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Biotechnology and Poverty Reduction in Developing Countries

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Abstract

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. We believe that in the modern age, biotechnology holds remarkable 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. 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 innovation products. Through the mechanism of a globally R&D supply chain, such products can ultimately reach the world's poorest and improve their dietary, health, and income status. For this to happen, three general conditions must be satisfied. First, property rights must be clearly delineated and recognized by more universal standards. Second, multilateral public and private initiative must be taken to lower …/.

Keywords: sustainable development, technology, food, health, agriculture

JEL classification: L31, I12, O13, O34, Q16

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barriers to diffusion. These include government intervention, imperfect contractual standards, and incomplete information. A broad spectrum of government policies—from outright protectionism to corruption—impedes the propagation of innovation between countries of all three Tiers. Incompatibility and incompleteness of legal systems are also major obstacles to international sharing of innovation. Finally, informational commons supported by institutions like the IPR clearinghouse are needed to facilitate innovation partnership.

We present a general vision of R&D networks extending from the capital and technology rich Tier I, through the dynamic Tier II emerging economies, to those, finally, in Tier III who most need enhanced agricultural and human productivity. We believe that achieving this goal is not only desirable, but imperative to global sustainable development. If the poor are to enjoy the full benefits of agricultural biotechnology, 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. By contrast, the latter benefit must be indirect, with lower food prices contributing favourably to real wages of the urban poor. Only dramatic increases in productivity can thus reconcile producer and consumer interests domestically, but biotechnology represents exactly such a promise.

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1 Introduction and background

Economic history can be read as a testament to the transformative power of technology in relation to the human condition. 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 first enlisted for industrial production. Across the entire chronicle, we see what a potent catalyst technology has been for economic growth and the 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 imaginings of prior generations. Despite our many successes, however, technology is still far from fulfilling its promise to all of us. The so-called industrial revolution is already over two centuries old, and today human voices can whisper between any two points on the globe in a heartbeat, yet such benefits have reached less than half of mankind.

The World Bank estimates that in 1998, 56 per cent of humanity lived on less than US$2 per day, while 24 per cent subsisted on less than half this amount. How can scientific discovery and technology make more significant contributions to the world's poor majority? We believe that more effective globalization of innovation processes can be put to work on the fundamental determinants of poverty, those factors that make people poor and keep them poor. Detailed analysis of poverty reveals that entry into this status and exit from it are asymmetric, yet they share some characteristics. In particular, the primary reason for a household falling into poverty is an adverse health event, including mortality.[1] On the up side, the main determinant of transit 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 recruitment and labour productivity. In the case of employment, economic growth and rising productivity, especially in the rural sector, are essential to increase the probability of exiting poverty.

We believe that technology in general, and biotechnology in particular, can greatly improve living standards in the developing world. As the touchstone for a new generation of rural development, biotechnology can increase food output, nutritional quality, and rural employment more quickly than populations will grow, alleviating direct nutritional deficiency and increasing incomes for the world's poor rural majority. Because it is also at the heart of a medical revolution, biotechnology has the potential to dramatically improve health status in developing countries, liberating the poor for more sustained and productive labour force participation.

Although it remains an area of controversy, biotechnology has already achieved productivity gains that appear to rival those of the green revolution (Evenson and Gollin 2001). Less controversially it has certainly begun to alter the landscape of preventative and therapeutic medicine. If the impetus for scientific discovery in life sciences can be further intensified, and if this innovation can be more effectively diversified from north to south, we believe that dramatic progress can be made in realizing the human and economic potential of all peoples. In this paper, we survey the challenges and opportunities that exist for two kinds of life science technologies, agricultural and

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1 For more detail on these issues, see e.g., Elbers, Lanjouw and Lanjouw (2000); Ravallion (1988).

medical biotechnologies. Together, these represent some of today's most dynamic areas of innovation, some of the greatest challenges to global technology diffusion, and some of the greatest opportunities for improving living standards. The extent to which agricultural biotechnology can help the world's poor will depend on two components: how these productivity gains penetrate smallholder agriculture, and how much lower food prices can increase real wages for the poor. Depending on patterns of diffusion and adoption, either or both of these benefits may occur, but the potential for each is very substantial, and policymakers should work to facilitate them. The extent to which medical biotechnology can help the world's poor will depend primarily upon the extent to which it is applied to medical conditions affecting poverty, which in turn will depend both upon access to therapeutics and diagnosics developed in industrial countries for common diseases and upon development of therapeutics and diagnostics for diseases specific to poverty.

2 Technology in a modern global context

History indicates that technological advancement and sustained increases in general living standards go hand in hand. Just as importantly, today's global income inequality is characterized by disparities in the scope and depth of technological assimilation. If the benefits of technology are to advance more widely and rapidly across the socioeconomic spectrum, whether through agriculture, medicine, or other sectors, we must better understand the barriers technology has encountered in the past. Generally speaking, north-south diffusion of technology and sustainable innovation has been hindered by three salient factors:

i) *Institutional capacity*: Countries who receive innovation often lack the institutional pre-requisites to facilitate orderly and sustained assimilation of new technologies. Among other things, this applies to

   a) Legal standards and enforceable property rights.
   b) Administrative and regulatory capacity.
   c) Public and private research capacity, including educational institutions.

ii) *Financial capacity*: Recipient countries often lack the financial resources necessary to capitalize the application of existing technologies or to invest in R&D for local innovation. In the absence of enforceable property rights, it is also difficult to recruit foreign capital that can alleviate this constraint.

iii) *Human capital*: Clearly, there are very significant global disparities in average education levels, and these seriously limit the geographic scope of technology use and development.

With these issues in mind, the challenge of globalizing technology becomes more transparent. In particular, we suggest a threefold classification of national economies, depending on the capacity to internalize and sustain technological progress.

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

Tier II Emergent innovators, including China and India, which are in transition and overcoming all three types of obstacles discussed above.

