AGRICULTURAL BIOTECHNOLOGY: ECONOMIC AND INTERNATIONAL IMPLICATIONS

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Agricultural Biotechnology:
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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 practiced. Mechanical, biological, and chemical innovations have, in turn, reduced labor requirements, increased yields, and reduced the impact of agricultural pests. More recently, computer and remote sensing technologies have improved input use 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, that will be introduced and discussed. The second purpose is to introduce some basic analytical considerations and methodological issues that will be important in the study of biotechnology. In particular, these methodologies will relate to the industrial organization considerations 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 U. S. experience implies to 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 U. S. companies generate revenues of over $4 billion annually. The evolution and structure of medical biotechnology

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[1] We 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.

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

I. Similarities

1. 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 licenses provide the majority of licensing revenues received by U. S. universities (Parker, Zilberman, and Castillo).

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 percent of the annual research budget.

Licensing arrangements vary. Exclusive licenses are appropriate for discoveries which require significant investment in development before they enter the marketplace, or which have narrow applications, since companies need the monopoly profit that exclusivity provides during the life of a patent to assure 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, nonexclusive licenses 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 these companies became successful, major pharmaceutical firms bought majority ownership stakes.

Some of these patterns can be seen in ag-biotech. University research discoveries have been crucial in the evolution of these 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 (e.g., Monsanto recently acquired Calgene, a leading ag-biotech 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.

2. 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 (e.g., 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 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 biotechnology 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.

3. The geographic profile of production. Commercial biotechnology is human capital intensive, requiring a scientific and managerial work force that is highly skilled and knowledgeable. The biotechnology industry has been 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 ag-biotech 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.

II. Differences

1. 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.

2. Differences in knowledge and complexity. Medical biotechnology has primarily focused on one species which has historically received most of the attention and research funds expended on biological study—humans. Contrast this with ag-biotech 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 ag-biotech products currently on the market have been based in single gene changes, the development of new varieties which contain a complete bundle of desired characteristics may require complex manipulations.

3. 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 ag-biotech products 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 ag-biotech research, development, and product introduction (FDA, Environmental Protection Agency, and U. S. Department of Agriculture). The regulations governing these activities have been much more rigorous than for equivalent products developed using nonmolecular 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, Miller, and Lemaux).

4. Need for geographic adaptation Most medical biotechnology products do not need to be adjusted for differences in the geographical location of the consumer. Ag-

biotech products, however, have to be incorporated into agricultural production systems and so must be modified according to varying ecological conditions. Thus, they may entail high adaptation costs and may not enjoy the large markets of some medical biotechnology products.

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 favor of ag-biotech. One would not expect as much private sector investment; therefore, the evolution of ag-biotech depends on the continuing support for public research of relevant disciplines. Marketing of ag-biotech products may not be as easy as marketing of 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, ag-biotech 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 resources 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 biotech firms, have strong marketing networks in place and enough financial resources to bear the costs of product registration. The fourth group 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.

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

M = Major corporations with established market presence in pharmaceuticals, chemicals, seeds, or food processing.
B = Biotechnology firm.
U = University.

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 argue, university research tends to produce fundamental new knowledge which results in dramatically different ways of conducting research and entirely new products. University research is supported from three sources: government funding, technology transfer revenues, 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 marketplace is shown on lines 1 - 3, wherein university discoveries are licensed to biotechnology companies for development, with subsequent activities handled either by the biotech 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. Pattern 6 is typical of the chemical industry, wherein large companies are involved in all stages—from research through 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 through 3, causing a significant reduction in the number and rate of technological advances. The rate at which discoveries reach the marketplace 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 behavior of the start-up companies, these innovation 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 phenomena is occurring in ag-biotech, with major corporations shaping the regulatory environment in a manner that disadvantages start-up businesses.

Modeling 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 sourced from virtually any organism). There are several distinct types of ag-biotech products, each with different technical and economic implications. Below we discuss separately four main lines of ag-biotech products:

1. <u>Supply enhancing products.</u> 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 subgroups. 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 with the highest nonnegative 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 $pf'\left(x_i^*, i\right) = W$. Profit per acre of technology i,

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

is calculated and the optimal variety i^* is the one with the highest nonnegative 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

$$\underbrace{p\left(y^* - y_1^*\right)}_{\text{yield-increasing effect}} + \underbrace{w\left(x_2^* - x_1^*\right)}_{\text{input-saving effect}} > \underbrace{v_2 - v_1}_{\text{extra genetic material cost}} .$$

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

[2]Just and Hueth 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.

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 that 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 new innovation. The main effects may be gains to consumers.

The adoption of such technologies may be enhanced by government programs 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 re-institute 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 environmental goals; e.g., bovine growth hormone may reduce the animal waste problem and save on water currently allocated to alfalfa and pasture.

2. Pest Control Products. This line of products consists of varieties that can tolerate, repel or kill pests, or withstand applications of herbicides and genetically engineered microorganisms. As Ollinger and Pope have shown, most of the experimentation with new ag-biotech products have 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 cost-effectively meet a need.

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 targeted by that pesticide, because their marketing network provides them 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 that have new products as well as research and development capacity. Another approach is to develop internal research capacity and to buy rights to university innovations to jump-start their knowledge base. Ag-biotech 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) are expanding their capacity in pest control, and the boundaries between pest control companies and seed companies are gradually eroding.

At the same time, some companies are reducing their involvement and may exit from 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 pesticide operations. Another group of companies that may be negatively affected are manufacturers that specialize in production of chemical pesticides after the patent life has expired. Such manufacturers are especially important in developing nations, and they enable producers in those nations 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 ag-biotech products currently underdevelopment 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 Bt 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.

