Economic Benefits and Costs of Biotechnology Innovations in Agriculture

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Abstract

The conceptual model necessary for an assessment of biotechnology's economic benefits and costs is outlined, emphasizing the need to account for the proprietary nature of biotechnology innovations. The model is illustrated with an application to Roundup Ready soybeans. The estimated value of this innovation is sizeable, with consumers and innovators claiming the larger share of net benefits. Also, disparities in intellectual property rights protection across countries affect the distribution of benefits. Consumer resistance toward genetically modified organisms (GMOs) and the issues of labeling and market segregation complicate the economic evaluation of biotechnology innovations, and a number of related regulation and public policy issues are discussed. Emerging output-trait GMOs are potentially less controversial and may bring more benefits to all participants in the agri-food sector, but this outcome depends crucially on the development of an effective, credible, and internationally harmonized regulatory system.

Key words: biotechnology, genetically modified organisms, identity preservation, intellectual property rights, R&D, transgenic crops, welfare evaluation

ECONOMIC BENEFITS AND COSTS OF BIOTECHNOLOGY INNOVATIONS IN AGRICULTURE

Introduction

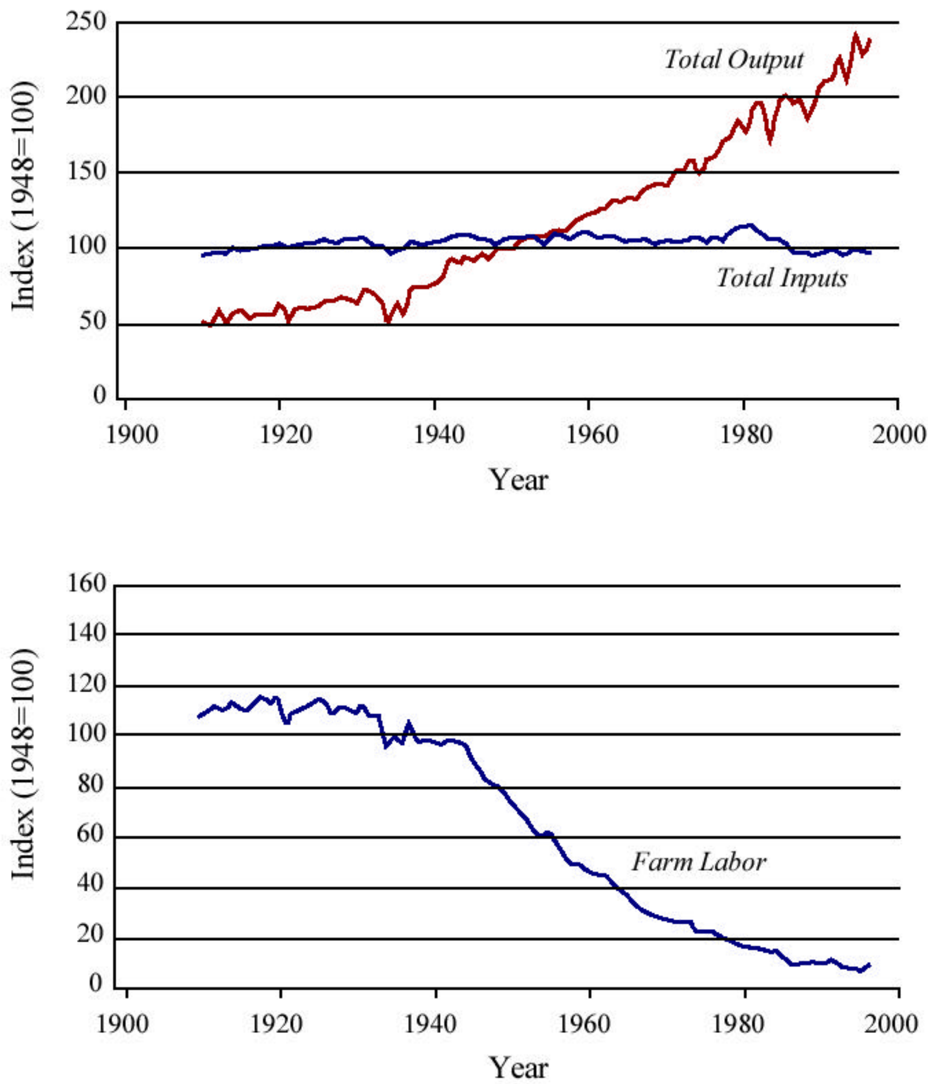
It has been said that, from a scientific point of view, the twentieth century belonged to physics and chemistry but the twenty-first century will belong to biology.[1] Some of the exciting science underlying biotechnology innovations certainly supports that point of view. As one would expect from truly novel developments, the nature and impact of these new technologies may also have profound economic implications. As I consider the question put to me by the conference organizers—What are the economic benefits and costs of biotechnology, and who is likely to reap the net benefits?—I must start by delimiting the scope of this paper. Biotechnology encompasses a broad array of innovations that affect many industries. Whereas agriculture and/or food production may not be the most important arena for the future of biotechnology (vis-à-vis pharmaceutical applications, for example), in keeping with the nature of this conference I will nonetheless concentrate my discussion on biotechnology from the point of view of agriculture.

Biotechnology's current impact on agriculture arises from the recent introduction of improved crops that belong to the class of genetically modified organisms (GMOs), marking the beginning of what appears to be a revolution that will bring substantial change to this sector. But change brought about by scientific breakthroughs and technological innovations is not a new development in agriculture. To put things into perspective, I start by briefly discussing agriculture before the advent of the current wave of biotechnology innovations, and I present the standard framework that is used to evaluate the economic benefits of agricultural innovations. I then explain how this model can be extended to assess the economic benefits and costs of biotechnology innovations, and their likely distribution. This is followed by a review of some problems that have been raised by the rapid adoption of biotechnology innovations in agriculture, including a discussion of GMO regulation and related public policy issues. Needless to say, such considerations are at present largely speculative, given the considerable scientific, regulatory, and market uncertainty that surrounds GMOs.

Agriculture before GMOs

Change brought about by science and technology has shaped agriculture since the industrial revolution, and the speed of the induced economic change has picked up pace in this century. Notable among innovations that have changed twentieth century agriculture is mechanization, as a continuous stream of more powerful and sophisticated machines have drastically changed the way production tasks are performed. Chemicals—fertilizers, pesticides, and herbicides—have also made a difference, bringing a newer class of extremely useful production inputs to agriculture. Breeders have provided an impressive array of improved crop varieties, the achievements of hybrid corn being a classic example of success. The difficulties of systematic genetic improvements in animal science have been mastered, along with the introduction of a number of techniques for efficient animal husbandry. And at the same time, of course, there has been a generalized improvement in the knowledge level of farmers themselves, affecting what is referred to as their human capital (Huffman and Evenson 1993).