Tier III Long-term importers of technology. These are the majority of today's economies, and a much larger majority of developing economies.

Membership in each of these groups is defined from today's perspective, and countries can be expected to transition between them over time. While all countries aspire to join the first group, it is, however, unlikely that many will move from third to first place in the short to medium term. For this reason, global technology diffusion will evolve unevenly, as will its attendant benefits, and institutional arrangements need to evolve accordingly. This is more than casual observation, however, because the mechanics of north-south technology diffusion will operate very differently, depending upon whether the recipient is a Tier II or Tier III economy. These mechanics will in turn affect optimal policies to facilitate the benefits of diffusion.

In the next two sections, we survey the main issues relating poverty and the two leading applications of biotechnology, in agriculture and medicine. In both of these areas, the challenges facing the world's poor are enormous, and we believe the potential for beneficial innovations arising from biotechnology to be of commensurate magnitude. Having passed through two great eras of modern technology, industrialization and the digital revolution, we see mankind moving toward a third era, one where life sciences will unlock tremendous potential in natural resources, agriculture, and health for improving living standards.

2 Challenges and opportunities for agricultural biotechnology

The demands on agriculture over the next generation, in developing countries and elsewhere, will be enormous. This is particularly so if agriculture is to meet all three of its primary global challenges:

i) To satisfy ever growing effective demand for food;

ii) Reduce poverty and malnutrition;

iii) Achieve environmental sustainability.

Because of population growth and rising incomes, demand in the developing countries is predicted to increase by 59 per cent for cereals, 60 per cent for roots and tubers, and 120 per cent for meat over this period (Pinstrup-Andersen and Pandya-Lorch 1999). This increased supply cannot come from area expansion since this is a rapidly diminishing source of output growth globally and has already turned negative in Asia and Latin America. Neither can it come from any significant expansion in irrigated area due to competition for water with urban demand and rising environmental problems associated with drainage, soil salinity, and chemical run-offs. While it will thus need to come from growth in yields, the growth rate in cereal yields in developing countries has been declining from an annual rate of 2.9 per cent in 1967-82 to 1.8 per cent in 1982-94, which is the rate needed to satisfy the predicted 59 per cent increase in demand for cereals over the next 25 years. The growth in yields cannot consequently be let to fall below this rate in developing countries without further increasing the share of food consumption that is imported. Of course greater international food trade might increase global welfare because of efficiency gains, and higher-income Asian economies have successfully bartered industrial comparative advantage against steeply rising food imports. For poor countries, however, long-term food import dependence can be risky when commodity price cycles are taken into account.

Secondly, the livelihood of the world's poor majority still depends critically on local agricultural profitability. With 1.2 billion people in absolute poverty (earning less than US$1 per day, see World Bank 2000) and 792 million underfed in the developing countries (FAO 2004), agriculture should also have a major role to play in reducing poverty and improving food security (i.e., the probability of not falling into hunger), particularly since some three quarters of these 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. Urban migration has provided an alternative in the most dynamic export economies, yet real income of poor consumers will continue to depend on the price of food. The only way to reconcile these interests domestically is productivity growth in agriculture, reducing costs to make room for rural income without reducing urban real wages by increasing food prices.

The potential does exist to confer, via the mechanism of north-south technology transfer, significantly higher food productivity and rural incomes on developing countries. There are many channels by which these effects may be propagated, and yet not all will accomplish net reductions in poverty and inequality.[2] Our overall assessment, however, is that there is substantial latitude for policymakers to choose policies that will facilitate these objectives as globalization and agricultural innovation continue their steady progress. Pragmatic and detailed institutional evaluation can support more proactive responses by the least advantaged stakeholders in global agricultural markets, the marginalized rural poor.

If poverty is to fall and the nutritional status of the poor is to improve at current levels of food dependency, the decline in growth rate of cereal yields must be arrested, and yield increases compared to current trends will have to occur, particularly in the fields of poor farmers around the world. Since the yield growth rates achieved with traditional 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. Yet, while biotechnology has advanced agricultural productivity growth in some of the more developed countries, it has had little actual impact so far in most developing countries, particularly in the farming systems of the rural poor.

Here we want to explore the necessary conditions for the current biotechnological revolution in agriculture could contribute to poverty reduction in developing 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

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2 See, e.g., Alston, Pardey and Taylor (2001) for an overview of these global trends.

ethical implications to withholding or obstructing the dissemination of a viable technology to those for whom it could make a material difference in welfare. Failure to develop and capture the potential of agricultural biotechnologies could further increase the income gap between developed and developing nations and could be a setback in the struggle to reduce poverty. At the same time, environmental and consumer risks that may, for example, derive from adoption of genetically modified organisms, will have to be carefully assessed and regulated for biotechnology to yield its potential benefits without undue risk of setbacks in the already constrained circumstances of the rural poor in developing countries.

3 Challenges and opportunities for medical biotechnology

Labour is the greatest asset in the hands of the world's poor. Judging from the historical experiences of north and south, it is this labour asset that holds greatest economic potential for the alleviation of poverty. Thanks to legal progress, most of the world's poor have economic entitlement to this asset, yet its productivity and thus its commensurate returns remain low. While there are many reasons for lower labour productivity in developing countries, one of the most significant and most challenging is health status. Initiatives to improve labour returns, directly through economic growth policies and indirectly through education and other human capital investments, can be seriously compromised by public and private health problems. Poor average health status reduces the private and social returns of all investments in job growth and education, reducing individual productivity and increasing effective dependency rates.[3]

Health status is also an important factor in the dynamics of poverty and inequality. Econometric evidence indicates that adverse health events, including individual illness, disability, and family bereavement, are the most important determinants of transit from non-poverty into poverty.[4] This being the case, health protection should be one of the highest priorities for social insurance. Unfortunately, social insurance schemes are not prevalent in developing countries, so more direct means are needed to target health status.

