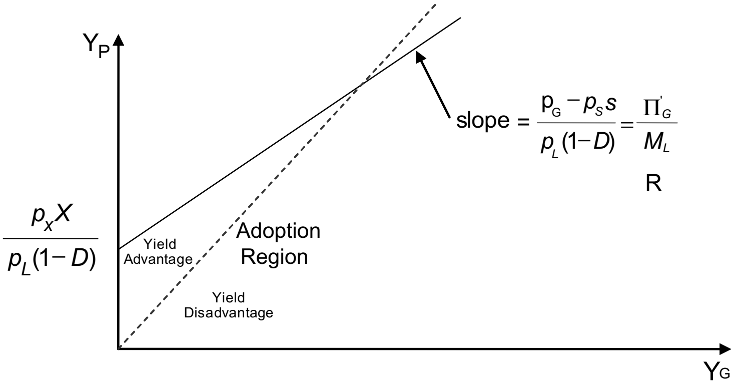

Figure 1. *Transgenic adoption by yield comparison.*

cost of the transgenic seeds. The likelihood of adoption can be expected to increase as (1) the price of the transgenic variety declines, (2) the pest pressure increases, (3) the effectiveness of traditional pesticides declines, (4) and the price of pesticides rises.

This analysis suggests that the adoption of pest-controlling transgenic varieties is likely to have a significant effect on average yields in locations with high levels of pest infestation and lack of effective chemical pest control (either because of cost or availability). In other locations, where pesticides are used effectively, adoption of pest-controlling transgenics may not have as great a yield effect but can reduce pesticide use and its attendant externalities. Indeed, in the United States and China the adoption of *Bt* cotton increased average yields by less than 10%, but substantially reduced pesticides use, and in the case of China it had measurable health benefits through decreased instances of farm worker poisoning (Pray *et al.*, 2002). The yield effects of *Bt* cotton adoption in India have fluctuated between 25% and 80% (Qaim & Zilberman, 2003). The yield effects in South Africa and Mexico have been quite high as well.

The studies in India also emphasize the greater gain from adoption when the modified variety is well adjusted to local conditions, compared to cases of adoption of generic varieties. The extent of adoption by heterogeneous growers suggests that holding everything else constant, more adoption is likely to occur and both the adoption effect and yield effect are higher if the new transgenic variety is a genetic modification of a local variety rather than of a generic variety. Furthermore, the larger supply shifts that are likely to occur with modified local varieties may lead to a greater reduction in output price, and thus, greater improvement in the welfare of food consumers.

The decision whether to import generic varieties or modify local varieties is an economic one, made by the firm or government agency that distributes or sells the transgenic varieties. It also may be facilitated by a black or grey market operating on the willingness of farmers to pay for seeds that promise to deliver some economic advantage. This decision will turn upon the cost of national or local adaptations of the transgenic (via backcrossing [6] or other means), compared to the net gains *vis-à-vis* the generic transgenic variety and the conventionally bred local varieties. The extra cost of modifying local varieties depends on national/local technical and regulatory infrastructure. In most Tier I countries, as well as Tier II countries with a strong crop breeding and agricultural science sector (India, China, and Brazil), it will not be very difficult or costly to modify a large number of local varieties through backcrossing from an initial transformation event (the laboratory transfer of the transgene coding for the desirable trait into an initial receptor variety that can then be used for breeding). In low-income countries in Asia, Latin America, and Africa, infrastructure constraints will restrict the capacity to modify multiple local varieties and may lead to significant introduction of imported generic transgenic varieties, which would negatively affect crop biodiversity.

The introduction of transgenic traits to local varieties is likely to suffer when regulatory testing, registration, and fees are required for each modified variety separately, and are not confined to the initial transformation event and all of the progeny varieties bred from it as a whole. For example, regulatory cost at the single variety level as currently required in India slows adoption of *Bt* cotton and substantially reduces the attendant yield gains, since as a result *Bt* is introduced in some locations using varieties that are not very effective to those local conditions. In contrast, the United States and China do not require registration for every single variety; they only require registration for the initial genetic transformation event. This likely contributes to the much larger number of *Bt* cotton varieties in the United States and China relative to India.

Finally, this analysis argues that the extent of adoption—and the gains from adoption—of transgenic varieties depends upon the price charged for those varieties. Adoption and gains both decline as the distributor of the transgenic variety takes advantage of any monopoly power and increases price. The number of modified varieties available may be further restricted because of barriers to cooperation and trade between the entities that control the conventional local varieties and the owners of the transgenic trait or distributors of seed containing it.