To briefly review some of the effects of innovation in agriculture, consider the evolution of productivity in the United States in the twentieth century as illustrated in Figure 1. Note that U.S. agricultural output in this period has increased fivefold, whereas overall input use has stayed roughly constant; thus, the U.S. sector has experienced sizable “productivity gains,” i.e., increased efficiency. The output trend is easily rationalized. For example, over the last 50 years the yield of major crops such as corn and soybeans has increased more that threefold; milk-per-cow has increased nearly fivefold. Naturally, such production gains have required increased use of some factors. In particular, the use of fertilizers, pesticides, and other chemical inputs has increased dramatically, and more and better machines have continued to change the way basic production tasks are performed. For example, in 1910 there were only 1,000 tractors



Source: U.S. Department of Agriculture.

FIGURE 1. Production in U.S. agriculture

employed in U.S. agriculture; by 1960 there were five million! In the last 40 years the number of tractors has not increased—the machines have just gotten bigger and better (the average horsepower per tractor has increased more than threefold). So, higher production has meant higher use of mechanical and chemical factors of production, but the top panel of Figure 1 indicates that overall input use in U.S. agriculture has been roughly constant.

So what has decreased? The bottom panel of Figure 1 illustrates the answer: labor has moved out of agriculture on a massive scale, off to better things perhaps.

This background is meant to emphasize that the impact of technological innovation on agriculture has been pervasive. The enormous efficiency gains implied by Figure 1 arguably have benefited society at large, by providing a bountiful supply of food available at lower resource costs. To illustrate the basic framework necessary to evaluate the economic benefits brought about by such innovation, consider the model illustrated in Figure 2. Improved production techniques (yield increasing, cost saving, etc.) shift the supply curve to the right, from $S_0(p,w)$ to $S_1(p,w)$, where it is made explicit that these supply functions depend on both the price p of agricultural output and the price(s) w of inputs. In this setting, of course, innovation is good for society, and the dollar value of the efficiency gain is measured by area *ABCE*. To answer the “who wins” question in this context, we can start by separating the effects on producers and consumers. Consumers unambiguously gain from the innovation, due to the price decline induced by more efficient production techniques. The monetary value of consumer benefits (the change in consumer surplus) is given by area $p_0 BC \tilde{p}_1$. Producer’s net benefits, on the other hand, can move either way (producers gain if area $E \tilde{p}_1 C$ is larger than area $A p_0 B$, and lose otherwise). Producers may be hurt by innovation because of the price decline induced by the increased supply—the crucial parameter in this setting, of course, is demand elasticity. Needless to say, the validity of the welfare evaluation discussed in Figure 2 is predicated on some crucial assumptions that ensure optimality conditions in the rest of the economy (i.e., competitive pricing conditions everywhere and no externalities and/or missing markets).

The benefit evaluation in Figure 2 is an ex post assessment. A full benefit-cost analysis of innovation needs to consider the cost to society of bringing about new technologies. The farmers’ competitive setting accounts for the latent demand for innovations. If a production process can be improved, or a new product brought to

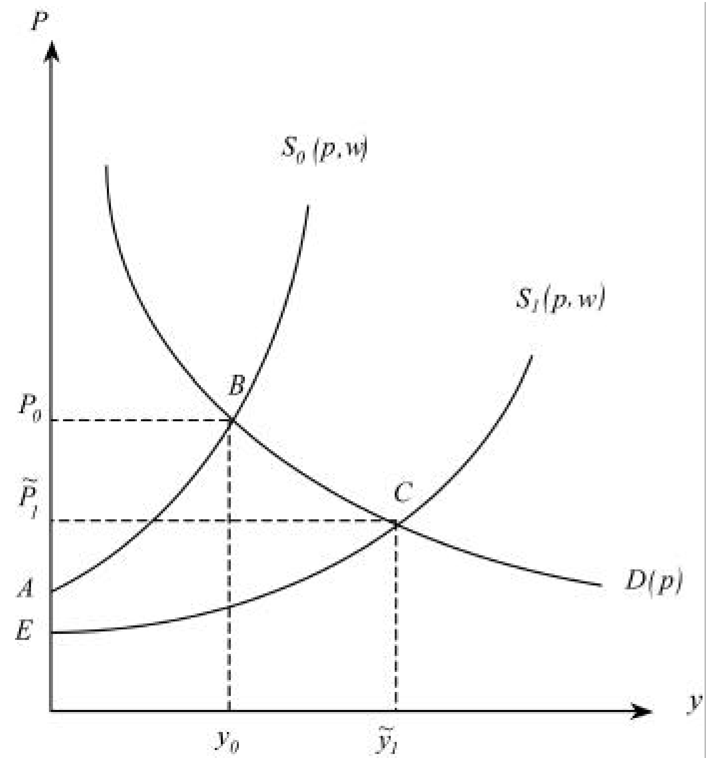


FIGURE 2. Economic benefits of agricultural innovations

market, competitive producers are willing to pay for such an innovation. On the supply side of innovations, scientific and technical capabilities are important in determining what is feasible, but that depends on investments into basic and applied research and development (R&D). Given proper incentives, the market will respond to the demand for innovations by supplying new and improved processes and products. But it is well known that the market, left to itself, may not work well in this setting. The possible "market failure" here is due to the fact that knowledge, in its purest form, is a "public good" (Arrow 1962). Thus, private agents may invest too little in scientific research. This observation is what has led to considerable public investment in agricultural R&D projects.

By explicitly considering the costs required to bring about the innovation, in addition to the gross benefits measured by the area *ABCE,* we can compute the rate of return of the innovation, a measure of the net benefit associated with research. Considerable empirical evidence has been amassed that supports the view that agricultural innovations have translated into considerable benefits for society.[2] Common wisdom supports the view that farmers also have benefited from innovations. But this achievement has necessitated a dramatic change in the way agricultural production is carried out. The massive exodus of labor from the agricultural sector, mentioned earlier, is perhaps the most obvious feature of a wider structural change that has affected the rural world at large, moving agriculture toward what has been characterized as its industrialization age.

As we ponder how genetic engineering may affect agriculture, it is instructive to understand what, say, mechanical engineering has already done for it.