While it is not a panacea, medical biotechnology can play an important role in improving health status and thus the quality of human capital in developing countries. Moreover, north-south chains of technology diffusion can facilitate this in ways analogous to their role in disseminating agricultural biotechnology.

To better understand both the potential and limitations of biomedical contributions to developing country health status, consider a more comprehensive perspective on health risk (Lichtenberg and Zilberman 1988) where risk is defined as the probability that a member of a population suffers from a negative health event or mortality within a given period of time. Following the literature on risk assessment, health risk can be decomposed into three components:

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3 The dependency rate is defined as the population below and above working age, divided by total population.

4 These results highlight obvious costs such as disability, but also less obvious ones in traditional societies, such as the substantial burden of death ceremonies.

i) External environment

  a) Food availability
  b) Contaminants
  c) Security danger
  d) Climate

ii) Individual exposure

  a) Protective or preventative behaviour
  b) Access to food (income)
  c) Protective resources

iii) Health

  a) Genetic or nutritional status
  b) Health care system
  c) Medicines.

For simplicity, since we will not be using an analytical model of risk, we will not distinguish between factors that are deterministic and those that are random, or between those that are given and those that can be controlled by policy.

The first factor represents the totality of an individual's ambient environment. These include prevalence of disease or pathogens in the surrounding population and environment, the state of infrastructure that may increase likelihood of accidents, environmental pollution, and other contamination levels.[5] Some of these factors can of course be affected or reduced by policy interventions, such as improved water, sanitation, or spraying for mosquitoes.

The second factor represents individual or group exposure to a given level of external factors. This includes behavioural variables affecting personal health, like use of filtration or of bottled water, protective bed nets and clothing, condoms, or avoidance of contaminated areas.

The third and final factor represents individual or collective health vulnerability. This factor can be divided into individual health parameters, such as genetics and nutrition, especially pre-natal and post-natal nutrition, and more communal parameters including the quality of the local health care system and available medicines.

This simple decomposition makes clear the scope and depth of the challenge to improve health status for the world's poor. The external environment component arises from both natural and anthropogenic factors, usually outside the control of individuals and even local authorities. It is often the result of long histories of complex incentive and externality problems that, even when they are resolved, can present enormous remediation costs. In the developing world, divergence between private and public interests can be large and persistent, imposing chronically high risks to both the environment and health status.

5 Juma (1999) elaborates usefully on some of these issues.

Biotechnology's contributions to environmental quality are well known and described elsewhere. These include things like bacterial waste treatment, phytoremediation technology, and renewable energy research. Despite these contributions, however, agbiotech and biomedicine cannot mitigate this component of health risk very significantly. Reducing ambient environmental contamination is an institutional exercise, usually involving substantial commitments to regulation and investments in public health related infrastructure.

The factor of individual exposure is often outside the control, ironically, of individuals, and indeed may be positively correlated with status quo living standards in developing countries. As already mentioned, agricultural biotechnology can mitigate exposure risk if it reduces agrochemical use, but, otherwise, exposure risks are endemic to the population in most low-income countries. Biotechnology has more limited relevance here, again, but may provide a number of indirect interventions by contributing to increased knowledge of biological systems and suggesting new strategies for limiting exposure to existing risk factors.

The health vulnerability component of overall risk is the one that biotechnology can most effectively influence because it incorporates the full universe of direct and indirect nutritional and medical interventions. In particular, the health component can be mitigated through biotechnology applications in agriculture that provide greater availability and nutritional content at lower prices and that reduce risk of shortages due to pest or drought conditions. Biomedical applications may provide effective instruments of disease prevention and treatment. For example, a great need for biomedical contribution in reducing health vulnerability is of course immunization technology. By contributing to the global commons of immunity, biotechnology can reduce the effective risk of ambient human and animal disease.[6]

In addition to immunization, biotechnology is developing a broad spectrum of therapies through the pharmaceutical R&D pipeline. Yet, its benefits have primarily been enjoyed by consumers in wealthier societies who finance R&D activities with large public and corporate budgets. This is not an option for the world's poor, so if biomedicine is to reduce health risk for the world's majority, the great challenge will be to reduce costs of innovation and production of relevant therapeutics and make them widely available.

There has been extensive and often spirited discussion on the pricing side of this issue, particularly in controversies about IPR and monopolistic practices (CIPR 2002). While pricing and access are important issues, they often neglect the more fundamental issue of underlying costs. Obviously, it is expensive to develop modern medications, and it makes little sense to simply advocate price cutting if one is talking about sustainable R&D to solve the health problems of future generations.

The best solution to the twin challenges of profitable R&D and affordable medicine is economies of scale, and here we see enormous promise for biomedicine at the global scale. The key to achieving affordable medicines is to integrate supply chains across the three tiers of countries defined earlier. Tier I countries are the principal innovators and rights holders, but their production costs are high and their markets limited to about 20

6 There is some controversy about application of this technology, particularly in animal feeds, undermining the same commons.

per cent of global population. Tier II countries (e.g. China, India, and Brazil) have lower production costs in any case, but they also sharply increase scale economies by adding another 50 per cent of global population to retail market size. Finally, a second round of scale increases can be realized by marketing second tier production to Tier III countries.

Of course the precedent for this has already been established in the generic drugs industry, where India's leadership gives clear indications about how IPR 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.

4 Factors affecting adoption and effectiveness of biotechnology; examples from agriculture

The term biotechnology refers to a wide array of approaches to applying recent developments in molecular and cell biology to commercial products. Thus far, biotechnology has very successful medical applications including a large number of therapeutics. It also has successful applications in agriculture, primarily for pest control thus far, but promises a wide range of other applications. Biotechnology has the potential to produce new biomaterials and address environmental problems. One of the key features of biotechnology is that its development and applications are outcomes of a division of innovative labour within the educational-industrial complex (Graff, Heiman, and Zilberman 2002). Many of the basic innovations were discovered by university scientists and have been patented and transferred to the private sector for development, regulatory, and commercialization via technology transfer agreements. Thus, the main industrial centres of biotechnology are linked and sometimes located quite near to research institutions. Frequently, university innovations are commercialized by startup companies that either evolve to become multinationals, as in the case of Genentech and Chiron, or are bought by major corporations: for example, Monsanto absorbed Calgene and adopted its technologies. The knowledge intensity of biotechnology makes management and control of intellectual property a key feature of industrial strategy within both universities and firms specializing in these technologies.

