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INTRODUCTION

Over the last 150 years, agriculture has been subject to several waves of innovation which have significantly altered its institutional structures, its products and the way it is practised. Mechanical, biological and chemical innovations have, in turn, reduced labour requirements, increased yields and reduced the impact of agricultural pests. More recently, computer and remote sensing technologies have improved input precision. Agricultural biotechnology is now emerging as a wellspring of innovations that will reshape agriculture as profoundly as any previous innovation paradigm.¹ This new technology has unique features which economists need to understand in order to formulate appropriate policy advice.

This paper has two main purposes. First, we provide an overview of agricultural biotechnology. There are lessons from medical biotechnology which can be applied to agriculture. In addition, there are new institutions, including technology transfer offices and arrangements for intellectual property rights, which will be introduced and discussed. The second purpose is to introduce some basic analytical considerations and methodological issues which will be important in the study of biotechnology. In particular, these methodologies will relate to the issues in industrial organization associated with the process of product research, development and introduction; issues associated with adoption of biotechnology; and issues associated with pricing. Thus far, commercial biotechnology has been concentrated in the United States, but this technology has important global implications. This paper will examine and project what the American experience implies for the rest of the world and show how biotechnology and its evolution fit within the context of the relationship between developed and developing nations.

LESSONS OF MEDICAL BIOTECHNOLOGY

While agricultural biotechnology is relatively underdeveloped, medical biotechnology has become a successful business in which United States companies generate revenues of over \$4 billion annually. The evolution and structure of

*University of California, Berkeley, USA (Zilberman and Yarkin) and Hebrew University of Jerusalem, Rehovot, Israel (Heiman).

medical biotechnology have some lessons for agricultural biotechnology, although the two also have some distinguishing features.

Similarities

Importance of university research, technology transfer and start-up companies

The formal process of technology transfer from universities to private companies has been crucial for the evolution of medical biotechnology. Research conducted at the University of California (UC) at San Francisco and Stanford provided the discoveries that have formed the foundation of commercial biotechnology, and university research discoveries continue to be an important source of medical biotechnology innovations. Universities' offices of technology transfer have registered patents to protect a number of these innovations and sold the right to private companies to develop and utilize them. In the United States, expansion in the number and size of university offices of technology transfer has been highly correlated with the evolution of medical biotechnology, and biotechnology licences provide the majority of licensing revenues received by the universities (Parker *et al.*, 1998).

Formal technology transfer provides incentives to researchers to invest resources in projects likely to lead to biotechnology innovations, since patent royalties are shared between the university, the inventor(s) and, sometimes, the department. Patent royalties may be substantial when linked to successful products and have been crucial for support of certain lines of research, although, even at the most successful universities, these revenues represent less than 5 per cent of the annual research budget.

Licensing arrangements vary. Exclusive licences are appropriate for discoveries which require significant investment in development before they enter the market-place, or which have narrow applications, since companies need the monopoly profit that exclusivity provides during the life of a patent to ensure that their commercialization costs will be recouped. For fundamental innovations that are essential for many applications, and which do not require much development effort in themselves, such as the Cohen-Boyer procedure of genetic manipulation, non-exclusive licences with low fees are necessary to facilitate broad diffusion.

Often, established companies are not interested in purchasing the rights to a discovery, but the innovations are developed through start-up companies established by the inventors and backed by venture capitalists. Two of the leading biotechnology companies in the United States (Genentech and Chiron) were established in this way. Once the companies became successful, major pharmaceutical firms bought majority ownership stakes.

Some of these patterns can be seen in agricultural biotechnology. University research discoveries have been crucial in the evolution of the technologies, and start-up companies have emerged through collaboration between researchers and venture capitalists. Large seed and agrochemical companies have bought control of some of these firms (for example, Monsanto recently acquired Calgene, a leading agriculture company). This pattern is likely to continue. Start-up companies will develop new discoveries, but marketing and

production of most final products will be undertaken by the large agrochemical, seed and food-processing companies.

The importance of intellectual property rights Intellectual property rights (IPR) have been of exceptional importance in the development of commercial biotechnology. Firms pay fees for use of patented processes (for example, manipulation of genetic material) and patented genetic knowledge (genes linked to specific traits). The incentive for violating IPR agreements is likely to increase significantly as the price of knowledge increases, so enforcement considerations set an upper bound on intellectual property fees. The relatively small numbers of entities that engage in medical biotechnology activities and their geographic concentration have probably facilitated enforcement of IPR arrangements to date. As biotechnology diffuses more widely, international policies regarding IPR will become more important.

The implications for pricing of IPR in developing countries require further study. Political pressure to respect IPR, unless accompanied by lower prices for the use of biotechnological knowledge in developing countries (at least for a transition period), is unlikely to result in broad adherence to these laws. Vigorous pursuit of IPR protection may inhibit the expansion of free trade, with adverse consequences for global welfare.

The geographic profile of production Commercial biotechnology is heavily dependent on human capital formation, requiring a scientific and managerial workforce that is highly skilled and knowledgeable. The biotechnology industry has become concentrated in a small number of regions that are anchored by the high-quality research institutions which are the main sources of these skills and knowledge. The San Francisco Bay area is a prime example: both Genentech and Chiron are located in this region, benefiting from proximity to Stanford, UC San Francisco and UC Berkeley. Similarly, the area around UC Davis has become a hub for biotechnology firms, as have other regions anchored by leading agricultural research institutions. Other regions wishing to establish the capacity to discover, develop and produce biotechnology products will need to establish a critical mass of research and commercialization infrastructure and, in most cases, public (national and international) support of research and development activities will be needed.