Agriculture and GMOs

Biotechnology innovations appear to have taken world agriculture by storm. Transgenic crops, in particular, began to be marketed in 1996, and by 1999 the total area devoted to transgenic crops in the world was already nearly 40 million hectares—about 100 million acres (Table 1). This spectacular success is attributable almost entirely to transgenic varieties of four crops: soybeans, corn, cotton, and canola. For soybeans and canola the transgenic attribute is that of herbicide resistance. The "Roundup Ready" (RR) varieties of these crops, for example, are resistant to glyphosate, a very effective post-emergence herbicide. For cotton and corn, both herbicide resistance and insect resistance have found widespread adoption. The latter include Bt-cotton (resistant to bollworm infestation) and Bt-corn (resistant to the European corn borer). It is also interesting to look at the commodity and geographical composition of these transgenic crops. As Table 1 illustrates, mass cultivation of transgenic crops has been, so far, a story of three countries: United States, Argentina, and Canada.[3]

Agricultural biotechnology innovations that have been most successful to date are crops that have been modified to express a particularly useful agronomic trait. This suggests that some of the economic considerations relevant here are rather standard. Other things being equal, transgenic crops reduce production costs or increase yield (expected yield, at least). Thus, farmers have an incentive to adopt these crops and, when

TABLE 1. Global area of transgenic crops, 1996-2000

	1996	1997	1998	1999	2000[a]	Percent (2000)[a]
	Hectares (million)					
By Country						
U.S.	1.5	8.1	20.5	28.7	30.3	70.5%
Argentina	0.1	1.4	4.3	6.7	8.8	20.5%
Canada	0.1	1.3	2.8	4.0	3.0	7.0%
China	…	<0.1	<0.1	0.3	0.5	1.2%
South Africa	…	<0.1	<0.1	0.1	0.2	0.5%
Australia	…	<0.1	0.1	0.1	0.2	0.5%
World	1.7	11.0	27.8	39.9	43.0	
By Crop						
Soybeans	…	5.1	14.5	21.6	24.8	57.7 %
Corn	…	3.2	8.3	11.1	9.9	23.0 %
Cotton	…	1.4	2.5	3.7	5.2	12.1 %
Canola	…	1.2	2.4	3.4	3.0	7.0 %
Other	…	0.1	0.1	0.1	0.1	
Total	1.7	11.0	27.8	39.9	43.0	

Source: Clive James, International Service for the Acquisition of Agri-Biotech Applications (ISAAA).
[a] Data for 2000 are provisional.

given the chance, they have done so. The economic benefits of yield-increasing (or cost-reducing) innovations are well illustrated by the model of Figure 2, discussed earlier. One is therefore tempted to conclude that here we have fairly standard implications of agricultural innovations: increased efficiency, the benefits of which are shared through the economic system. But, although the economic effects of transgenic crops appear to work through a standard mechanism, the economic model underlying Figure 2 does not apply. The reason is that most of these innovations have been produced by private industry, and are protected by intellectual property rights (IPRs).

Given that a sizeable (and growing) portion of agricultural R&D is now performed by private firms that supply inputs to agriculture (Fuglie et al. 1996), it is not surprising that IPRs are becoming increasingly important in agriculture. Indeed, patent protection is now being routinely sought for many innovations developed by public institutions as well. A number of developments over the last twenty years, starting with the 1980 U.S. Supreme Court decision of *Diamond v. Chakrabarty*, have also contributed to IPRs becoming extremely relevant for biotechnology innovations. Chakrabarty, working for General Electric, had inserted plasmids into a *Pseudomonas* bacterium that enabled it to degrade oil, but this discovery had been denied a patent (on the grounds that it was outside the statutory subject matter established by U.S. patent law). But in the landmark *Diamond v. Chakrabarty*, the Supreme Court found that biological material is patentable if obtained through human intervention. The broad applicability of this ruling was supported in a 1985 decision by the U.S. Patent and Trademark Office involving a tryptophan-overproducing mutant of corn (*Ex parte Hibberd*), whereby it was ruled that plants can be patented (even though other forms of IPRs, such as breeders' rights, are available for plants). Utility patents for plants have found widespread use in the commercialization of transgenic crops, a notable early achievement of biotechnology, both in the United States and elsewhere. Other nonhuman multicellular organisms, including animals, can now also be patented.[4]

In addition to utility patents for biotechnology innovations, trade secrets law offers further protection of intellectual property that is relevant to biotechnology. In fact, secrecy and lead time tend to be most emphasized by U.S. manufacturing firms (Cohen, Nelson, and Walsh 2000). Although biotechnology firms are more keen to patent than firms in other sectors, scientific advancements that allow genetic identification of material covered by trade secret rights are changing the "cost" of monitoring and enforcing such rights, making them more appealing. As recent cases demonstrate, intellectual property in the life sciences can be effectively protected by trade secrets as well.[5] It is apparent, therefore, that any attempt at modeling the welfare impact of biotechnology innovations must account for the proprietary nature of such innovations.

Benefits of Agricultural Innovations under IPRs

The immediate implication of explicitly considering the IPRs of most biotechnology innovations is that the competitive price conditions underlying the model in Figure 2 cannot be invoked. Essentially, the model in Figure 2 applies to innovations that are the result of public scientific research and that are physically provided either directly by the government or by competitive agents. But when innovations are protected by IPRs, firms marketing them have an institutionalized market power which needs to be modeled explicitly (Moschini and Lapan 1997). Patents, for example, essentially confer (limited) monopoly rights to the discoverer (Besen and Raskind 1991). This market power influences the price that can be charged for innovated inputs, and the pricing of the innovations in turn affects its adoption and the resulting private and social benefits and costs. Biotechnology innovators that hold IPRs can either use their discovery exclusively or they can "license" it to others for a fee. For example, the new RR soybean technology has been transferred to U.S. farmers by written licenses in exchange for a "technology fee." In 1999 such a technology fee was set at $6.50/bag, which translated roughly into a 40 percent markup on conventional soybean seed prices.