(c) *Linking biodiversity and property rights*

This relationship between biotechnology and biodiversity is understandably a contentious one, and is generally not well understood. On the one hand, there is a public perception that biotechnology reduces biodiversity. On the other hand, there is a widely held sentiment that agricultural technology institutions (public and private) seek appropriate biodiversity resources from low-income countries in the South. Both are dependent to some extent on institutions and instruments of intellectual property (IP) rights.

Yet, as we have just illustrated, biotechnology actually has the potential to enhance biodiversity, enabling local varieties to be made pest resistant and obviating the need to adopt and adapt more homogeneous generic varieties, as was the norm during the height of the Green Revolution. For example, the United States now has more than 1,000 varieties of soybean tolerant to glyphosate herbicides, most of which are single-gene variants of local legacy varieties (Qaim, Yarkin, & Zilberman, 2003). Far from homogenizing the gene pool, the introduction of agricultural biotechnology in OECD markets has acted to protect and even increase crop biodiversity (Sneller, 2003).

The issue of biodiversity prospecting and (implicitly) South-to-North transfer of property rights might seem more ambiguous. Genetic material from the South has certainly contributed to science and practical technology in OECD economies, but the productivity gains resulting from transfer of these refined technologies back in the opposite direction have been enormous. There is a growing literature on the economics of biodiversity that shows that for most locations, the potential value of a "source" or "lead" derived from biodiversity is very low (Simpson, Sedjo, & Reid, 1996). The economic value of a species is more likely to be discovered and developed if concentrated in one of a small number of "hot spots" (Rausser & Small, 2000), Thus, the scope of compensation for biodiversity is limited and should not be foreseen as a major source of income for less developed countries (Dalton, 2004; Simpson & Sedjo, 2004).

Like the Green Revolution, public and private agency will accomplish their primary objective (public welfare and profit, respectively) only if they achieve their secondary mission, increasing agricultural productivity and food security in the developing world. From an economist's perspective, land is an immobile factor of production, and for this reason globalization of agricultural biotechnology cannot succeed without local assimilation. Some observers see the advent of agricultural biotechnology as a process of global consolidation, but emerging evidence on the *Bt* trait reveals the opposite, a process of technology dispersal and localization. Instead of adapting innumerable growers to a few varieties, agricultural biotechnology appears to be adapting a few technologies to innumerable local varieties. This suggests not the imposition of agro-industrial market power on a global scale, but a partnership to overcome barriers to increased production for the world's majority enterprise, small farming, building upon the global legacy of biodiversity.

Having said this, the evolution and eventual success of such a partnership will depend critically on innovation and technology sharing, where the latter encompasses both man-made and natural technology (e.g., biodiversity). This in turn will depend upon clear delineation, ownership, and market articulation of property rights, and much remains to be done in these areas. Public institutions will have to fill many gaps for more complete markets to develop in this area. And more needs to be done to increase transparency and reduce transactions costs in the exchange of biological material, genetics, and germplasm.

5. AN AGENDA FOR MORE EFFECTIVE NORTH–SOUTH BIOTECHNOLOGY DIFFUSION

Until now, biotechnological innovation and product development have been confined largely to research systems in OECD countries, yet the economic and social potential of these technologies is global in scope. For example, *Bt* cotton has been widely adopted in the United States and has conferred significant gains there in terms of reduced pesticide dependence and lower prices for consumers. Yet, recent studies in India (Qaim & Zilberman, 2003) show even more dramatic per hectare gains, and studies in China (Pray *et al.*, 2002) associate adoption with improved worker health and reduced environmental side effects. More generally, higher pest intensity in low-income countries and more limited alternatives for pest control further amplify the relative benefits of pest mitigating biotechnologies, including collateral gains in terms of reduced chemical loading of soil, water, and other resources.

Despite this emerging evidence, the world remains sharply divided when it comes to biotechnological research, innovation, and diffusion. Instinctive resistance to radical innovations might seem prosaic for everyday consumer technologies, but it has graver implications in the context of human nutrition and health. In low-income countries, especially in some of the poorest Tier III countries, there has been precious little basic or applied research of any kind, in either the public or the private sector. Even in China and India, which have strong scientific traditions and many public and private laboratories, many of the technologies we describe in the previous section are only beginning to be explored.