Differences

Revenue-generating potential of products Many medical biotechnology products have high revenue-generating potential because affluent populations have a substantial willingness to pay for medical advances. In contrast, demand for most agricultural products has a low income elasticity and, while expenditures on medical care have increased faster than the overall rate of inflation, the income share of food expenditures has declined over the last 50 years.

Differences in knowledge and complexity Medical biotechnology has primarily focused on the human species, which has historically received most of the

attention and research funds expended on biological research. Contrast this with agricultural application, which requires the knowledge of a vast variety of organisms and ecosystems but has enjoyed neither the funding levels nor the academic interest that have characterized medical research. While the agricultural biotechnology products currently on the market have been based on single gene changes, the development of new varieties which contain a complete bundle of desired characteristics may require complex manipulations.

Environmental regulation Society is more tolerant of taking risks in search of cures for human diseases than in developing new agricultural products. In part this difference arises because disease is more of a threat than famine in most of the world. In addition, agricultural innovations are deployed in fields, not hospitals, so the monitoring of them is more complex than for their medical counterparts.

In the United States, public perceptions of relative risks, and historical differences in the mandate and purview of regulatory bodies governing the two areas of biotechnology, have resulted in a divergence in the costs and outcomes of regulation. Pharmaceutical products developed using biotechnology are regulated by a single agency, the Food and Drug Administration (FDA), and have been subject to virtually the same safety and efficacy requirements as conventionally derived drugs. In contrast, three agencies have purview over various facets of agbiotech research, development and product introduction (FDA, the Environmental Protection Agency and the United States Department of Agriculture). The regulations governing these activities have been much more rigorous than for equivalent products developed using non-molecular techniques. Unduly stringent regulation has reduced investor interest and, while agricultural and medical biotechnology investments were roughly equivalent in the first decade following the emergence of these technologies, they diverged significantly as regulatory hurdles became more daunting in agriculture (Huttner *et al.*, 1995).

Need for geographic adaptation Most medical biotechnology products do not need to be adjusted for differences in the geographical location of the consumer. In agriculture, however, products have to be incorporated into farm production systems and so must be modified according to varying ecological conditions. This can involve high adaptation costs and products may not enjoy the large markets of some medical biotechnology items.

The differences between agricultural and medical biotechnology suggest that some of the forces that helped to establish medical biotechnology would not work as effectively in favour of agriculture. One would not expect as much private-sector investment; therefore innovation is likely to depend more on the continuing support for public research of relevant disciplines. Marketing, also, may not be as easy as for medical biotechnology products, and in many cases experiment station and extension efforts will be needed in order to facilitate adoption of biotechnology products.

STRUCTURE OF AGRICULTURAL BIOTECHNOLOGY

A few stylized facts will facilitate a conceptual analysis of agricultural biotechnology. In simplified form, its products can be thought of as the result of a linear five-stage process: (1) research, (2) development, (3) testing and registration, (4) production, and (5) marketing. These stages result in three major outputs. Research produces new knowledge about genetic manipulation techniques or the properties of a genetic sequence. By obtaining a patent, intellectual property rights are established, and users must acquire the rights to use the discovery. Development leads to a product or process that has clear commercial potential, which is then retained in-house or licensed to a third party for testing and regulatory approval before moving finally into commercialization.

The interaction among five economic agents determines the outcomes of biotechnology discoveries. First is the university which conducts research that leads to important discoveries. Second are small biotechnology firms made up of researchers and supported by venture capitalists, which tend to concentrate on developing biotechnology products, often combining efforts and resource through alliances with pharmaceuticals, other biotech firms and academic researchers. The third group are large companies which, in addition to internal R&D capabilities and alliances with biotechnology firms, have strong marketing networks in place and enough financial resources to bear the costs of product registration. The fourth element is government, which supports research at the universities, and regulates biotechnology-related activities. Finally, there are the buyers who, in the case of pharmaceuticals, are physicians and, for agriculture, are farmers.

Patterns of the division of responsibilities between entities for the introduction and production of biotechnology products are presented in Table 1. As Parker and Zilberman (1993) argue, university research tends to produce fundamental new knowledge which results in dramatically different ways of conducting research and entirely new products. University research receives support from three sources: government funding, technology transfer revenues

TABLE 1 *Division of responsibility for various stages of product development*

Patterns	Discovery	Development	Registration	Production	Marketing
1	U	B	B	B	B
2	U	B	B	M	M
3	U	B	M	M	M
4	U	M	M	M	M
5	B	B	M	M	M
6	M	M	M	M	M

Notes: M = major corporations with established market presence in pharmaceuticals, chemicals, seeds or food processing; B = biotechnology firm; U = university.

and grants or support for collaborative research activities from industry. Currently, government funding dominates other sources and supports the basic research which results in breakthrough discoveries. Translation of these discoveries to the market place is shown on rows 1–3, wherein university discoveries are licensed to biotechnology companies for development, with subsequent activities handled either by the firm or by multinationals.