The actual representation of benefits when innovations are proprietary depends on the structure of the relevant model, including the nature of the innovation (Moschini and Lapan 1997). But the bottom line is that the price of improved inputs will increase, and this will affect the use of the new technology and the actual benefits realized. Although in this situation it is not possible to represent total ex post benefits in the output market alone, Figure 3 gives the basic insight. Here $S_1(p,w_0)$ represents the new technology supply curve if the innovated inputs were priced at the original competitive level w_0. But if the price of the innovated input is $w_1 > w_0$, the realized market supply will be $S_1(p,w_1)$, and market equilibrium is $\{p_1, y_1\}$ rather than $\{\tilde{p}_1, \tilde{y}_1\}$. As Figure 3 illustrates, the existence of proprietary innovations reduces consumer gains (relative to the benchmark of the same innovation provided competitively), and also affects farmers' returns and society's total benefits. What Figure 3 does not show, however, are the benefits to the industry producing the innovation (the seed industry, for example), which also needs to be accounted for in the computation of social benefits.[6]

It should be emphasized, at this juncture, that protecting intellectual property does confer social benefits. By securing to the inventors what may be called "natural property

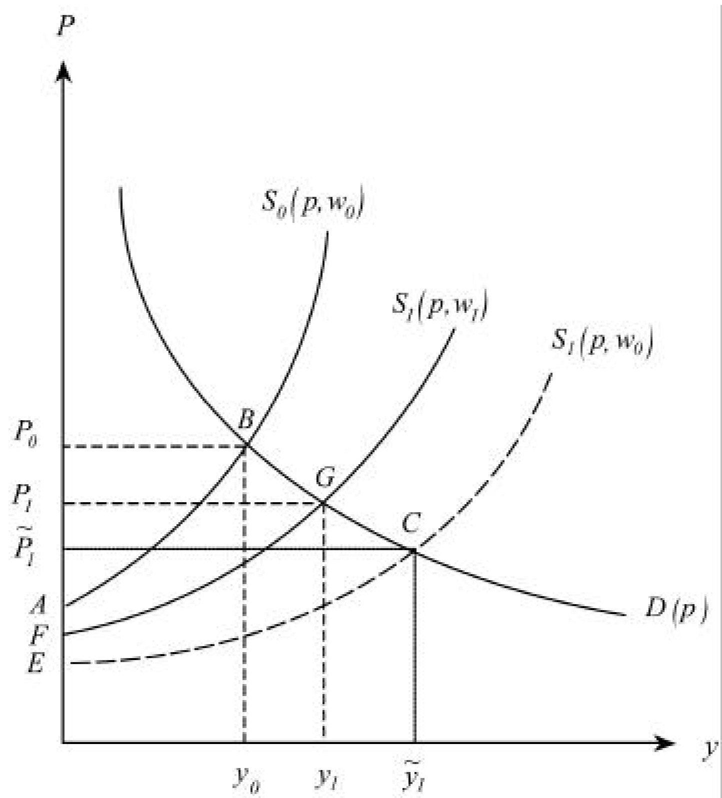


FIGURE 3. Effects of "proprietary" agricultural innovations

rights" for the product of their creative activity, IPRs stimulate would-be inventors to undertake risky R&D projects. Hence, patents can mitigate the market failure ascribed to the public good nature of inventions (which is thought to lead to underproduction of innovations). It is believed that strengthening IPRs in the United States over the last 20 years has had considerable impact on agricultural research, in particular by stimulating investments into biotechnology R&D. But whereas stronger IPRs guarantee a higher level of R&D investment, they also have implications for the actual use of the innovations, and it is the latter that directly determines the ex post benefits of an innovation.

It is also important to note that biotechnology innovations can have external benefits (and costs) that are not captured in the market models of Figures 2 and 3. Later in the paper I will mention possible adverse environmental effects of GMOs. But in fact, the transgenic crops introduced to date have some clearly desirable effects on the environment as well. For example, the glyphosate used with RR soybeans is a more benign herbicide than alternative ones that work with conventional soybeans (Gianessi and Carpenter 2000). Also, using Bt corn reduces the need for insecticides that might otherwise be required to control the European corn borer (Gianessi and Carpenter 1999). Such benefits are in addition to the market benefits illustrated in Figure 2, although, as for most externality effects, their monetary valuation is difficult to assess.

An Example: The Case of Roundup Ready Soybeans

A recent study evaluates the ex post benefits of RR soybeans with a model that encompasses the analytical elements discussed thus far (Moschini, Lapan, and Sobolevsky 2000). Specifically, to capture the essence of the trading blocks characterizing this market, the model explicitly considers three regions: the United States, South America, and Rest of the World (ROW). Three distinct commodities are identified within an integrated soybean complex: soybeans, soybean oil, and soybean meal. For each commodity, trade flows from the United States and South America to the ROW, and the spatial configuration of prices takes into account tariffs and shipping costs. The innovation is modeled in a structural way that explicitly accounts for the incentives open to farmers as well as for the pricing of RR soybean seeds by a multinational firm that holds IPRs. In particular, within each region the farm-level supply of soybeans is modeled as dependent on unit (per-hectare) profit, and two technologies are available: traditional soybeans and RR soybeans. For the latter we estimate the per-hectare cost savings, and also account for the “technology fee” associated with the seeds of RR soybeans. This markup on seed prices is possible because the new technology is patented. But the model also recognizes that IPRs are not uniform, or uniformly enforced, throughout the world. Thus, the seed markup is lower in South America than in the United States, and still lower in the ROW.

The model, calibrated on recent benchmark data, is solved for various scenarios to evaluate the production, price, and welfare impacts of RR soybean adoption. In each region the model accounts for benefits to local consumers of the three commodities and returns to farmers that produce soybeans (it is assumed that no rent is created in the crushing sector). Furthermore, in this setting the innovator can capture some of the ex post benefits (through the markup on soybean seeds). This monopoly rent is geographically attributed to the United States (when dealing with a multinational, of course, this point is somewhat moot). Some of the results are illustrated in Table 2, which reports the estimated worldwide efficiency gains of RR soybean adoption, as well as its "vertical" distribution (i.e., across farmers, seed companies, and consumers) and its "horizontal" distribution (i.e., across regions). For the case of 1999 adoption rates, for example, innovators (seed companies) get the largest share of the economic gains (44 percent). It should be pointed out, however, that for innovators these are "gross" returns because we have not imputed the cost of developing the new technologies. For farmers and consumers, on the other hand, the gains represent net benefits. Clearly, consumers are the main winners of the net economic gains, claiming 40 percent of the total ex post benefits. Farmers also benefit, obtaining 16 percent of the total efficiency gains, although as a group they receive the smallest share of the ex post benefits. Looking at the regional distribution of economic benefits, the United States gains substantially from this superior innovation (74 percent of the total efficiency gains). A good share of the estimating benefits accruing to the United States take the form of ex post returns for the innovating firms, which emphasizes the principle that a direct consideration of the "innovation industry" is crucial to assessing the benefits from biotechnology innovations.