Most of the biotechnology industry is concentrated in developed countries and aims to develop applications that tap demands and problems of the developed world where the ability to pay resides. Therefore, medical biotechnology aims to find cures for cancer, diabetes, and heart problems while downplaying investment in development of immunization systems towards diseases afflicting the poor. Agricultural biotechnology has introduced solutions to crops of the north, like cotton, canola, soybeans, and corn and underemphasizes development of varieties important only in the south, such as cassava and millet. However, the same technology, for example Bt and resistance to RoundUp, can be applied to the crop varieties of the poor in developing countries. Other technologies that may not have a viable market in the north, such as vitamin A or iron supplementation of crops, can also be applied in developing countries where micronutrient deficiencies are a serious public health concern. The key challenge is to obtain the resources and develop research and outreach infrastructure for applications that are relevant to poor and developing countries. Biotechnology is not unique in this regard. In many cases, technologies that were developed in the north have been adapted, refined for the south.

Much of the potential of biotechnology—and the controversy about its use—relate to agricultural applications. Therefore, we will address some of the concerns about genetically modified varieties (GMV) below, and, in particular, pest damage reducing GMVs, that are the most popular forms of agricultural biotechnology employed today. Much of the results will apply to other biotechnologies as well.

An important feature of agricultural biotechnology is that new varieties are obtained by slight modification of existing varieties, while, with traditional breeding, new varieties may be substantially different than traditional varieties. Therefore, it is possible, in principal, to modify each existing variety, and the adoption of biotechnology can lead to preservation of the existing crop biodiversity *in modified form*. This insight has received too little attention in the popular debate on links between biotechnology and the environment. The extent to which it will happen depends on the economics and regulation of biotechnology. An analysis by Ameden, Qaim, and Zilberman (2005) considered the case where a producer with a traditional variety has to make the choice whether to adopt a modified pest-controlling variety.

Consider an individual farmer with a local variety L whose yield is Y_L, where

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

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

$$\begin{aligned} \Pi_L &= p_L Y_L - p_x X \\ &= p_L (1 - D) Y_P - p_x X \end{aligned}$$

If, on the other hand, the same farmer were to adopt a pest resistant GMV, profits would take the form

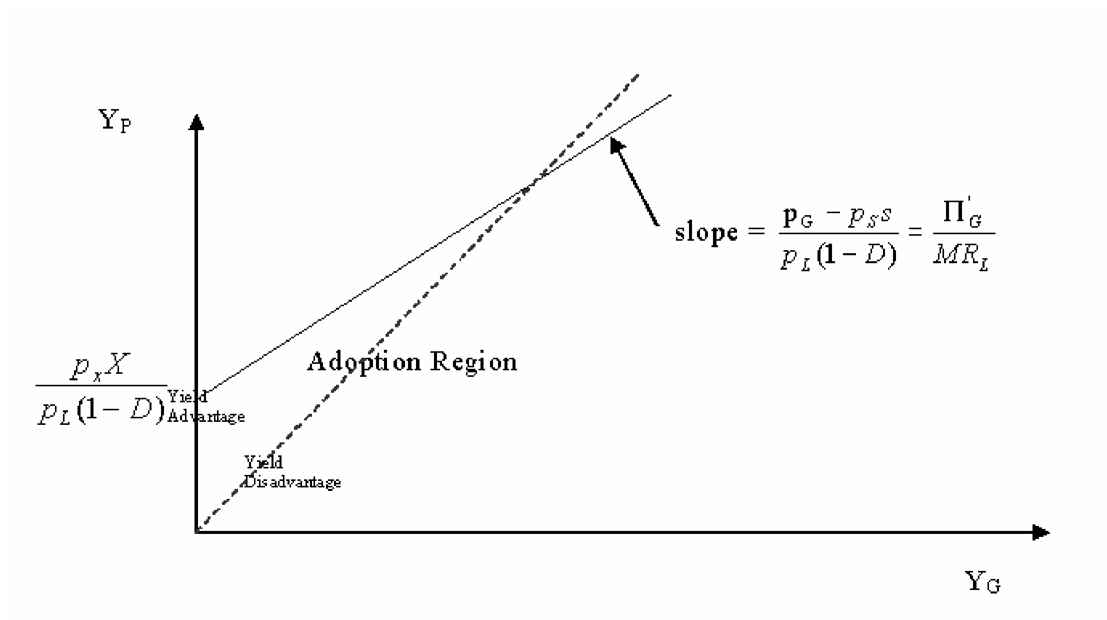
$$\begin{aligned} \Pi_G &= p_G Y_G - p_S S_G \\ &= (p_G - p_S s) Y_G \end{aligned}$$

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

In the static case, we assume farmers are fully informed and risk neutral, so the adoption decision partitions the space of varietal yields as 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 GMV profitability to marginal revenue on gross (before pest damage) output of the local variety. Clearly, pest resistance confers a yield advantage on the GMV. It should be noted, however, that GMVs generally will

Figure 1
GMV adoption by yield



have lower gross yields than localized 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 GMV (p_S) will be essential determinants of the adoption decision.

Adoption of a GMV will reduce pest damage and pesticides application. The impact of GMV adoption is 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 GMV is based on a generic variety, adoption may actually lead to lower yield in periods of low infestation. If farmers are risk-averse, they will adopt the GMV if expected utility of GMV income 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 cost of the GMV seeds. The likelihood of GMV adoption can be expected to increase as (i) the price of the GMV declines, (ii) the pest pressure increases, (iii) the effectiveness of traditional pesticides declines, (iv) and the price of pesticides rises.

