Innovation and Trade with Endogenous Market Failure:

The Case of Genetically Modified Products

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and

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Abstract

We build a partial-equilibrium, two-country model to analyze some implications of the introduction of genetically modified (GM) products. In the model, innovators hold proprietary rights on the new technology, whereas farmers are (competitive) adopters; some consumers deem food produced from GM products to be inferior to traditional food; countries trade both traditional and GM products; countries can adopt regulations (such as mandatory labeling of GM products) that have direct trade implications; and, crucially, the mere introduction of GM crops affects the costs of non-GM food (because it makes it necessary to implement costly identity preservation). The analysis shows that, although agricultural biotechnology innovations have the potential to improve efficiency, some agents (consumers and/or producers that adopt the innovation) can actually be made worse off by the innovation, and indeed it is even possible that the costs induced by the innovation outweigh the efficiency gains. The study also illustrates the potential for protectionist policies that arise in the context of regulating GM products. In particular, mandatory labeling of GM products (as being implemented by the European Union) is unnecessary, inferior to a system of voluntary labeling, and has costly implications from the perspective of an exporting country that adopts GM products. But this costly labeling policy may actually benefit the importing country that implements the labeling requirement.

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I. Introduction

Biotechnology is emerging as one of the fundamental forces that will be shape agriculture in the twenty-first century. Scientific and technological breakthroughs in life sciences are making possible an increasing array of new products that have great potential commercial value and considerable scope for adoption. Among early biotechnology innovations for agriculture, transgenic crops have enjoyed a spectacular diffusion in a very short time. Virtually unknown before 1996, genetically modified (GM) crops engineered to be resistant to some herbicides and/or specific pests are currently estimated to account for 130 million acres worldwide (James, 2001). This success is attributable almost entirely to transgenic varieties of four crops: soybeans, corn, cotton, and canola. But so far, mass cultivation of transgenic crops has been concentrated in only three countries—the United States, Argentina, and Canada—and GM products have elsewhere been greeted by considerable public opposition and have given rise to very restrictive (and increasingly divergent) national regulations.

Much of the controversial GMO regulation, such as mandatory labeling of GM food, ostensibly is in response to consumers' demand for the "right to know" whether or not the food they buy contains GM products. Apparently, GM products are "weakly inferior" goods; that is, final consumers deem food from GM ingredients to be, at best, equivalent to non-GM food, and indeed GM food is considered strictly inferior by some consumers. If the superior product cannot be distinguished from the inferior one, the pooled equilibrium likely to emerge in the market would contain too high a proportion of low quality product, as in Akerlof's (1970) "lemons" model. Regulation in such a setting may be desirable to maintain product diversity, which typically can be efficiently achieved with certification systems paid for by sellers (Beales, Craswell and Salop, 1981). Mandating that GM product be identified by a "GMO label" may seem to address this informational problem and to preserve the consumers' right to choose between GM and non-GM products. But the relevant information needs to be produced before being disclosed to consumers, and in this particular case, the production of information can be quite costly because of the need of "identity preservation" activities in an otherwise commodity-based market. Furthermore, the incentives to incur such information production costs naturally reside with the suppliers of the superior product (the non-GM food), and forcing the suppliers of the inferior good (the GM food) to also incur costs ultimately may be counterproductive from a welfare perspective.

An interesting additional feature of our setting is that the "lemon" problem is due to the innovation process that has brought the new GM products to market. Economic theory suggests that a new product will not be introduced unless it is profitable for the innovator to do so. Furthermore, if existing markets are competitive and distortion free, then the potential profitability of the innovation typically implies that its adoption is welfare enhancing. The case of new GM products—which are potentially inferior to, but not readily distinguishable from, existing products—is a possible exception to this generalization because the introduction of these products may be viewed as creating a negative externality that raises production costs for existing producers. The negative externality arises because, when both goods are present in a given market, distinguishing GM from non-GM products entails real costs (to segregate and test products in order to preserve the identity of the superior product). In this sense, the "lemons" market failure is endogenous to the innovation process. In such an environment, whether private decisions (by GM product innovators) will be socially optimal needs to be ascertained, and in fact there may be scope for government intervention that can be welfare enhancing.