The fourth pattern, in which university research discoveries are licensed by major corporations which then conduct the development, registration, production and marketing, is also common. Sometimes biotechnology companies make discoveries and then sell the developed product to multinationals (row 5). Pattern 6 is typical of the chemical industry, wherein large companies are involved in all stages, from research to production. As products become more complex, these patterns will become more complicated, but the framework in Table 1 is useful for thinking about the effects of alternative public policies.

Reduction of government support for academic research will stifle patterns 1 to 3, causing a significant reduction in the number and rate of technological advances. The rate at which discoveries reach the market-place is also affected by the conditions facing venture capitalists who finance start-up companies which develop the most novel innovations. Major corporations have often been unwilling to undertake development of path-breaking academic discoveries so, without the risk-taking behaviour of the start-up companies, these innovations might not have been developed. Private profit-maximization considerations may deter large firms from pursuing a socially desirable rate of technological change. Even if production and marketing are handled by a small number of large companies, university research and development funded by venture capitalists keep the industry competitive, facilitating a higher rate of technological change.

The government can also affect the structure of the biotechnology industry through registration requirements. Some of the most important biotechnology products have emerged through patterns 1 and 2 in Table 1, in which university discoveries are developed and registered by biotechnology companies. Strict registration requirements impose costs on registrants, reducing the expected profitability of a given product. Extra costs impede start-up companies' ability to proceed independently and reduce the incentive for venture capitalists to invest in these firms. In this way, registration requirements can serve as barriers to entry, giving relative advantage to large corporations that have the institutional infrastructure and financial wherewithal to meet intensive registration requirements, and which can then take advantage of their market power. Some have suggested that this phenomenon is occurring in agricultural biotechnology, with major corporations shaping the regulatory environment in a manner that disadvantages start-up businesses.

MODELLING BIOTECHNOLOGY

Agricultural biotechnology is an extension of traditional breeding techniques that increases precision (allowing for selection of individual traits) and versatility (permitting genes to be obtained from virtually any organism). There are

several distinct types of products, each with different technical and economic implications, four of which are mentioned below.

Supply-enhancing products

Supply-enhancing biotechnology will generally improve consumer welfare, but may disproportionately benefit certain groups of producers. The beneficiaries will be determined by the characteristics of the technology and the distribution of producers across regions and sub-groups. These technologies can be conceptualized as improvements in the technological relationship linking inputs to outputs. Suppose a firm faces a choice among m varieties. The optimal variety choice for a given location is a two-stage process involving discrete and continuous choices. First, the optimal input levels for each variety are determined at a level where the value of marginal product of each variable input is equal to its price. Then the profit per acre under each variety is calculated at optimal input levels, and the optimal variety is the one with the highest non-negative profits per acre. Suppose per acre profits can be represented by the equation:

$$\max_{i,x} pf(x) - \sum_{j=1}^m w_j x_j - V_i$$

where p denotes output price, $f(x)$ is the production function, x is a vector of variable inputs, w_j denotes price of input j , and v_i denotes price per acre of payment for access to genetic inputs i . Then the optimal input level for technology i is determined at a level x_i^* where $pf'(x_i^*, i) = W$. Profit per acre of technology i ,

$$\pi_i = pf(x_i^*, i) - Wx_i^* - v_i,$$

is calculated and the optimal variety i^* is the one with the highest non-negative profits per acre.

Economic conditions and policies will determine the likelihood of adoption of new varieties. In cases of two varieties, when $i = 1$ is the traditional and $i = 2$ is the biotechnological variety, it is likely that variety 2 increases yield and is input-saving for most users. It will be relatively more attractive in situations with high input prices, but, if it is costlier than existing varieties, it will be adopted only if the increases in variable profits, from yield increases and reduced variable input costs, exceed the extra seed cost.² Thus variety 2 will be adopted if

$$\begin{array}{ccc} p(y_2^* - y_1^*) & + & w(x_2^* - x_1^*) & > & v_2 - v_1 \\ \text{yield-increasing} & & \text{input-saving} & & \text{extra genetic} \\ \text{effect} & & \text{effect} & & \text{material cost} \end{array}$$

In the case of innovations which conserve a variable input, especially at locations of low quality, crop acreage may increase owing to entry of land

previously fallow or in other crops. Differences in land quality will become less important, so that regional disparities in profitability may decline as the new technology is introduced. A related set of technologies would allow utilization of saline water or mitigate the effects of ecological conditions such as frost. These varieties may expand the range of locations where high-value crops can be grown, reducing the rents for locations with special amenities.

The likelihood of adoption will also depend on exogenous market conditions and on other policies affecting agriculture. Reduction of input subsidies or increased input taxes will enhance adoption of varieties that increase input use efficiency. Induced innovation models suggest these changes will also prompt development of varieties that can substitute for affected inputs. Note that the introduction of variable-input-saving technology may increase resource use if demand is relatively elastic or market prices rise because of increased demand resulting from, say, increased income. Consumers gain if demand is not infinitely elastic, and high-quality locations may lose and producers on marginal lands may gain.