An issue of some interest that was emphasized by Moschini, Lapan, and Sobolevsky (2000) is the fact that the United States finds itself in the interesting position of exporting both the final product (i.e., soybeans and soybean products) as well as the new technology that allows a more efficient production of the final product (i.e., RR soybeans). Quite clearly, exporting the new technology potentially impacts the competitiveness of the U.S. soybean sector. Less obvious, perhaps, is the role that IPR protection has in this context. For commodities for which there is a highly integrated world market, such as corn and soybeans, the fact that intellectual protection differs widely across countries has major repercussions. Consider again the case of RR soybeans. As discussed earlier, next to the United States, Argentina has been very keen in adopting RR soybeans. Indeed, for the current crop, it is estimated that RR soybeans will

TABLE 2. Estimated economic benefits of Roundup Ready soybeans (U.S.$ million)

Region	Consumer Benefits	Producer Benefits	Innovator Profit	Total Benefits	Horizontal Distribution
			At 1999 Adoption Rates		
U.S.	82	156	358	596	74%
S. America	37	27		64	8%
ROW	201	–58		144	18%
World	319	126	358	803	
Vertical distribution	40%	16%	44%		
			At Complete Worldwide Adoption		
U.S.	230	135	819	1183	54%
S. America	103	120		223	10%
ROW	568	224		791	36%
World	900	479	819	2198	
Vertical distribution	41%	22%	37%		

Source: Moschini, Lapan, and Sobolevsky (2000).

account for more than 90 percent of the Argentine harvest. But, to date, Monsanto has not obtained a patent for their RR technology in Argentina. Monsanto can of course appeal to basic "breeders' rights," but the company cannot require written agreement from farmers in Argentina. And farmers can legally save part of their harvest for use as seed on their own farms.

Table 3 summarizes the effects of this "exporting" of the RR technology. Insofar as this transgenic crop increases efficiency, its adoption outside the United States leads to increases in overall global benefits. But the United States as a country only marginally benefits from this spreading of the technology, and U.S. farmers are negatively affected in a significant way by competition from overseas soybean producers. Moschini, Lapan, and Sobolevsky's (2000) conclusions on this score are supported by a recent U.S. Government Accounting Office (GAO) (2000) analysis. In addition to the IPR considerations noted above, there is apparently a thriving black market in RR soybean seeds in Argentina, which has even penetrated part of Brazil where the RR technology is still officially not allowed. The bottom line is that, as illustrated by Table 4, RR soybean

TABLE 3. Effects of "exporting" Roundup Ready technology (U.S.$ million)

Region	Consumer Benefits	Producer Benefits	Innovator Profit	Total Benefits
	Only United States Adopts			
U.S.	91	391	546	1028
S. America	41	–124		–83
ROW	226	–65		161
World	358	202	546	1106
	United States and South America Adopt			
U.S.	187	213	735	1136
S. America	84	178		262
ROW	463	–132		331
World	735	259	735	1729
	Complete Worldwide Adoption			
U.S.	230	135	819	1183
S. America	103	120		223
ROW	568	224		791
World	890	479	819	2198

Source: Moschini, Lapan, and Sobolevsky (2000).

seeds are much more expensive in the United States than they are in Argentina, which tilts the competitiveness of the oilseed sector in favor of the Southern hemisphere. This table is also interesting in that it illustrates why IPRs matter. Observe, in fact, that the price range for Bt corn seed is essentially the same in these two countries. The reason is that Bt corn concerns hybrid seeds, and here the hybrid technology (which means that harvested seeds will not reproduce true to type) effectively substitutes for the lack of a strong IPR system.

In conclusion, spillover of the new technology to foreign competitors erodes the competitive position of domestic soybean producers, and export of the technology per se may not improve the welfare position of the innovating country. With strong overseas IPR protection, the innovator-monopolist could extract a substantial share of the efficiency gains, thus benefiting the home country. But with weaker IPR protection,

TABLE 4. Seed prices in the United States and Argentina, 1998

	RR Soybean $ / 50 lb. Bag	Bt Corn $/80,000 kernel bag
United States	20–23	83–122
Argentina	12–15	75–117

Source: U.S. General Accounting Office, 2000.

profits from foreign sales of the new technology just offset the loss of domestic producer welfare. Consumers in every region gain from the adoption of RR soybeans.[7]

Given that consumers reap a good share of these benefits, it would seem to be a fallacy to argue, as many do today, that current GMOs do not benefit consumers. Consumers do in fact benefit, although the benefit is a mundane one: a slightly lower price for something that is somewhat removed from their table. Yet such benefits can be a sizable portion of the overall efficiency gains.

Labeling, Product Differentiation, and Market Segregation

The foregoing analysis has emphasized the efficiency gains arising from GMOs. On the one hand this is quite appropriate because, as discussed earlier, the most popular transgenic crops today embody agronomic traits that increase yields and/or reduce production costs. For such innovations, a homogeneous product model such as that sketched out can provide important insights. On the other hand, this modeling approach does not address a particular feature that may turn out to be very relevant to the analysis of the economic benefits flowing from GMOs. Specifically, following considerable public resistance toward GMOs, regulations have been introduced in Europe and elsewhere that have the potential to affect directly the manner in which agricultural commodities are marketed. The changes that are forthcoming, mandatory labeling in particular, provide incentive for the development of product differentiation and market segregation in a system that was, up to this point, largely a commodity-based one. The costs of developing an appropriate marketing system and the apparent consumer reluctance toward GMOs can have larger effects on the economic valuation of such innovations, as well as on the distribution of the associated costs and benefits.

Consumer resistance toward GMOs might appear incongruous, given the earlier claim that this class of innovations undoubtedly benefits consumers. Such a claim, of course, was predicated on the fact that efficiency gains in production typically are eventually reflected in a price decline at the consumer level. There are at least three considerations that are relevant here. First, the price effect is small (less than 1 percent for the soybean study discussed earlier). Second, for each individual consumer the benefit, even when correctly perceived, is still quite small. For wealthy consumers of the developed world, it is easy to dismiss the importance of efficiency-induced price reductions, even though that is the bread and butter of what has made our agricultural and food system the efficient mechanism that it is today. Third, the consumer quite reasonably worries about other things. For example, risk (perceived in terms of food safety and/or environmental safety) and ethical reservations about genetically manipulated living organisms figure prominently in the explanation of why some consumers may oppose GMOs in food.