(a) *Higher education and North–South partnership in human capital development*

One of the key features of biotechnology—both agricultural and biomedical—is that its development and applications are the outcomes of a sometimes complex division of innovative labor within an educational–industrial complex (Graff, Heiman, & Zilberman, 2002). Many of the basic breakthrough innovations have been made by university scientists but then patented and moved into the private sector via technology transfer agreements for further development, regulatory approval, and commercialization. Thus, the main industrial centers of biotechnology are interlinked with and sometimes located quite near to the major research institutions. Frequently, university spawned technologies are commercialized by start-up companies, which can remain key niche players in the industry, can be bought up and integrated by major corporations, or can evolve into multinationals in their own right. The knowledge intensity of biotechnology makes management and control of intellectual property a key feature of technology development strategy for both universities and firms (CIPR, 2002). It has thereby become apparent that to succeed in biotechnology, a country needs to develop and maintain higher education and research in order to buildup an educational–industrial complex to generate simultaneously the necessary human capital and the potentially marketable knowledge capital. This observation alone defines an agenda for education- and innovation-oriented development assistance, whether it be private or public, bilateral or multilateral (Bezanson & Oldham, 2005; IAC, 2005; Juma, 1999).

Research and development generally, and biotechnology R&D in particular, are strong complements to human capital development, and conversely biotechnology R&D is especially human-capital intensive. The geographic and institutional symbiosis between research universities and the technology clusters of particular sectors is an important example of this. Yet, it is an example that low-income countries have difficulty in emulating for many reasons. A combination of underinvestment in education, insufficiency of private capital, and, in many cases, access only to small size markets has prevented the emergence of significant technology clustering in most low-income countries. Even those Tier II low-income countries with large and long established scientific traditions, like China and India, are in the earliest stages of building and integrating the sophisticated public–private research institutions that are the hallmarks of dynamic technology sectors in OECD countries.[7]

These facts reveal the need for expanded international partnership, both public and private, to develop the capacity for biotechnology innovation and commercialization in the South. On the public side, aid agencies should reaffirm their commitments to human capital development generally, and scientific capacity in particular, recognizing this as the key to sustained productivity growth and higher living standards. Private interests, for their part, can take new initiatives to leverage the nascent knowledge capital in low-income countries, transferring technology and business capital into new markets and thereby gaining first-mover advantage in these emerging biotechnology markets. China, India, and other large, populous low-income Tier II countries are already attractive candidates for this kind of investment both by multinational corporations and by entrepreneurs who are returning émigrés with advanced degrees as well as technical and business experience (Saxenian, 2002). Smaller, less advanced Tier II countries could be seen similarly in a "regional gateway" perspective.

(b) *IP clearinghouse institutions for North–South technology transfer*

Once national and international research centers and public and private aid agencies fund or consider investment to enhance biotechnology research and development capacity in low-income countries, technology transfer and access to intellectual property becomes the next primary issue. One way to facilitate this is the establishment of an intellectual property clearinghouse (see Graff & Zilberman, 2001), a model of institution that can serve several purposes.[8]

To understand some of the potential benefits of the intellectual property (IP) clearinghouse, it is important to compare the way intellectual property management differs between the private and public sectors. The private sector recognizes IP constraints as part of the cost of doing business, and new projects not introduced without "freedom to operate," that is, access to all input technologies needed for development and commercialization, acquired either through public access, through outright ownership of the proprietary technologies, or through receiving permissions to use via licensing agreements with the technology owners.

In the course of pursuing their own research agendas, public sector scientists generally ignore IP restrictions and proceed with projects that may in fact be at risk of IP infringement. In particular, public sector researchers lack accurate and timely information on the current status of property rights within different countries over basic technologies, the means of accessing permission to use those technologies without violating other's property rights, or both. While usually immaterial to their progress in basic (i.e., non-commercial) research, this limitation can seriously undermine the potential for any commercialization of resulting innovations, particularly in crops that may enter globally traded commodity channels. The objectives of an IP clearinghouse organization are to provide researchers with information about and access to IP protected technologies, to navigate the constraints and reduce the transaction costs associated with intellectual property.

Private sector organizations typically leverage their existing IP holdings to secure access to other needed components of intellectual property, thus reducing IP constraints and transaction costs. Indeed, the primary reason for cross licensing, strategic alliances, and merger arrangements between firms is to enlarge and diversify their IP portfolios, thereby increasing their flexibility in research, development, and commercialization (Graff, Cullen, Bradford, Zilberman, & Bennett, 2003).