In contrast to the foregoing, a new technology which increases output per acre proportionally across locations will especially benefit locations with higher land quality, so differences in returns between locations with high and low qualities will widen, and supply will increase mostly through adoption of the technology on lands with higher quality. Increased supply will lead to lower output prices when final product demand is inelastic, and thus some land of lower quality may not be utilized as a result of the introduction of the innovation. The main effects may be gains to consumers.

The adoption of such technologies may be enhanced by government programmes such as price supports, although their diffusion may actually reduce welfare (at least in the short run). Movement to a less distorted agricultural sector will reduce the likelihood that such innovations will be introduced in situations where they do not enhance welfare. If a period of excessive supply ensues, however, there may be political pressure to reinstitute price supports and similar policies that are now being eliminated. Under situations of competitive markets and inelastic demands, these proportional productivity-enhancing biotechnologies may help to achieve environment goals; for example, bovine growth hormone may reduce the animal waste problem and save on water currently allocated to alfalfa and pasture.

Pest control products

This line consists of varieties which can tolerate, repel or kill pests, or withstand applications of herbicides and genetically engineered microorganisms. As Ollinger and Pope (1995) have shown, most of the experimentation has concentrated on the first two categories, and their commercial use in the last two or three years has been significant. The commercial success of this line of products is due to the relative simplicity of the genetic manipulation that they entail and the fact that they seem to meet a need cost-effectively.

The relationship between new pest-controlling biotechnology innovations and chemical pesticide regulation is complementary and, to a large extent,

these innovations are induced by pesticide policies. Whenever chemicals are banned or restricted, an unmet need arises, creating a market opportunity for substitutes. Conversely, if regulators are aware that a new alternative is likely to become available, they may take a stricter approach to a problematic chemical pesticide.

The finite life of patents provides another reason for development of pest control biotechnology. As their pesticide patents expire, companies may invest in development of biotechnology-based controls for the pest problem addressed by that pesticide, because their marketing network provides them with an edge in introducing and promoting a substitute product. Some pesticide companies may not have the scientific infrastructure to produce biotechnology solutions. One way to acquire this capacity is to buy start-up companies possessing new products as well as research and development capacity. Another is to develop internal research capacity and to buy rights to university innovations to jump-start their knowledge base. The biotechnology giant, Monsanto, has taken both approaches.

Pest control biotechnology offers new market opportunities to seed companies that generally have a relative advantage in biological processes. In the past, seed companies did not play a major role in pest control that mostly emphasized chemical solutions. These companies have a significant marketing capacity in the field and are likely to take advantage of their biological research and productive capacity to develop new products in pest control biotechnology. Indeed, some of the major seed companies (Pioneer, for example) are expanding their capacity in pest control, and the boundaries between pest control companies and those in seed are gradually eroding.

At the same time, some companies are reducing their involvement and may leave the pesticide market altogether. Stricter regulation of chemical pesticides, as well as the lack of an internal infrastructure for biotechnology, make it unprofitable for them to continue their operations. Another group of companies that may be disadvantaged are manufacturers specializing in production of chemical pesticides after the patent life has expired. Such manufacturers are especially important in developing nations, and they enable local farmers to buy cheaper pest control products. These companies generally lack the capacity to undertake biotechnology research or production.

The impact of agricultural biotechnology depends on the progress that is made in research and development and the pricing policies of producers. If the pest-controlling products currently under development reach the market at reasonable prices, these new varieties will diffuse widely. The supply of some major commodities may increase, both through reduction in crop damage and through expansion of utilized land. Naturally, price feedbacks will moderate these changes. These patterns will first be observable in cotton and soybeans, where new varieties are being intensively introduced. It is possible that trends in recent years (decline in acreage and agricultural productivity) will be reversed, and both land utilization and productivity rates will increase.

Quality-modifying biotechnology innovations

Biotechnology techniques allow modification of agricultural products to enhance desirable characteristics. As Ollinger and Pope (1995) observed, there has been less research and investment in biotechnology to modify quality than to address pest control attributes. Furthermore, while pest control biotechnology is being pursued by established companies, experimentation with quality-augmenting biotechnology is often done by start-up companies and university researchers.

Shelf life is a key quality attribute for highly perishable products and was the target of the first product to reach consumers, a type of tomato. The unexceptional market performance of this product was due in part to vocal opposition by anti-technology groups, but also to the fact that consumers were unimpressed by other quality attributes, such as flavour. A related quality dimension is the extension of the harvest period for desirable crop varieties. As Parker and Zilberman (1993) show, there is a significant price premium for high-quality, early or late-season varieties of fresh fruits and vegetables. A new variety with an altered harvest period may be valuable, although the market potential is limited because the affected crops have relatively small acreages and limited markets and, as supply expands, prices may fall.

Modifications that make a product more attractive or sweeter, or introduce desirable health characteristics, may be quite profitable if consumers' willingness to pay for the attributes exceeds innovation and extra production costs. The genetic manipulations required for development are relatively complex, however, and the risk associated with research is high, hence most of it has been done by universities. As promising innovations are discovered, the process of technology transfer will determine how commercial products are developed. As suggested earlier, even if the initial development is done by start-up companies, the final marketing and production may eventually end up in the hands of major agribusiness firms.

If a small group of companies gains control, through IPR, over significant portions of genetic knowledge about major agricultural products, they will be able to establish monopolistic power and capture rents which would otherwise have gone to agricultural producers. Furthermore, although many of the major companies are concentrated in developed countries, by controlling the rights for biotechnologies that enhance food quality, they may capture much of the value added by production that occurs in developing countries.