The analysis suggests that adoption of GMV 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, the GMV adoption may not have as great a yield effect but can reduce pesticide use and its attendant externalities. Indeed, In the US and China the adoption of Bt cotton increased average yields by less than 10 per cent, but substantially reduced pesticides use, and in the case of China it had measurable health benefits through decreased instances of farm worker poisoning. The yield effects of Bt cotton adoption in India have fluctuated between 25-80 per cent. The yield effects in south Africa and Mexico have been quite high as well.

The studies in India cited in Ameden, Qaim, and Zilberman also emphasize the greater gain from adoption when the modified variety is well adjusted to local conditions, compared to cases of generic GMV adoption. The extent of GMV adoption by heterogeneous farmers suggests that, holding everything else constant, more adoption is likely to occur if the new variety is a genetic modification of a local variety rather than of a generic variety. These results suggest that if local varieties are modified, both the adoption effect and yield effect are higher than if the GMV is a generic variety. Furthermore, the larger supply shifts that are likely to occur with modified local varieties may lead to a lower reduction in output price, and thus, greater improvement in the welfare of consumers, including the poor, relative to the case where the GMV is a generic variety.

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 GMVs. This in turn will depend upon the cost of national or local adaptations of the GMV (via backcrossing[7] or other means), compared to the net gains vis-à-vis the generic variety and the traditional ones. 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 that strong crop breeding sector (India, China and Brazil), it will not be difficult or very costly to modify a large number of traditional varieties of crops like corn or soybeans through backcrossing from the initial 'transforming event' (new transgenic trait to be inserted) which is created by transferring the genetic sequence with genetic coding for a desirable trait to a particular receptor variety. In less advanced developing countries in Asia. Latin America and Africa, infrastructure constraints will restrict the capacity to modify local variety and may lead to significant introduction of imported GMVs, which will negatively affect biodiversity, and the impacts of biotechnology on outputs and prices.

The modification of local varieties is likely to suffer when regulatory cost and efforts are required for each modified variety, and are not confined to the transformation event. The regulatory cost at the variety level slows adoption of Bt cotton in India and substantially reduces the attendant yield gains, since in some locations Bt is introduced with varieties that are not very effective to the local conditions. By contrast, the US and China do not require registration for every modified variety (they apply only at the level of the genetic transformation event) and this probably contributes to the much larger number of Bt cotton varieties in these countries relative to India.

Finally, Ameden, Qaim, and Zilberman argue that the extent of adoption and the gains from adoption of GMVs depend on the price of the modified varieties. Adoption and gains will decline as the distributor of the new varieties takes advantage of monopoly power. The number of modified varieties available may be restricted because of barriers to cooperation and trade between the entities that control the traditional varieties and the owners or distributors of the rights to the genetic modification. While this analysis and the wider literature address mostly pest control biotechnology, the general conclusions are likely to apply to other categories of technology such as stress resistance or nutritional quality. The same rational that favours adoption of a genetic modification of the local variety over a generic GMV with the new genetic trait, applies to other traits as well. Therefore we can conclude that the gains from introduction of GMVs in developing countries will be enhanced (i) when it is associated with the availability of

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7 Backcrossing is a breeding technique that mates a new variety to local variety over successive generations.

crop breeding capacity that will allow modification of existing varieties, (ii) when registration requirements are at the transformation event level and not the variety level (i.e., do not require separate registration for downstream backcrossed varieties), (iii) when there are low transaction costs and barriers to trade between owners of the new biotechnology and the local varieties and (iv) as the cost of the modified variety declines.

5 An agenda for more effective north-south biotechnology diffusion

Until now, biotechnological innovation and product development has been confined largely to research systems in OECD countries, yet the economic and social potential of these technologies is global in scope. In agriculture, for example, Bt cotton has been widely adopted in the United States and conferred significant gains there in terms of reduced pesticide dependence and lower consumer costs. Recent studies of India (Qaim and Zilberman 2003) show even more dramatic per hectare gains, and research in China (Pray *et al.* 2002) associates its adoption with improved worker health and reduced environmental side effects. More generally, higher pest intensity in developing 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 emergent evidence, the world remains sharply divided when it comes to biotechnological research, innovation, and assimilation. 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 the developing world, especially in some of the poorest countries, there has been precious little basic or applied research of the kind we are discussing, either of the public or private sector variety. Even in China and India, which have strong scientific traditions and many public and private laboratories, the trends we delineated in the previous two sections are only beginning to be established.

Application of biotechnology generally, and especially in developing countries, requires more intensive public sector investment in research, development, and commercial licensing because such investment may be desirable from a social perspective, given the distribution of benefits to consumers and users of the technology, but may not be profitable from a private perspective. Fortunately, national and international research centres and public and private aid agencies are funding or considering investment to enhance biotechnology research and development capacity in developing countries. In this case, lack of access to intellectual property is one of the primary obstacles. One way to overcome this is establishment of an intellectual property rights (IPR) clearinghouse (Graff and Zilberman 2001), a model of institution that can serve several purposes.[8]

To understand some of the potential benefits of the IPR clearinghouse, it is important to compare the way intellectual property management differs between the private and

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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.

public sectors. The private sector recognizes IPR constraints as part of the cost of doing business. New projects are not introduced without ‘freedom to operate’, i.e., access to all intellectual property needed for development and commercialization (whether through ownership or licensing agreements).

In the course of pursuing their own research agendas, public sector scientists generally lack this freedom. In particular, they lack information on ownership of technologies, means of accessing permission to use those technologies, or both. While usually immaterial to their progress in basic (i.e., non-commercial) research, this limitation can seriously undermine the potential for any future commercialization of resulting innovations. The objectives of the intellectual property clearinghouse organization are to provide researchers with information and access, to overcome the constraints and reduce the transaction costs associated with intellectual property.