Because of the resulting restrictions and transaction costs, private ownership of patents by corporations is perceived to be a major constraint of technology use in low-income countries, where less ability to pay has resulted in "orphan" crops. However, in some cases, obtaining permission to use technology protected by patents owned by universities may be just as difficult. Some researchers in low-income countries have maintained that they have had a harder time obtaining rights to utilize technologies from university offices of technology transfer than from private companies (Graff & Zilberman, 2001). Companies are on occasion willing to provide proprietary technologies for use in "orphan" crops simply for the sake of public relations or out of a sense of corporate social responsibility. Conditions, however, are placed on these donations limiting the use of technology to products that do not threaten their established markets and that are unlikely to create potential liabilities with regulators. For university managers of technology transfer, the institutional mandate to license a technology for royalty income, combined with institutional policies and bureaucratic inertia for how technology transfer is to be managed, can actually prevent universities from executing similar technology donations. One possible role of the clearinghouse is thus to establish and harmonize technology transfer policies that allow for easier donation of rights to use university patented technologies for applications in orphan crops.

Barriers to technologies that originate in the public sector are also the result of imprecise or excessively broad terms in licensing contracts. Companies often sign an exclusive license with a university for use of a patented technology in all markets, while in reality the company may only be interested in applying the patented technology to a few major crops in high-income countries. Yet, once the rights have been exclusively licensed, liability considerations, transaction costs, and other factors arising from aversion of either party to test the limits of that contract may limit the ability of others to obtain sublicenses or donations of the technology to utilize in orphan crop markets. One possible role of the clearinghouse is to share knowledge and research cost to develop more precise technology licensing terms that will lead to more efficient and socially beneficial IP management by universities.

The above analysis suggests several objectives for an IP clearinghouse for agricultural biotechnology:

—reduce transaction costs for the commercialization of innovations (Shapiro, 2000),
—expand the universe of accessible technologies (reduce uncertainty about terms of access),
—improve the efficiency of technology transfer mechanisms and practices in public sector institutions,
—increase transparency of ownership and clearly define the boundaries of property rights,
—provide mechanisms to expedite IPR negotiation (turn single stage games into repeat games),
—consolidate the public interest in technology origination and development.

In fact, there have been several recent attempts to develop intellectual property clearinghouses in biotechnology.

(i) *The Public Intellectual Property Resource for Agriculture (PIPRA)*

The Rockefeller and McKnight Foundations have collaborated with over two dozen major universities and plant science research institutes in the United States as well as leading centers of the CGIAR system to establish the Public Intellectual Property Resource for Agriculture (PIPRA). [9] This initiative aims to increase public sector scientists' freedom to operate and provide access to proprietary technologies to develop new innovations for orphan crops. The new organization of PIPRA will have two core elements: (1) a database of member institutions' IP ownership in agricultural biotechnology and the availability of those technologies for different types of applications, and (2) licensing mechanisms, such as patent pools, to make aggregated technology systems available *ex ante* while reducing transaction costs and uncertainty. PIPRA consists of over two dozen member institutions that will share information on their technologies with each other and with other technology users, especially researchers in low-income countries. PIPRA will aim to provide a set of enabling technologies and research tools that will enable research and development across a broad range of agricultural biotechnology applications.

Public sector institutions account for a very significant share of the intellectual assets in agricultural biotechnology, suggesting this strategy of coordinating access just to public-sector-owned technologies (Graff *et al.*, 2003). By 2000, 24% of US agricultural biotechnology patents were owned by public sector entities, concentrated in research universities in the United States and other OECD countries, while 41% were owned by the main corporations involved in agricultural biotechnology (Monsanto, 14%; Pioneer-DuPont, 13%; Syngenta, 7%; Bayer CropScience, 4%; and Dow AgroScience, 3%). The rest of the private sector, mostly start-ups and smaller companies, owned 33% of agricultural biotechnology patents. Similar proportions are observed in other OECD patent systems (the European Union and Japan), and globally (in Patent Cooperation Treaty applications). Using cluster analysis of the full patent data set, Graff *et al.* (2003) documented that public sector organizations have in fact patented broadly across most of the various technology classes necessary to create a wide range of transgenic crops. [10] In addition, the range of research projects that could be supported by public sector owned IP is also significantly enhanced by a wide range of unpatented or off-patent innovations that are accumulating in the public domain.