One implication of this scenario is that agricultural cooperatives and other farmers' organizations should organize to put themselves in a better position to secure rents by obtaining ownership of genetic material and the product that it may generate in the future. An important question for future research is to what extent farmers' organizations should be engaged in purchasing rights to new technologies that directly affect their industries, as a means to counter possible monopoly power by agribusiness firms and other entities outside their industry. As the cost of biotechnology research declines and the certainty associated with it increases, there is likely to be more involvement by agricultural producer organizations and large food packers and distributors in support of research on improving product quality.

Another effect of falling costs in biotechnology research and development will be to intensify the growing tendency towards product differentiation and monopolistic competitive behaviour in agriculture, particularly in speciality crops but also in poultry and other livestock products. It will become possible for producer groups and agricultural wholesalers to develop their own genetic varieties, as has already occurred with food processing companies such as Frito-Lay.

One development that may become important in the evolution of quality improvements is the interest of large biotechnology firms in support for university research for which they retain the right of first refusal to resulting patents. It has been argued that the rate of return to such complementary support of public research may be particularly high, especially when it allows companies to affect the way that the research capacity of the university is directed. Reduction of support for university research from public sources will probably increase the value and purchasing power of complementary support for university work by private companies. In the long run, it may have significant implications for market structure and income distribution in agriculture and the food sector.

New products

If we define farming as cultivation and production of commercial output using living organisms, biotechnology is likely to expand the range of agricultural activity significantly. Note that breweries, bakeries and similar activities are specifically excluded from our definition. There are already signs that, with biotechnology, one can expand the range of species that are 'farmed', as in production of fine chemicals (beta carotene) from algae, for example. Another important application is 'pharming', in which animals and plants are modified to produce pharmaceutical products. As we have seen in horticultural crops for which the market value of the product is sensitive to the level of effort and skill applied all along the value chain, farms raising these new products are likely to have contractual relationships with companies that provide the genetic materials and process and market the products, or may be subsumed into a vertically integrated entity that will also handle processing, marketing and some research and development activities. For example, pharmaceutical companies may establish farming operations to produce medical substances, or contract with independent growers. In this way, biotechnology will contribute to the industrialization of agriculture.

For new, land-intensive, grain or oilseed varieties, biotechnology companies may make their money through the sale of seeds to existing farmers, retaining or reinforcing a competitive structure in farming. Canola is a recent example of a new crop that was integrated within the traditional competitive farm production system. For reasons discussed above, however, few new biotechnology products will provide opportunities for the expansion of the competitive farm structure, but instead most will provide new farming opportunities within vertically integrated or contractual arrangements.

BIOTECHNOLOGY AND PRECISION AGRICULTURE

An intriguing question is the complementarity and substitution relationship between biotechnology and precision agriculture. Precision agriculture uses advanced information technologies to optimize the use of inputs. For example, it facilitates planting of different plant varieties, in a single field, to adjust for heterogeneity in land conditions and similar variation in pest control needs.

The possibilities which precision farming offers for increasing productivity through optimization of finely tailored seed varieties may generate an expanded market for biotechnology products, especially in areas with sufficient local variation in ecological conditions. In this respect, biotechnology and precision agriculture are complementary, and the diffusion of one will help push forward that of the other. Seed companies and agrochemical suppliers promoting precision farming in the United States may in the future promote biotechnology products as well.

The introduction of precision farming has been accompanied by the emergence of agricultural consultants, some of them independent and others employed by agricultural chemical and seed dealers. Furthermore, there are companies which provide custom services in the use of precision farming. All these professional infrastructures, which increase the capacity of agriculture to utilize scientific data effectively, will be increasingly important with the introduction and expansion of biotechnology products. The range of available plant varieties may expand greatly if agricultural consultants are able to identify conditions under which diversity can yield sufficient extra profits. One may also expect continuing development of software that will enable farmers and consultants to optimize their choice of varieties and equipment in farming activities. Thus the integration of biotechnology and precision farming may be the cornerstone of a more science-based agriculture.

An additional benefit of precision farming is that tailored applications of inputs reduce the residues which are the main cause of ground and surface water contamination. Increased precision may also provide better control of certain pest problems, though that may reduce the potential market for certain biotechnology products. Overall, it seems that the complementarity between biotechnology and precision agriculture will be much greater than the substitution, and the two technologies will build on one another.

INTERNATIONAL CONSIDERATIONS AND INTELLECTUAL PROPERTY RIGHTS

Within a partial equilibrium model, the main results supporting free trade are derived from a framework that maximizes the global aggregate net surplus. The classical model ignores the possibility of increasing returns to scale and the existence of public goods. These assumptions are especially important in crafting international arrangements concerning development of biotechnology products and processes. Using a standard public goods argument, the optimal level of research in a global context occurs where the marginal cost is equal to the sum of the marginal benefit across all users. However, when nations make

research investments, they maximize the net benefits for their own citizens, not all users. If industry controls research, investment levels will be determined by even more limited criteria. Currently, research levels are largely determined by the developed nations, which implies that there is underinvestment in biotechnology research, resulting in sub-optimally high-priced intellectual property.