Private sector organizations use their own IPR holdings to secure access to other needed components of intellectual property. One reason for cross licensing, strategic alliances, and merger arrangements between firms is to enlarge and diversify their IPR portfolios, thereby increasing their flexibility in research, development, and commercialization (Graff, Rausser, and Small 2003). Private ownership of patents by corporations is perceived to be a major constraint of technology use in developing countries and for orphan crops. However, in some cases, obtaining the access to patents that are owned by universities may be as difficult or even more difficult (Graff and Zilberman 2001). Some researchers in developing countries actually maintain that they have a harder time obtaining rights to utilize technologies from public offices of technology transfer than from private companies. Companies provide technologies to orphan markets simply for the sake of public relation gains. Such goodwill motives may induce them give away the rights to use the technology, especially in developing products that do not threaten established markets or other financial interests. For some university inventors, the income from use of technology is of major importance, and they may be reluctant to waive away their rights to the revenues generated by their technology. One possible role of the clearinghouse is thus to establish arrangements for facilitating access to public sector and especially university patents for orphan markets.

Greater transparency can also facilitate clear delineation of market scope, reducing risks of spillovers to competing interests. In this sense, some barriers to technologies that originate in the public sector may be the result of imprecise marketing. Companies may obtain the rights of a patent for all markets, while in reality they may be interested in applying the patent to a small number of crops in OECD countries. Once they own the rights, liability considerations, transaction costs, and other factors may limit the capacity of researchers to utilize technologies for orphan markets. One possible role of the clearinghouse is to share knowledge and research cost to develop precise technology transfer procedures that will lead to more efficient and socially beneficial IPR management. The above analysis suggests several objectives for an IPR clearinghouse for agricultural biotechnology:

- Reduce transaction costs for the commercialization of innovations (Shapiro 2000);
- Expand the universe of accessible technologies accessible (for research and product development);

- Improve efficiency of technology transfer mechanisms and practices in public sector institutions;
- Increase transparency of IPR ownership;
- Provide mechanisms to expedite IPR negotiation and access;
- Consolidate the public interest in technology origination and development.

There have been several recent attempts to develop IPR clearinghouses in biotechnology. The Rockefeller and McKnight Foundations are collaborating with 24 major universities and plant science research institutes in the United States to establish the Public Intellectual Property Resource for Agriculture (PIPRA). This initiative aims to increase public sector scientists' freedom to operate and provide access to IPR to develop technologies for orphan crops. The new organization of PIPRA will have two core elements: (i) a database of member institutions' IPR ownership in agricultural biotechnology and the availability of those technologies, particularly for 'orphan' crop applications, and (ii) licensing mechanisms, such as patent pools, to make aggregated technology systems available *ex ante* while reducing transaction costs and uncertainties. PIPRA consists of over two dozen member institutions that will share information on their technologies with each other and with technology users, i.e., researchers in developing countries. Namely, the member universities basically combine information on all technologies that they control into a database, with licensing status information available to one another and to subscribing PIPRA clients, and with basic information available to the public. Then, the technologies can be analysed, sorted, and arranged according to their functions, to ease freedom-to-operate access within the IPR maze to particular enabling technologies and genetic applications. PIPRA will aim to provide a set of technologies that will allow pursuit of 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 per cent of US agricultural biotechnology patents were owned by public sector entities, concentrated in research universities in the United States and in the OECD countries, while 41 per cent were owned by the 'Big 5' (Monsanto, 14 per cent; DuPont, 13 per cent; Syngenta, 7 per cent; Bayer, 4 per cent; and Dow, 3 per cent). The rest of the private sector, mostly start-ups and smaller companies, owned 33 per cent of agricultural biotechnology patents. Similar proportions are observed in other OECD patent systems (including the EU, Japan, and Patent Cooperation Treaty applications). Using cluster analysis of the full patent dataset, Graff *et al.* (2003) documented that public sector organizations have in fact patented broadly across the various technology classes necessary for most applications of agricultural biotechnology.[9] In addition, the range of research projects that could be supported by public sector owned IPR is also significantly enhanced by a wide range of unpatented or off-patent innovations that are accumulating in the public domain.

9 The sheer complexity of this system, and some if the efficiency implications, is explained by Shapiro (2000).

Yet, while the public sector has significant IPR ownership, it is diffused among many institutions. No individual public institution has more than 2 per cent of total patents. The diffused ownership of IPRs by public sector institutions means that the transaction costs involved in putting together technologies from the public sector are not insignificant. The role of a PIPRA as an IPR clearinghouse would be to coordinate information on and access to the public sector's technologies.

In addition, the rights to public sector technologies have in some cases[10] already been transferred to the private sector through exclusive licensing agreements. It is essential to know the actual scope of technologies still controlled by the public sector, i.e., not subject to contracts that have transferred exclusive control to commercial partners. Information on the licensing of technologies is often confidential and thus not available. This lack of transparency increases risk and transactions cost for potential entrants in research and product development, hindering innovation and the realization of its benefits. A fundamental role of PIPRA is to collect updated information about technology ownership and licensing status and to advise users on where to obtain technologies they need. Additionally, PIPRA's team can advise researchers, administrators, and managers about practical intellectual property management strategies.

Another clearinghouse is the African Agricultural Technology Foundation (AATF). Also supported by the Rockefeller Foundation, it aims to facilitate research and introduction of new sophisticated crop varieties (including biotechnology) in sub-Saharan Africa. It emphasizes technology transfer from the private sector and will help scientists to overcome IPR and regulatory requirements. AATF aims to coordinate with participating companies in the private sector directly to obtain licenses for use of their technologies in Africa for humanitarian causes. 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. The AATF will be the licensee, and then sublicense the technologies to research teams and developers.