Yet, while the public sector has significant IP ownership, it is diffused among many institutions. No individual public institution has more than 2% of the patents in agricultural biotechnology. The diffused ownership of IP by public sector institutions means that the transaction costs involved in putting together technologies from the public sector can be significant, including search costs, negotiation costs, and potential problems of hold up and stacked royalties.

In addition, where the rights to public sector technologies have already been transferred to the private sector through licensing agreements, [11] it is essential to know the actual scope of rights still available from the initial owner. Information on the licensing of technologies, as for any such private transaction, is often confidential and thus not publicly available. This lack of transparency increases the level of risk and transaction costs for others potentially interested in using the same technologies in research and product development, thus hindering what otherwise might be perfectly viable innovation. A fundamental role of PIPRA is to collect updated information about technology ownership and licensing status. Additionally, PIPRA's team can advise researchers, administrators, and managers about practical intellectual property management strategies and where to obtain technologies they need.

(ii) *The African Agricultural Technology Foundation (AATF)*

Another clearinghouse is the African Agricultural Technology Foundation (AATF) [12] based in Kenya. Supported by the Rockefeller Foundation and other donors, it aims to facilitate research and introduction of new crop varieties using biotechnology in sub-Saharan Africa. It emphasizes technology transfer from the private sector and will help African scientists to overcome IP and regulatory requirements. AATF aims to coordinate with participating companies in the private sector directly to obtain permission and assistance for use of their proprietary technologies in Africa specifically by smallholders. This organization will go beyond technology transfer, providing some funding for research, biosafety management, and development. Its main emphasis, however, is to work with technology owners and project partners, including donors, to negotiate overall licenses and stewardship of the technologies employed. The AATF is in all cases the responsible licensee, and then grants and manages sublicenses for use of the technologies throughout Africa by smallholders. The AATF has already been involved in developing an herbicide tolerant hybrid maize variety effective in combating infestation by striga, an insect resistant *Bt* maize resistant to stem borers, a maize biofortified with provitamin A, and a high yielding cowpea.

(iii) *The Centre for the Management of Intellectual Property in Health Research and Development (MIHR)*

Finally, in the medical arena, a related prototype clearinghouse institution is MIHR, [13] a new organization also supported by the Rockefeller Foundation. Its motivation is to facilitate access to IP for developing vaccines and drugs for diseases (tuberculosis, AIDS, and malaria) specifically afflicting the poor. Its main areas of work include (1) identification and codification of best practices for licensing to achieve the goals of the public sector; (2) provision of training to scientists, universities, and research institutes in managing intellectual property to benefit the public sector in both high- and low-income countries; and (3) consulting services to non-profit groups concerned with research and product development.

There has been extensive and often spirited discussion on the pricing side of this issue, particularly in controversies about IP and monopolistic practices in low-income countries (CIPR, 2002). While pricing and access are important issues, they often neglect the more fundamental issue of underlying costs. Obviously, it is expensive to discover, develop, and test valuable transgenic crop traits just as it is for biotherapeutics, and it makes little sense to simply advocate price cutting or public expropriation of existing transgenic traits or therapies if the long term goal is sustainable R&D to drive ongoing innovation for future generations.

The best solution to the twin challenges of profitable R&D and affordable products of biotechnology is accessing economies of scale, and here we see enormous promise for agriculture and for biomedicine at the global scale. The key to achieving affordable biotechnology products is to integrate supply chains across the three tiers of countries defined earlier. Tier I countries are today host to the principal innovators and rights holders, but their costs of conducting R&D are high and their markets are limited to about 20% of global population. Tier II countries (e.g., China, India, and Brazil) enjoy lower R&D and production costs, and they also sharply increase scale economies by adding another 50% of global population to market size. Finally, an additional round of scale increases can be realized by marketing Tier II innovation and production in Tier III countries.

Of course the precedent for this has already been established in the generic drugs industry, where India's leadership gives some indications about how IP reform might increase market size to reconcile profitability and affordability objectives. To achieve this will require more than spontaneous entrepreneurship, however, and we are currently undertaking detailed research on IPR mechanisms and policies to facilitate North–South technology transfer with these objectives in mind.