Developing nations may feel that, because this key element of international resource allocation is biased against them, they are justified in ignoring international property rights. Dissatisfaction may be further exacerbated by the fact that, although the genetic material is integral to many agricultural crops originating in developing countries, farmers in those countries may, in the end, be required to pay for use of the materials.

Another source of concern for developing countries is product registration requirements. The rules governing agricultural biotechnology in the United States are considered unduly strict, thus providing existing companies with protection from the entry of competitors. Developing countries may aim to have a biotechnology infrastructure to produce goods for export markets, but strict registration requirements in the United States, and sometimes in Europe, may deter investment. Thus an objective assessment is required of the value of the registration policies and regulations since they can be barriers to the introduction of alternative biotechnology products outside the United States.

The establishment and enforcement of less restrictive biotechnology safety regulations and intellectual property rules in developing countries make economic and political sense. This perspective is contrary to that of American environmental groups, as well as some agribusiness and farmers, supporting the imposition of strict global biotechnology safety regulations. American biotechnology firms and agribusinesses have lobbied for strict and broad intellectual property right rules, backed up with strong enforcement. These policies may not be sound economics or sound politics. Countries differ in their willingness to take certain risks and in the trade-offs associated with particular policy choices. In many cases, the perceived environmental safety of strict limits on biotechnology is, in effect, a luxury good, and willingness to accept possible environment risk in exchange for reduced hunger, increased income and other benefits may be higher in developing countries than in developed ones. Indeed, it is quite possible that environmental risks from biotechnology are dwarfed by the risks associated with constraining this line of innovation. Therefore the key policy question for the United States concerns the size of global externalities from biotechnology risk rather than the local externalities. The aim should be to institute and enforce standards offering the locally desired level of safety, rather than setting maximum levels which may be counterproductive.

Pressure to broadly define IPR on biotechnology knowledge and to enforce those rights aggressively may also backfire. From a global efficiency perspective, broad dissemination of knowledge in most cases is optimal, especially when research capabilities are also widely distributed. On the basis of both efficiency criteria and political common sense, it is preferable that corporations obtain returns to their investments in scientific infrastructures from the direct sales of seeds and services, rather than from broadly enforced IPR. There is a strong case for relatively low prices for use of knowledge, especially

in developing countries, and narrowly defined property rights are inconsistent with that goal. The emphasis in trade negotiations should be on vigorously preventing non-market barriers of trade rather than emphasizing protection of strict IPR that are perceived to be discriminatory, and using trade barriers as a tool to enforce them.

Clearly, economic research on biotechnology and IPR is in its infancy. This research must better understand how the markets work and incorporate elements of political economy and international trade theory to be rigorous. However, on the basis of our knowledge from other areas of economics, there are some hypotheses to be further investigated. We would like to use them for starting intellectual debates on serious research agenda.

One issue that occupies much of the debate on IPR is the value of biodiversity in genetic material. The notion of option value, and some theories of pricing options under uncertainty (Dixit and Pindyck, 1994), may suggest that biodiversity is underpriced and that, if the price is corrected, many of the problems associated with the use of natural resources in developing countries will be solved. Similar arguments have been raised to justify establishing restrictions on the use of genetic material that is stored in gene banks throughout the world, as well as for raising the price of genetic materials that have been collected in developing countries.

Unfortunately, the 'option value' perspective has raised inflated expectations among scientists and governments in developing countries regarding their potential for making money from biodiversity and genetic material. First, as the Dixit and Pindyck model suggests, correct recognition of uncertainty may actually lead to delays in investment and, most importantly, will reduce the value of uncertain assets. These theories imply that the high uncertainty associated with biodiversity makes it less, not more, valuable. Obviously, preserved biodiversity has some value; therefore incentives should be developed to preserve biodiversity in a way that reflects option value and other values (Randall, 1990). Further, developing countries should not expect to get rich from licensing rights to prospect the genetic materials of their forests and natural environments because the experience of university technology transfer has been that the earning capacity is quite low for basic knowledge or genetic material that requires much downstream investment.

Some new schemes are being considered to preserve biodiversity and to alleviate the inadequacies of biotechnology research from a global perspective. For example, the concept of farmers' rights has been used in proposals to pay farmers in developing countries for the rights to continue use of certain traditional practices and varieties, and to justify transfer payments that recognize the contribution gene pools preserved by traditional farmers have made towards improving genetic material that is available globally. Much work is needed to design such programmes effectively. The experience of the Conservation Reserve in the United States suggests that, with the right target selection criteria, modest funds can preserve significant amounts of environmental quality (Babcock *et al.*, 1996).

PRICING AND BIOTECHNOLOGY

In order to understand the economic and policy implications of biotechnology, we need to develop an understanding of the pricing of IPR. A full-blown model of price and quantity determination in biotechnology has not been developed, but some basic principles can be sketched to point out one direction that modelling could take. Conceptually, the key distinction is between two types of goods: market products, that are the result of biotechnology, that embody the results of research, and components of knowledge, which are required to produce products, and are covered by IPR arrangements. This may be knowledge about genes or about processes. For simplicity, we also distinguish between two separate types of production units or organizations that produce and sell marketable goods and others selling knowledge and owning property rights.