In the medical arena, a clearinghouse institution is MIHR (Management of Intellectual Property in Health). Its motivation is to facilitate access to IPRs for developing therapies to diseases (tuberculosis, AIDS, malaria) afflicting the poor. Its main areas of work include: (i) identification and codification of best practices for licensing to achieve the goals of the public sector; (ii) provision of training to scientists, universities, and research institutes in managing intellectual property to benefit the public sector in both developed and developing countries; and (iii) consulting services to developed and developing county groups concerned with research and product development.

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 clearly strike a balance between facilitating the former and mitigating the latter, and effective policies toward biotechnology must reflect this. Facilitating access to IPR, while maintaining the ability

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10 About 20-30 per cent of universities' agricultural life science patents have, depending upon the field of technology, been licensed according to recent data from PIPRA.

to use IPR to incentivize further development, is the primary impetus for the initiatives discussed above, but other considerations are also important.

6 Clear patent delineation

Designing optimal patents and licensing contracts is a challenge (Gilbert and Shapiro 1990; Klemperer 1990; Anand and Khanna 2000; Burk and Lemley 2003). If patents are too broad, they may hamper future research and undermine access to the commons of intellectual and scientific discovery. If they are too narrow, they will undermine incentives for private discovery and incentives for following up discovery with development and commercialization. This latter incentive effect may be even more important because it applies to both private and public discovery. Research to develop methodologies for precise patenting and licensing contracts and their implementation are of paramount importance.

Currently, genomic knowledge is patentable to varying degrees around the world, and the discovery of a gene sequence and its use can confer some degree of market power. However, it is argued that genomic discoveries are not in fact novel and, therefore, do not justify patenting in most cases. Companies deciphering genetic codes, such as Celera, famous for its role in sequencing the human genome, now earn their primary income via information services (i.e., selling access to their databases). On the other hand, functional genomic discoveries, those that identify the function of genes and their potential applications, are more logical candidates for patenting. The evolving legal distinctions between genomic and functional genomic innovations illustrate the importance of adjusting patent criteria as the state of knowledge advances.

7 Biodiversity and biotechnology: A two-way street

The relationship between biotechnology and biodiversity is 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, there is a widely held sentiment that agricultural technology institutions (public and private) seek to appropriate biodiversity resources from developing countries.

On the first point, biotechnology actually has the potential to enhance biodiversity. Bt-insect resistance technology, for example, enables local varieties to be made pest resistant, obviating the need to adopt and adapt more homogeneous ‘global’ varieties as was the norm during the Green Revolution. As a result, the US now has more than 1000 varieties of RoundUp Ready soybean, most of which are single-gene variants of local legacy varieties (Qaim, Yarkin, and Zilberman 2003). Far from homogenizing the gene pool, the introduction of agricultural biotechnology in OECD markets has acted to protect and even increase biodiversity (Sneller 2003).

The issue of biodiversity prospecting and (implicitly) north-south property rights might seem more ambiguous. Genetic material from the developing world has certainly contributed to science and practical technology in OECD economies, but the productivity gains of technology transfer in the opposite direction have been enormous.

There is a growing literature on the economics of biodiversity that shows for most locations, the potential value of biodiversity it is very low (Simpson, Sedjo, and 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 and Small 2000), Thus, the scope of compensation for biodiversity is limited and should not be foreseen as a major source of income for developing countries (Dalton 2004; Simpson and 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 farmers 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. The IPRC can perform an essential service here, by increasing transparency and reducing transactions costs, but public institutions will have to fill many gaps in global standards for more complete markets to develop in this area.

8 Education: A north-south partnership in human capital development

Biotechnology is in its infancy. The tools of molecular biology promise a future where biological solutions for many industrial problems will become more efficient and environmentally friendly than the conventional (in most cases chemical) main stream alternative. While most of the technology has been developed in the north, most of the world's genetic resources are in the south. At the present, much of the research is aimed at developing tools to utilize genetic materials, but many of the biggest opportunities in the future will arise from better understanding of functional genomics. Much of this research can, and in fact will need to be facilitated by north-south partnerships. It will be important for the south to participate more fully in such partnerships, and on more equitable footing. Better capacity to take advantage of their own biodiversity will allow the south to take a better bargaining position to negotiate its role in R&D partnerships.

Biotechnology has, to a large extent, originated and been sustained by public sector research, and many of the entrepreneurial centres of this industry have been built in proximity of universities. It has thereby become apparent that, to succeed in biotechnology, a country needs to develop and maintain superior higher education, developing the educational-industrial complex to generate simultaneously the necessary human capital and the potentially marketable intellectual property. This observation alone defines an agenda for education-oriented development assistance, whether it be private or public, bilateral or multilateral.[11] Perhaps the greatest challenge, but ultimately the greatest opportunity, for fuller north-south partnership in biotechnology innovation is education.

Technology development generally, and biotechnology development in particular, are strong complements for human capital development, and conversely research and development are especially human-capital intensive. The geographic and institutional symbiosis between modern universities and the technology clusters of particular sectors is an important example of this. Yet, it is an example that developing countries have difficulty 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 research capacity in most developing countries. Even in those 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 relations that are hallmarks of dynamic technology sectors in OECD countries.

These facts reveal the need for expanded international partnership, both public and private, to develop 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, should take new initiatives to leverage human resources in developing countries, transferring technology and capital into new markets and thereby gaining first-mover advantage in these emerging biotechnology markets. China, India, and other large, populous developing 'Tier II' countries are already attractive candidates for this kind of entrepreneurship, while smaller, less advanced 'Tier II' countries should be seen in a regionalized perspective.