Private ownership of technology will remain a controversial subject for the foreseeable future, since it embodies both the promise of sustained innovation and the consequences of monopolization. The responsibility of public entities is to clearly strike a balance between facilitating the former and mitigating the latter, and effective policies for the transfer of biotechnologies must reflect this. Facilitating access to technology while maintaining the effectiveness of intellectual property rights as an incentive for further development is the primary impetus for these IP clearinghouse initiatives.

6. CONCLUSIONS AND EXTENSIONS

Throughout human history, technology has proven its ability to contribute to higher material living standards, yet the work of poverty alleviation is far from complete. Biotechnology holds significant potential for reducing poverty and its attendant adversities. However, the extent to which this promise is fulfilled will depend as much on institutions as it does on innovation. History is also replete with examples of technologies that have contributed to immiserization because of inadvertent or even deliberate misapplication.

If the poor are to enjoy the full benefits of agricultural biotechnology, then its productivity gains must be conferred on both rural and urban low-income households. The former will benefit directly if biotechnology is appropriate (both in terms of technology and incentives) for penetration into smallholder production systems. In contrast, the latter benefit must be indirect, with lower food prices contributing favorably to real wages of the urban poor. Increases in productivity can thus reconcile producer and consumer interests domestically, but the range of innovations emerging from biotechnology hold forth such promise.

Our analysis of adoption of transgenic varieties and much of the current literature addresses only pest control biotechnologies, but our general conclusions are likely to apply to other categories of biotechnology as well. We can conclude that the gains from introduction of transgenic varieties in low-income countries will be enhanced (1) when it is associated with the availability of crop breeding capacity that will allow modification of the existing varieties, (2) when registration requirements are at the level of the initial transformation event and not at the level of each separate resulting variety (i.e., no separate registrations for downstream backcrossed varieties), (3) when there are low transaction costs and barriers to trade between the new biotechnologically created trait and the locally optimized conventional varieties, and (4) as the cost of resulting transgenic varieties decline.

In these early stages of development, biotechnology is concentrated in the most developed, Tier I countries. In this paper, we envision future biotechnology diffusion around the world, with large emergent Tier II economies playing a catalytic role in propagating affordable and appropriate innovations. Through the mechanism of a globally distributed and articulated R&D supply chain, such products can ultimately reach the world's poorest and improve their dietary, health, and income status.

To realize this, the public and private sectors must establish institutions with local capacity for technology innovation and adaptation, reduce transaction costs in the international transfer of technology, and provide standardization, transparency, and access to information for property rights over technologies. These conditions can be met by significant investment in higher education and research capacity in low-income countries, definition and recognition of property rights institutions, and the establishment of what we call IP clearinghouses to directly facilitate technology transfer and diffusion.

NOTES

1. See, for example, Elbers, Lanjouw, and Lanjouw (2003); Morduch (1994); and Ravallion (1988).

2. See, for example, Gertler and Gruber (2002).

3. See, for example, Feder, Just, and Zilberman (1985); Lee and Roland-Holst (1998); Zilberman and Sunding (2000); Graff and Zilberman (2001); Graff, Small, and Rausser (2003); Qaim and Zilberman (2003); Ameden,

Qaim, and Zilberman (2005); and de Janvry, Graff, Sadoulet, and Zilberman (2005).

4. Even so, there are cases, such as a new herbicide tolerant maize designed to combat striga infestation in Africa, where the herbicide tolerance trait is expected to be a strong complement to labor through its yield effect.

5. These models have become the preferred tool for empirical policy analysis, and are especially well suited to quantifying the complex indirect effects of pervasive innovations such as biotechnology. For general background and applications of this methodology (see, e.g., Lee & Roland-Holst, 1998).

6. Backcrossing is a breeding technique that mates a new variety containing desired traits with an already used local variety over successive generations in order to incorporate the desired trait into the basic germplasm of the local variety.

7. The software and computer technology cluster around Hyderabad and the biotechnology sector around Shanghai are two leading examples.

8. This idea extends the R&D facilitation arguments of Castillo, Parker, and Zilberman (1998). Wright (1998) also emphasizes the importance of facilitating institutions for dispersion of public research benefits in biotech.

9. See http://www.pipra.org.

10. The sheer complexity of such a system of mutually interdependent intellectual properties, and some of the efficiency implications, is explained by Shapiro (2000).

11. About 20–30% of universities' agricultural life science patents have, depending upon the field of technology, been licensed either exclusively or non-exclusively, according to more recent data from PIPRA.

12. See http://www.aftechfound.org/.

13. See http://www.mihr.org.

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