In the case of agricultural biotechnology, varieties are obvious examples of market products, with biotechnology processes and genetic information as the components. The production of varieties in the future will rely heavily on biotechnological techniques. Over time, the available tools of genetic manipulation and the library of genetic knowledge will increase, and it is plausible that biotechnology companies will be able to 'assemble' a range of finely tailored varieties. As in the case of the computer industry, there could be significant competition in the assembling of varieties. Much of the monopolistic power will accrue to firms owning proprietary rights to the components. Companies such as Monsanto and Pioneer will accumulate IPR for processes and important genetic sequences, set prices for these components and will be paid whenever they are used (it has been said that Monsanto desires to be both the Microsoft and Intel of agricultural biotechnology). To model this situation, assume that there are K distinct components required in order to produce a crop cultivar, with k being a component index, allowing i to assume values from 1 to I .

Let U_k be the price of component k which may be the fee paid to IPR holders. Let δ_{ik} be an indicator equal to 1 if component k is integrated into variety i and 0 otherwise. The price of variety i is

$$V_i = c_i + \sum_{k=1}^0 \delta_{ik} U_k$$

where c_i is the per-unit assembly cost.

In an ideal system, growers would have choices among many varieties and could make choices about each genetic component. Under such circumstances, a grower would purchase a genetic product if its price (U_k) was lower than the added benefits it generated. In reality, the product choice facing many growers is likely to be quite limited because of production and marketing costs and profitability considerations of variety producers. In this case, the decision whether or not to select a variety with a specific genetic component will depend less on the benefits of the component itself and more on the merits of complementary genetic products packaged in the varieties where it is included. Certain desirable components may not be purchased if they are not available in the most profitable variety.

Under these conditions, major corporations will design pricing policies for both products they make, and access to IPR they control, to maximize their profits. Profit will include revenues minus payments for IPR minus the cost of production and registration. Standard industrial organization theory implies that the value of IPR will be smaller when there is less purchased, as when there is an oligarchic pharmaceutical or agribusiness sector making the final product. High registration costs reduce the value of IPR directly and by contributing to reducing competition, as argued above. An interesting area for future research is the gaming situations that may occur under different IPR and industrial organization structures.

Further research will be needed to analyse the effects on resource allocation of monopolistic power that producers may have with respect to genetic material and the cost of assembly and distribution. It is clear, however, that the welfare of end users will be diminished in situations where a small number of firms have the ability to control the set of varieties available on the market. In such cases it will be important for government policies to be enacted to ensure competition in the assembly production of biotechnology items and to prevent the use of monopolistic power to limit choice and increase prices.

CONCLUSIONS

It has been suggested that the emergence of biotechnology will profoundly affect the future of agriculture, altering its institutional structures, its products and the way it is practised. Ten major points summarize our conclusions.

- (1) Biotechnology is very research-intensive, and successful utilization of new technology will require continuous improvements in our knowledge about the properties of genetic materials and the function of biological systems. Some of the research will be done by private companies, but public sector-supported research will continue to provide breakthrough innovations and fundamental new knowledge. The process of technology transfer will provide some support for the universities, but it will not be enough to cover the research costs.
- (2) Public research and extension activities are essential to foster competition and facilitate broad access to genetic materials, gene modification techniques and new varieties. Reduction in public investments in agricultural biotechnology may lead to underprovision of innovations, high prices for essential genetic materials and techniques, and a decrease in the rate of technological advance.
- (3) Currently, biotechnology is being used to develop varieties which expand pest-control options, have better storage and handling attributes, and express more intensely traits important to food processors. These types of innovations are likely to continue to be developed and controlled by existing agrochemical, seed and food-processing companies. In the long run, biotechnology will be used to develop new varieties tailored to specific production conditions or consumer preferences, promoting product differentiation in agriculture. Biotechnology will

permit development of value-added products that will allow substitution of agricultural for industrial processes in the manufacture of pharmaceuticals and fine chemicals. Biotechnology techniques may be used to ameliorate adverse consequences of agricultural production through microbial waste management technologies. These fundamentally different types of biotechnology may be associated with the establishment of new firms, the entrance of consumer goods firms into agricultural production, and expansion of contracting and vertical integration in agriculture.

- (4) It is difficult to generalize about the distributional effects of biotechnology. Some innovations, such as Canola, engineered to replace tropical oils, will shift production from developing to developed regions. Other modifications, such as disease resistance and salinity tolerance, may provide new opportunities for marginal producers.
- (5) Clearly defined and enforceable intellectual property rights are essential for private-sector research and development of new biotechnology products. However, overly broad patents may grant excessive market power to patent holders, reducing their incentives to provide socially desirable levels of production or investment in innovation. Unduly broad patents and/or overly restrictive licensing of academic inventions will diminish the capacity for new entrants to compete.
- (6) Biotechnological processes and products must be monitored for safety and efficacy. However, registration and safety regulations that are unduly restrictive will lead to concentrations of research and production capacity, which may stifle the growth of agricultural biotechnology and in some cases result in less desirable health and safety outcomes.
- (7) Biotechnology provides a means to address many needs specific to developing countries; but to realize these opportunities, nations will have to develop their own research capacity to handle it. Additional investments in information and extension services will be needed to support adoption of new varieties.
- (8) Developed countries should not be overzealous in their enforcement of intellectual property rights in developing countries. First, excessive fees will encourage cheating and, second, undue emphasis on IPR protection may conflict with other goals, such as promotion of free trade. Consideration should be given to establishing two-tiered pricing systems for intellectual property rights, with developing countries paying lower prices.
- (9) Revenues from the sale of options to develop indigenous genetic resources will not be sufficient to protect natural areas that are reservoirs of biodiversity. Other mechanisms must be developed to protect these resources at globally desirable levels.
- (10) Biotechnology provides new research challenges and opportunities for agricultural economists. New methodologies are needed to understand the welfare implications of alternative intellectual property rights policies under different industry structures and technology attributes, with attention to the role of universities' technology transfer practices. Welfare economics should be extended to questions regarding patent breadth, enforcement policy, and investment in public versus private research.