Whereas the United States has chosen a hands-off regulatory approach toward GMOs, the vociferous public opposition to GMOs in the European Union (EU) has resulted in new legislation aimed directly at regulating GMOs (Moschini and Corrigan 1999). One of the most significant elements of this regulation is the legislation concerning "novel foods," which establishes a mandatory EU-wide pre-market approval for all foods obtained from GMOs and mandates "labeling" of foods and food ingredients that contain (or are derived from) GMOs. More recently, Australia, New Zealand, Japan, and South Korea also announced plans to implement their version of mandatory labeling of GMO foods.

Labeling GMOs can be seen as an extreme form of grading, a feature of the marketing channel of agricultural products that has been the object of some study (e.g., Hennessy 1995). The mandatory labeling of GMOs and GMO-derived products adopted in Europe, and forthcoming elsewhere, could prove to be a powerful incentive to develop handling and processing systems characterized by market segregation and/or identity preservation. Identity preservation has become increasingly common, independent of the rise of GMOs, as specialty crops (such as high oil corn) have developed to fill particular market niches. But implementing an identity preservation system in our setting is costly, because to supply food that is free of GMOs it is necessary to keep traditional crops segregated from the new transgenic ones throughout the production and marketing system, through production, storage, transportation, processing, and distribution. Hence, in this differentiated products setting the equilibrium price for non-GMO food products will be higher than the price for corresponding GMO products, and also higher than the pre-innovation consumer price (Fulton and Keyowski 1999).

From the point of view of evaluating consumer benefits from biotechnology innovations, two distinct issues are relevant. First, given that heterogeneous preferences are explicitly allowed in the model, normative general statements about consumer benefits are conceptually problematic; at a minimum, one would need to make conditional welfare statements (e.g., applying to consumers with a preference for traditional non-GMO products or applying to consumers with a preference for innovated products). Postulating that the differentiated demands arise from a representative consumer with preferences over differentiated products (as in the "love of variety" approach of Dixit and Stiglitz 1977) sidesteps such difficulties, but even in this case it is crucial to understand that the market segregation required to deliver such differentiated products entails real resource costs, which will be reflected in the final prices paid by consumers. In other words, consumers can conceivably be made worse off as a result of the introduction of more efficient (but not universally accepted) techniques for producing crops (Giannakas and Fulton 2000).

Whereas such qualitative observations are quite useful, empirical analysis has yet to shed light on the magnitude of the costs and benefits of market segregation for GMO and non-GMO products. In particular, an important element of identity preservation (and more generally of any grading system) is the "tolerance" level that is specified, that is, the acceptable percentage deviation from purity for the trait of interest (Buckwell, Brookes, and Bradley 1999). The notion of GMO-free food sets the highest level of purity, but even the 1 percent threshold level proposed by the EU at this time may entail large real resource costs along the production, marketing, and distribution chain. The very recent StarLink fiasco in the United States (*New York Times* 2000) illustrates the extraordinary difficulties that might be involved in a zero-tolerance system.[8] Thus, the objective to supply GMO-free food is rather ambitious, and it is not clear that cost estimates obtained from existing identity preservation practices (e.g., Bender et al. 1999) provide much guidance for the case of GMOs.

More on Regulation and Public Policy

From the foregoing it is apparent that the evaluation of the total economic benefits flowing from an innovation and the analysis of the distribution of such benefits both horizontally (i.e., between trading partners) and vertically (i.e., between agents involved at various stages of the production and marketing chain) critically depend on a given institutional setting. Regulatory activities, in particular, are crucial to defining a proper institutional setting within which the "market" is then allowed to operate. Insofar as the relevant regulation is induced, as is arguably the case for the innovations at hand, it is necessary to consider its influence on the size and distribution of benefits.

In particular, the mandatory labeling of GMOs and GMO-derived products adopted in the EU, and forthcoming elsewhere, is a highly controversial feature that sets these countries' regulation apart from that of the United States. In the United States, in fact, the predominant view has been that there is no compelling need to label foods obtained from GMOs (Miller 1999a). The regulatory philosophy here is that the "product," rather than the "process," should be the object of concern. If, as is arguably the case for existing products, foods derived from GMOs are substantially equivalent to traditional ones (Miller 1999b), there should be no need to label a GMO food as such.

To evaluate the appropriate policy response to consumer concerns, it is important to first identify the problems that are (allegedly) caused by the introduction of GMOs. Supporters of this regulatory action claim that labeling is essential in order to give consumers a choice on whether to endorse and/or consume products derived from GMOs. At least four reasons are cited as to why consumers should have a right to that choice. First, there is a concern about food safety. It is feared that transferring genetic material from one organism to a completely different one may induce the transformed organism to produce unwanted toxins and allergens. The absence of risk from eating such food, it is claimed, has not been adequately documented. Second, there is concern about the environment. It is feared that the herbicide- and insect-resistant traits of new crops may spread to other plants in the wild; that genetically modified plants may be deleterious to other species; and that specific genetic sequences conferring antibiotic resistance, which are used as “markers” in the genetic engineering process, may unwittingly aid the development of antibiotic resistant germs that could eventually harm humans. Third, some people believe that transferring genetic material between different organisms is unethical. Fourth, others question whether private R&D activities in a rapidly consolidating biotechnology sector is concentrating too much power in the hands of a few multinational companies.

Articulating the rationale for regulating GMOs helps to identify the appropriate policy response for each case. Justifying the labeling requirements with the consumers’ “right to know” argument, for example, has attracted considerable criticism (McHughen 2000). In an abstract sense, it is difficult to argue with the “right” of consumers to know about GMOs. From the point of view of economics, however, demands for more information should be counterbalanced by a consideration of the costs that may be involved in providing the additional information. The costs of GMO-labeling, especially the cost of establishing an identity preservation system, could turn out to be rather sizable.

As for the emerging concern about the increased concentration in the seed and chemical industry (Hayenga 1998), some impetus for this concentration can certainly be ascribed to the particular nature of GMO innovations being developed, which points to a synergism between seed and chemical industries. Also contributing to this concentration is the fragmentation of intellectual property: sometimes consolidation is desirable purely to acquire critical enabling patents that allow firms the freedom they need to pursue specific commercial products. Although some monopoly power due to patents is perfectly legal (and socially desirable, as discussed earlier), the concern here is that this industry concentration may bring about noncompetitive behavior that can harm agriculture. But such concerns about concentration of economic power fall under already established antitrust principles, and should apply equally across the board, in particular to any sector in which patentable R&D is fundamental (such as pharmaceuticals).[9]

Ethical concerns about biotechnology cannot and should not be dismissed summarily. But because ethical concerns can be quite varied across individuals, a private rather than a public response may be appropriate. For example, allowing a voluntary labeling system supported by a tight identity preservation program might in this situation be superior to a mandatory labeling system.