9 Technology and poverty

Technology effects on poverty can be direct or indirect. A technological innovation can help reduce poverty directly by raising the welfare of the poor who adopt a new technology themselves or benefit from productivity enhancement in their work. Benefits for households who adopt new technology in their own production activities derive from increased production for home consumption, more nutritious foods, higher gross revenues derived both from higher sales volumes and higher unit value products, lower production costs, lower yield risks, lowered individual and soil productivity, exposure to toxic chemicals, and improved natural resource management. For poor workers, adoption of new technology by their employers can raise their productivity, enhance human capital, improve safety, and make work less onerous. Other direct benefits from technology may include improved health status from better health care, improved

[11] Development assistance to overcome the north-south technology gap is simply an example of the old 'giving a fish versus teaching to fish' adage, but with more profound growth implications because of endogenous growth externalities.

sanitation, and reductions in other public health risks. All these contribute directly to worker productivity, earning potential, and quality of life.

Technological change can help reduce poverty indirectly through growth and efficiency effects. Technology adoption in agriculture can increase yields and lower food costs for the urban poor. Technology or productivity induced economic growth elsewhere in the economy will spill over to rural markets via accelerating food and labour demand. Through these production, expenditure, and savings linkages, the agricultural sector will rise with the rest of the economy. Finally, if innovation improves international competitiveness, agriculture will enjoy foreign exchange benefits through expanding exports.

Through the price of food, indirect effects can benefit a broader spectrum of the national poor, including landless farm workers, net food buying smallholders, nonagricultural rural poor, and the urban poor for whom food represents a large share of total expenditures. Indirect effects via employment creation are important for landless farm workers, net labour supplying smallholders, and the rural nonagricultural and urban poor. Hence, the indirect effects of technological change can be very important for poverty reduction not only among urban households, but also in the rural sector among the landless and many of the landed poor who buy food and sell labour.

When are there trade-offs in technology between achieving direct and indirect effects? 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. Small farmers typically prefer farming systems that offer greater value-added per unit of land, are capital-saving, and less risky, while large farmers prefer farming systems that are labour-saving, and they can afford to assume more risk if they are compensated by higher expected incomes. In this case, there will exist trade-offs between achieving indirect and direct effects if budget constraints in research requires priority setting, i.e., if technology is designed for one system but not another. The more unequally land is distributed and the more market, institutional, and government failures are farm-size specific, the sharper the trade-off will be.

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.[12] In these models, the direct effects include the change in agricultural profit for adopting farmers, the changing opportunity cost of home consumption for own production, and the change in self-employment on one's own farm. The indirect income effect comes from changes in nominal income from all sources other than own agricultural production. The indirect price effect comes from the change in prices, excluding the effect through the opportunity cost of home consumption.

In more detailed analysis (Graff, Roland-Holst, and Zilberman 2005), we conclude that, if there are trade-offs between creating direct and indirect effects due to constraints on research budgets, care must be taken to allocate budgets optimally between these

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12 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 and Roland-Holst (1998).

technological options to maximize poverty reduction. While surprisingly little formal analysis has been made of these trade-offs, optimal allocation needs to be determined for each nation and region for which research programmes are organized.

10 Technology and rural development

Biotechnology may offer a significant potential for poverty reduction in smallholder agriculture. There are however, four caveats to be considered. One is that potentially cheaper and faster sources of income gains than agricultural technology may not have been exhausted, particularly through greater 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 technological advances other than biotechnology may be more appropriate for enhancing smallholder incomes. This is the case for many products of traditional approaches to research that have never been targeted at smallholders. This includes improved farming systems, agro-ecological farming practices, and traditional breeding for the specific, and often highly particular, contexts where they are located. These approaches will often not be substitutes but complements to biotechnology.

The third is that, for any kind of technology to be adopted by smallholders, many market failures that affect the smallholders need to be eliminated, institutional gaps removed, complementary public goods provided, and policies that do not discriminate against the agricultural sector or poor farmers put into place. This includes in particular access to credit and to risk management tools such as mutual insurance and safety nets, and low transactions costs in factor and product markets. Unless these conditions are in place, adoption will not happen.

Finally, for technology adoption to result in maximum poverty reduction, the other dimensions of welfare also need to be accessible. This includes in particular the components of basic human needs (health, education) and the more qualitative dimensions of welfare such as empowerment and 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 was intended, and complements income gains with access to the other dimensions of welfare.

11 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. We believe that in the modern age, biotechnology holds remarkable 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 immiseration because of inadvertent or even deliberate agency that misapplied them.

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 innovation products. 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. Agricultural biotechnology can directly and indirectly raise incomes for the world's rural poor majorities, while medical biotechnology can improve health status and capacity for gainful employment. To realize this, public and private agency must be reconciled into global R&D partnerships that satisfy three necessary conditions:

i) Local capacity for technology adaptation

ii) Least-cost, responsible regulation

iii) Unrestricted informational access.

In a survey paper like this, we can only sketch the institutional reforms needed to accomplish global biotechnology diffusion, but a few salient features deserve emphasis. First, property rights must be clearly delineated and recognized by more universal standards. Second, multilateral public and private initiative must be taken to lower barriers to diffusion. These include government intervention, imperfect contractual standards, and incomplete information. A broad spectrum of government policies—from outright protectionism to corruption—impedes the propagation of innovation between countries of all three Tiers. Incompatibility and incompleteness of legal systems are also major obstacles to international sharing of innovation. Finally, informational commons supported by institutions like the IPR clearinghouse are needed to facilitate innovation partnership.

Those who seek to expand technology's contributions, including the present authors, need to more completely delineate the institutional reforms that can facilitate truly global innovation processes. Here we gave a general vision of R&D networks extending from the capital and technology rich Tier I, through the dynamic Tier II emerging economies, to those, finally, in Tier III who most need enhanced agricultural and human productivity. We believe that achieving this goal is not only desirable, but imperative to global sustainable development.

If the poor are to enjoy the full benefits of agricultural biotechnology, 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. By contrast, the latter benefit must be indirect, with lower food prices contributing favourably to real wages of the urban poor. Only dramatic increases in productivity can thus reconcile producer and consumer interests domestically, but biotechnology represents exactly such a promise.

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