Furthermore, it is also very important that we understand the economics of biotechnology within a development and international context.

NOTES

¹We define biotechnology as the application of the tools of molecular biology, primarily recombinant DNA and related techniques, to modify organisms in order to increase productivity, improve quality or introduce novel characteristics.

²Just and Hueth (1993) expanded this line of reasoning and argued that, in many cases, biotechnology varieties can be viewed as complementary or substitutes of variable inputs. Their adoption is likely to increase as the price of substitutes increases and price of complements declines.

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DISCUSSION REPORT SECTION II

*Hassan Serghini (Morocco)*¹ said that he had much enjoyed listening to McCalla and Valdés as they carefully sifted through the semantics involved in deciding whether ‘diversification’ can be regarded as a ‘policy’ or as a market ‘response’, with particular reference to agricultural trade. It did appear to him, however, that the subject is difficult to discuss in isolation and that much depended on circumstances in specific countries. From his viewpoint, the Maghreb has great advantages of climate, which helps in the production of numerous seasonally differentiated high-value crops which are potentially exportable, but the export opportunities are constrained by the nature of the agricultural policies followed in the European Union, which is the obvious market. The nature of the import restrictions, as well as the manner in which they have changed (or are changing) as a result of the completion of the Uruguay Round, for fruit and vegetables in particular, is extremely complex. It appeared to him that there does have to be a measure of guidance, stemming from the official level, if producers and traders are to be able to benefit from any marketing opportunities which do exist.

This type of issue also became evident in the comments of *Bradford Barham and Michael Carter (United States)*² as joint openers of discussion on the paper by Delgado and Siamwalla. They had experience of watching the development of agroexports in Latin America where, in examples such as that of Guatemala, something of a boom was occurring. The case in point was growth of winter vegetable supply, notably to North America, based on producer marketing cooperatives involving thousands of small-scale farmers (most having under two hectares). Here the issue was not so much one of entering export markets or organizing supply, where the cooperation structure appeared to offer considerable advantages. The important concern lay in the difficulty of encouraging poor farm households to engage in high-value activities. There remains a preference for subsistence crops – this is a type of implicit insurance as a risk-reducing measure – despite there being a much lower rate of return to their land and other factors. As scale increases, indeed as expected, the willingness to adopt agroexport crops also rises. It was then emphasized, however, that Latin America has a highly inequalitarian agrarian structure, which makes it difficult for the mass of poorer farmers to participate in new types of activity. They are hampered by their own low adoption rates, but there are good reasons why adoption should be tempered with caution.

¹University of Hassan II, Rabat.

²University of Wisconsin-Madison.

Given their experience, the discussants felt a large measure of agreement with the authors. The latter, after all, did stress the need to make markets work well for smaller farmers. Cooperatives, contract farming and other institutional innovations can reduce the transaction costs that create competitiveness problems for smaller-scale operators. But they see a conceptual flaw in the Delgado/Siamwalla paper. The authors stress 'diversification' of income sources as a helpful step. Part of the process, according to the discussants, is obviously 'commercialization', though even that could imply more 'specialization', or 'intensification', rather than seeking yet more potential income sources. It could well be apposite for sub-Saharan Africa, which they quoted as a region of considerable 'diversification'. But no matter how the semantics is approached, it is never going to be easy to overcome the barriers which lie in the way of adoption of new opportunities. It is even more difficult, according to the discussants, to promote 'equitable growth'.

Agricultural biotechnology was commented on by *Rafael Posada (Colombia)*³. He was impressed by the clarity of the paper by David Zilberman and his colleagues, commending special study of the complex roles and motivations involved in making final use of a biotechnology product. The worry must be that inequitable development will occur, partly because the property rights involved are rather tightly drawn and could isolate many countries from innovative technology, but mainly owing to the sheer lack of the capacity in the Third World to carry out research in the early discovery and development phases. To overcome this, special efforts are needed to promote arguments that will convince current and potential donors that investment in biotechnology in the Third World has positive benefits for the whole of global society, and also convince commercial firms that location of research facilities in developing countries could be privately beneficial. In short, there appears to be no inherent reason why they should not participate at all stages in the discovery and application process. This is important because a biotechnology output could be the source of an advantage in agricultural production for a developing country, while lack of anything could signal a serious loss of competitiveness. The most desirable situation is obviously one in which the outcomes of research, taken overall and bearing in mind that numerous potential products are involved, will be as neutral as possible in terms of interregional competitiveness.

³Centro Internacional de Agricultura Tropical (CIAT).