In addressing the issue of "risk" in the context of GMOs, one must recognize that some risks are bound to be associated with any change from the status quo, especially when the change involves a new technology. Indeed, risk taking has been a central theme in the history of scientific and technological progress. Although as a society we accept that some risk is inevitable, there is agreement that innovations that pose some risk may need to be regulated. Still, developed countries have followed very different avenues to regulation. The lack of harmonization is perhaps best illustrated by the differences between the notion of "substantial equivalence" and the "precautionary principle." The notion of substantial equivalence is used widely in the U.S. regulatory system (Miller 1999b). For example, the fact that transgenic soybeans give oil and other products that are essentially the same as those derived from standard soybeans is used to argue that RR soybeans should be treated like traditional soybeans. The precautionary principle, on the other hand, is used as the central concept in European regulation. It states that lack of scientific certainty should not be used as a reason to delay taking precautionary steps (such as banning a product) if there is the possibility of adverse consequences, even when there is no scientific evidence that such negative outcomes are likely and/or probable (Freestone and Hey 1996). To use a metaphor that no doubt oversimplifies the issue, the principle of substantial equivalence presumes that new GMO products are "innocent until proven guilty," whereas the precautionary principle presumes that new GMOs are "guilty until proven innocent."[10]

Reconciling these two regulatory philosophies is bound to be difficult, especially at the international level. The Biosafety Protocol that was agreed upon in Montreal in January 2000, which aims at regulating the international shipment of GMOs, explicitly adopts the precautionary principle. But existing World Trade Organization (WTO) obligations already bind countries to adopt trade policies based on scientific evidence. In fact, one of the fundamental principles under which the General Agreement on Tariffs and Trade (GATT) has operated is that those barriers to trade which are permitted should be transparent. Furthermore, the agreements on technical barriers to trade and on the application of sanitary and phytosanitary measures have stipulated that such measures will be based on scientific principles and scientific evidence (Swinbank 1999). The United States, in particular, insists that reliance on science is critical in preventing the use of health regulations for protectionist purposes, and that maintaining transparent, science-based regulatory procedures also helps to sustain public confidence in the objectivity and reliability of WTO members' public health regimes (Larson 2000).

Future Trends for GMOs in Agriculture

Despite the considerable uncertainty that surrounds biotechnology innovations in agriculture, GMOs will have a crucial role in shaping the future of agriculture. The type of GMOs that will be brought to market will define, to a large extent, the nature of this impact, as well as the size and distribution of associated benefits. A useful distinction, in this context, is between "input traits" and "output traits." All of the very successful GMO innovations to date concern input traits. Although they are embedded in new products (the transgenic seed) they ultimately affect the process of producing a rather standard commodity. They increase efficiency, to be sure, but that is all. "Output traits" brought about by genetic engineering, on the other hand, hold the promise of introducing novel products into the market that will target types of demands that have not been exploited to date.

Current and prospective biotechnology research (Miflin 2000) suggests that in the future we are likely to see a combination of input- and output-trait GMOs come to market. On the input-trait side we can expect more innovation in herbicide tolerance and insect resistance, as well as new crops engineered to be resistant to disease (such as those caused by bacteria and viruses) and to environmental stresses (such as heat and soil salinity). But the major change may be the systematic introduction of output trait crops.

Crops can be manipulated to produce grains and oilseeds with enhanced nutritional value, for example, enhanced vitamin levels, as in the case of the recently announced "golden rice" engineered to produce high levels of provitamin A (beta-carotene). Similarly, researchers are trying to understand and manipulate synthesis of micronutrients to improve crop nutritional quality. For example, work is underway to improve the iron content of rice. Indeed, the new term "nutritional genomics" is being used to describe work at the interface of plant biochemistry, genomics, and human nutrition. Also on the horizon, suitably transformed plants may be used to manufacture a wide list of protein molecules that can be turned into vaccines, industrial enzymes, cosmetics and vitamins.

Evaluation of the benefits of output trait biotechnology innovations will require a different economic framework than that discussed in this paper. It is of course possible to put a monetary value on the introduction of a new product, but at this stage it is premature to attempt such a measurement for output-trait innovations. Because such innovations increase the set of possible demands for agricultural products, however, it is possible that they may bring benefits to all participants in the agricultural marketing chain (including farmers). One additional benefit from output-trait GMOs, routinely cited, is that they may be more attractive to consumers and may remove the hostility toward transgenic crops that besets the current generation of input trait biotechnology innovations.[11]

More generally, the potential market impact of output-trait GMOs fits in well with the emerging trend of agriculture toward targeting differentiated product markets. Specialty crops and organic farming are gaining more importance as they try to tap specific niche markets. But the development of a broad portfolio of output-trait GMOs can considerably accelerate this change toward efficient and specialized differentiated product markets. Such output-trait GMOs will find synergistic reinforcement in the spread of information technology throughout our economy, including the increased relevance of business-to-business and business-to-consumer electronic transactions. Thus, we might soon have a broad array of differentiated products, the informational ability to segment market demand, and the technical ability to deliver in an efficient manner the new products to the consumers that want them.

As this transition to a world of differentiated products takes place, a number of adjustments are likely to emerge in the market organization of the agro-food system. First, identity preservation will be crucial to the delivery of differentiated products. For this reason, the current market resistance toward the implementation of a segregated market system for non-GMO food is possibly misplaced. Perhaps the identity preservation of non-GMO food should be seen as an opportunity to innovate the marketing system so that it can be in a competitive position to handle the demand for differentiated products likely to emerge in the future.

The increased precision and coordination requirements of differentiated product markets will provide incentives for agriculture to become progressively integrated, possibly through the increased use of contracting. Because of the expanded range of possibilities brought about by new information technologies, many feasible configurations of a coordinated system that is market-based and suitable to deliver differentiated products to consumers are possible. Which production decision will be made by whom and who will own and contribute what productive resource in the "value chains" for such differentiated product markets are open questions. But it seems clear that we are moving toward a world where access and control of knowledge and information will matter more and more. In such a setting, the providers of new knowledge and innovations, and the system of intellectual property rights afforded to these innovators, may turn out to be crucial in the division of the sizable economic benefits that are associated with the introduction of output trait biotechnology innovations.