3. Quality-Modifying Biotechnology Innovations. Biotechnology techniques allow modification of agricultural products to enhance desirable characteristics. As Ollinger and Pope documented, 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 ag-biotech product to reach consumers, the Flavr Savr (tm) tomato. The unexceptional market performance of this product is 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 flavor.

A related quality dimension is the extension of the harvest period for desirable crop varieties. As Parker and Zilberman 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, sweeter, or introduce desirable health characteristics may be quite profitable if consumers' willingness-to-pay for these attributes exceeds innovation and extra production costs. The genetic manipulations required to produce such products are relatively complex, however, and the risk associated with such research is high, so most of the research in this area has been done by universities. As promising new innovations are discovered, the process of technology transfer will determine how commercial products are developed. As discussed above, 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 significant monopolistic power and exert significant trade and capture rents that would otherwise would 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 capture 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 will likely be more involvement by agricultural producer organizations and large food packers and distributors in support of biotechnology research that improves product quality.

Another effect of falling costs in biotechnology research and development will be to intensify the growing tendency toward product differentiation and monopolistic competitive behavior in agriculture, particularly in specialty 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-enhancing biotechnology 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 likely increase the value and purchasing power of complementary support for university research by private companies. In the long run it may have significant implications for market structure and income distribution in agriculture and the food sector.

4. <u>New Products.</u> If we define farming as cultivation and production of commercial output using living organisms, then 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, such as production of fine chemicals (beta carotene) from algae. 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 that raise these new products will

likely 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 grain or oilseed varieties that are land intensive, 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.

The Relationship Between Biotechnology and Precision Agriculture

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

The possibilities 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 regard, biotechnology and precision agriculture are complementary, and the diffusion of one will help push forward the diffusion of the other. Seed companies and agrochemical suppliers which promote 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 independent agricultural consultants. Some of the consultants are independent and others are employed by agricultural chemical and seed dealers. Furthermore, there are companies that provide custom services in the use of precision farming. All these professional infrastructures, which increase the capacity of agriculture to effectively utilize scientific data, will be increasingly important with the introduction and expansion of biotechnology products. With ag-biotech, the range of plant varieties available might expand greatly if agricultural consultants are able to identify conditions under which this diversity can yield sufficient extra profits. One may also expect continuing development of software that will enable farmers and consultants to optimize their choices 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 precise applications of inputs reduce the residues that are the main cause of ground and surface water contamination. Increased precision may also provide better control of certain pest problems. To the extent that precision farming reduces pest problems, it 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 Consideration 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 public goods. These assumptions are especially important in crafting international arrangements pertaining to the research and 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 suboptimally 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. This dissatisfaction may be further exacerbated by the fact that, although the genetic material is integral to many agricultural crops originated in developing countries, farmers in those countries may, in the end, be required to pay for use of those genetic materials.

Another source of concern for developing countries are product registration requirements. The registration requirements for agricultural biotechnology in the United States are considered unduly strict, thus providing existing biotechnology companies with protection from the entry of competitors. Developing countries may aim to have a biotechnology infrastructure to produce products for the export markets, but strict registration requirements in the United States and/or Europe may stymie investment. Thus, an objective assessment is required of the value of the registration policies and regulations since these policies 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 U. S. environmental groups, as well as some agribusiness and farmers, who support 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 nor 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 environmental risk in exchange for reduced hunger, increased income, and other benefits may be higher in developing countries than 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 is the 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 aggressively enforce those rights 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. Based on 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 IPR are inconsistent with this goal. The emphasis in trade negotiations should be on vigorously preventing nonmarket 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 has to both better understand how the markets work and to incorporate elements of political economies and international trade to be rigorous. However, based on our knowledge from previous areas of economics, we present here some opinions that one has to consider as 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 Pyndick) may suggest to some that biodiversity is underpriced and, if the price is corrected, a lot 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 and 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 Pyndick model suggests, correct recognition of uncertainty actually may 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). 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 “farmer’s 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 toward improving genetic material that is available globally. Much work is needed to design such programs effectively. The experience of the Conservation Reserve Program in the United States suggests that, with the right targeting criteria, modest funds can preserve significant amounts of environmental quality (Babcock et al.).

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 below we sketch some basic principles that suggest one direction modeling could take. Conceptually, the key distinction is between two types of goods: (a) market products that are the result of biotechnology that embody the results of research and (b) components of knowledge, which are required to produce products, and is 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—organizations that produce and sell marketable goods and others that sell knowledge and own IPR.

In case of ag-biotech, varieties are obvious examples of market products and biotechnology processes and genetic information are the components. The production of varieties in the future will heavily rely 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 may 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 biotech processes and important genetic sequences, set prices for these components, and will be paid whenever they are used (it's been said that Monsanto desires to be both the Microsoft and Intel of ag-biotech). To model this scenario, let us assume that there are K distinct components that are required in order to produce a crop cultivar. Let k be a component index and let i 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) is lower than the added benefits it generates. 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 produce 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 producing 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 analyze 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. It will be important that government policies be enacted to assure competition in the assembly production of biotechnology products and prevention of the use of monopolistic power to limit choice and increase prices.

Conclusions

We have argued that the emergence of biotechnology will profoundly affect the future of agriculture, altering its institutional structures, its products, and the way it is practiced. Ten major points summarize our conclusions.

1. Biotechnology is very research-intensive, and successful utilization of this new technological paradigm 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 need to develop their own research capacity to develop and produce biotechnology products. 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 vs. private research. Furthermore, it is also very important that we understand the economics of biotechnology within a development and international context.

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