Conclusion

Biotechnology is ushering in a new wave of possibly profound changes in agriculture, the latest instance of a pattern of technical advances that has characterized agriculture (and, for that matter, the rest of the economy) for much of the twentieth century. The economic forces that typically bring about and sustain innovation are very much at work here. New products and processes that are both technically feasible and useful will be developed and adopted in a modern market economy. A particular GMO product may or may not be accepted by the marketplace, but it seems likely that the stream of innovations grounded on genetic manipulations of living organisms is not going to stop.

Innovations bring about sizable economic benefits, which are typically shared across various agents, sectors of the economy, and countries. Biotechnology holds the promise of considerable benefits to society at large, through the introduction of more efficient and more environmentally friendly techniques of producing standard crops, and by the development of a potentially exciting array of new products. Not everyone, of course, is bound to gain from the introduction of a new product and/or process. In this paper I have highlighted some of the features that are likely to be relevant to assess the size and distribution of the benefits and costs of biotechnology innovations. Whereas specific conclusions are difficult at this stage, because they depend on a number of unresolved issues, two sets of considerations appear particularly relevant.

First, biotechnology innovations tend to be produced by private firms and to be protected by IPRs. Private R&D is gaining increasing importance in agriculture, overturning the once dominant position of public R&D. The pricing of the resulting proprietary innovations will necessarily reflect the particular market power that an innovator can exploit. By impacting the pricing and adoption of innovations, IPRs affect the size and distribution of benefits from innovations. Ex post benefits are reduced by the exercise of market power, because an innovated product or process is not used as widely as socially desirable. Perhaps more importantly, the exercise of market power due to IPRs affects the distribution of the net benefits arising from an innovation. Consumers gain less from the introduction of a particular innovation (relative to it being competitively supplied), and farmers' welfare change is also reduced (but because farmers' net benefit could go either way under competitive pricing of the innovation, the impact of IPR pricing per se is ambiguous). Innovators can now directly capture a larger share of the ex post benefits, and a direct consideration of the "innovation industry" turns out to be crucial for the proper assessment of the net benefits from biotechnology. Of course, some ex post efficiency losses are inherent in an IPR system and are generally perceived to be necessary to implement this particular second-best solution to a market failure. A complete analysis would therefore also need to consider the impact that stronger IPRs have on the overall level of R&D.

Second, there is the issue of consumer acceptance of biotechnology innovations, the regulatory responses that are likely induced by these innovations, and, more generally, the evolving market and institutional setting where these innovations take place. Whereas potentially large societal benefits are possible with biotechnology, they may not be realized, or they may be realized only at a large cost to a sizable part of society. For example, an extremely efficient commodity-based system for the provision of basic food ingredients may need to be replaced by a new marketing system characterized by product segregation and identity preservation. Whereas such a system can allow the market to supply an increased array of differentiated products, thereby increasing gross benefits to society, evaluation of the net benefits will need to consider the (potentially sizeable) new costs that such a system entails. Concerns are also being raised about the ability of the market system to handle the new risks that some people associate with biotechnologies. Private firms are obviously not well positioned to internalize costs and benefits for which there are no market transactions. At this point it is crucial to have an effective regulatory system, capable of providing a transparent, objective, and credible institutional framework for GMO innovations to take place.

The above considerations have direct implications for the international distribution of the benefits from biotechnology innovations, and for international trade itself. By their very nature, new biotechnology products can be drastically innovative and thus can affect traditional comparative advantages in production and trade. How this is played out will depend, to a certain extent, on which innovations are actually developed. A recurrent theme on this score, for example, is whether biotechnology R&D is targeting the needs of developing countries as much as it does of developed countries. In any event not only do the new technologies themselves have the potential to affect comparative advantages directly but also indirect effects are likely to be important. Lack of harmonization in IPRs and in government regulation, for instance, can clearly have a large impact on where (and by how much) the new technologies are adopted. Such effects are challenging the current international trade system and call for effective institutional arrangements capable of handling the novel implications of biotechnology innovations.

Endnotes

1. The insight that both centuries may, in fact, be ruled by economics does not seem to command widespread attention.

2. See, for example, the 292 published studies identified in Alston et al. (2000).

3. Differing regulations can explain much of this lopsided pattern. James (2000) lists a total of 12 countries that, to date, are growing some commercial transgenic crops.

4. The first U.S. animal patent, pertaining to the "Harvard oncomouse," was issued in 1988. A patent for this invention was eventually awarded in Canada as well in 2000.

5. In October 1998, Pioneer sued Cargill for selling seed corn that included genetic material that Pioneer owned. This trade-secret litigation was eventually settled in May 2000, with Cargill agreeing to pay $100 million to Pioneer (*Wall Street Journal* 2000). (Also, Cargill had already agreed to return $200 million to Monsanto, from the sale of its international seed business, because of settlement arrangements related to this suit).

6. Moschini and Lapan (1997) show how this can be done by explicitly considering the market for innovated inputs.

7. Somewhat similar conclusions are found in Falk-Zepeda, Traxler, and Nelson (2000), for both cotton and soybeans, although they impute a larger share of the benefits to U.S. farmers and a lower share of the benefits to consumers. Although the model that they use is also rooted in Moschini and Lapan's (1997) framework, the particular parameterization and calibration chosen can account for the nature of their results (when one postulates linear demand and supply functions and parallel shift in supply, as they do, farmers cannot lose from a productivity-enhancing innovation).

8. StarLink is a maize variety developed by Aventis that, in 1998, was approved for animal consumption but not for human consumption by U.S. authorities. This unusual outcome was prompted by the fact that the Bt protein (Cry9C) expressed by StarLink apparently breaks down more slowly in the human digestive system than the proteins expressed by other Bt corn varieties, raising the possibility (not demonstrated at this point) that it might be an allergen. Despite some precautions used by Aventis in marketing this variety, and those used by mills in buying corn destined for human consumption, StarLink found its way into taco shells and a number of other products. Some 300 food products have now been recalled, and a major program (led by the U.S. government and Aventis) is underway to buy out the entire StarLink crop (about 0.5 percent of U.S. corn production) and divert it to animal feed or industrial use.

9. Industry consolidation, of course, is a common feature in many other sectors, and most economists believe that concentration per se is not necessarily associated with noncompetitive behavior.

10. As a counterpoint illustrating that conservative regulation under risk is not just an EU phenomenon, note that the U.S. choice not to approve StarLink maize for human consumption, mentioned earlier, can be viewed as an application of the precautionary principle.

11. For example, a recent survey found that, whereas European consumers' opposition to food containing GMOs is on the rise, these consumers remain supportive of medical and environmental applications of biotechnology (Gaskell et al. 2000).

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