In this paper we address some of the critical economic issues that arise because of the biotechnology innovation in the agricultural and food industry, with particular emphasis on the international trade implications. Interest in international economic issues in this context is natural given that the three countries that have embraced GM crops are also large exporters of agricultural commodities, while the most restrictive domestic regulations aimed at genetically modified organisms (GMOs), which necessarily interfere with imports, are being implemented by countries that are natural importers of agricultural products. Specifically, to address the international trade implications of GM product innovation, in this paper we build a partial-equilibrium, two-country trade model that captures some critical elements of the problem at hand. On the supply side, the model explicitly represents the interplay between a monopolistic innovator that sells the seeds of new GM crops and a farming industry that implements these innovations subject to the adoption incentives of a competitive industry (Lapan and

Moschini, 2000). On the demand side, the model allows for differentiated demand for GM and non-GM products, with the former being modeled as weakly inferior goods. Furthermore, the analysis of market equilibrium explicitly models the effects of segregation and identity preservation costs that are necessary in order to meet the differentiated demands for GM and non-GM products. A number of questions, related to both the introduction of new GM products and the effects of regulation and GMO labeling requirements, are investigated. A country's decision to impose GMO labeling requirements, or to enforce standards banning importation of some GM products, has immediate implications for international trade and may entail welfare redistribution effects across national boundaries. The specific impacts that arise from the need for segregation and identity preservation to meet GMO labeling requirements are also studied.

II. Background

Agricultural biotechnology innovations that have been most successful to date are crops that have been modified to express a particularly useful agronomic trait that allows a reduction in production costs and/or an increase in yields. As illustrated in Table 1, most of the area planted to GM crops currently affects four commodities: soybeans, cotton, corn, and canola. For soybeans and canola, the transgenic attribute is that of herbicide resistance, whereas for cotton and corn, both herbicide resistance and insect resistance have found widespread adoption. For example, the "Roundup Ready" (RR) varieties of these crops 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). Although at least 12 countries are growing some commercial transgenic crops (James, 2001), Table 1 shows that 98% of current GM crop production takes place in three countries: the United States, Canada, and Argentina.

The geographical concentration of production for GM crops can be explained mostly by restrictive regulations in many countries, justified by apparent public opposition to the introduction of

GM products.[1] The experience of the European Union (EU) is emblematic in this setting. The earlier regulatory approach to these new crops was not unlike that of the United States, and 18 products were approved prior to 1998. But following considerable public resistance and mounting consumer concerns, the EU instituted a *de facto* moratorium on new approvals, pending an extensive re-examination of the regulatory framework for GM products that is, to this day, unresolved. No new GM varieties have been approved since October 1998; in fact, many EU countries have taken steps to unilaterally ban, within their own national borders, products already approved in the EU.

A major element of existing and forthcoming EU regulations is the requirement that food and feed consisting of, or produced from, GM crops be clearly labeled as such, and that a system be instituted to guarantee full traceability of products put on the marketplace (Commission of the European Communities, 2001). The stated objective for such regulations is to protect human health by achieving a high degree of food safety, to protect the environment, and to ensure consumers' "right to know." The mandatory labeling requirement will apply to feed produced from GM crops (such as corn gluten feed and soybean meal) and also to food products from GM products even when they do not contain protein or DNA from the GM crop (such as soybean oil or corn syrup). Extensive testing (for GM content) of all import shipments is envisioned, as well as extensive record keeping to ensure traceability. But the proposal also allows for a 1% adventitious presence of (authorized) GM products in food that will not need to be labeled.[2] Although the proposed EU rules might be the toughest yet proposed, they are part of a wider trend. At least 16 countries, in addition to the EU, have adopted or announced plans to implement mandatory labeling of GM products.

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[1] At least four reasons typically are cited for this opposition: food safety risk, concern about the environment, ethical beliefs, and the concentration of ownership of these new crops in the hands of a few multinational companies.

[2] But, of course, zero tolerance applies for unauthorized GM products. Because a number of GM products approved in the United States are not yet authorized in the EU, the implicit requirement of zero tolerance for such GM products is bound to impose strains on international trade.

Mandatory labeling of GM products adopted in the EU, and forthcoming elsewhere, is a highly controversial feature that sets regulation in these countries apart from that of the United States. In the United States, the predominant view has been that there is no compelling need to label foods obtained from GM products, based on the regulatory philosophy that the “product,” rather than the “process,” should be the object of concern (Miller, 1999a). If, as is arguably the case for existing products, foods derived from GM products are substantially equivalent to traditional ones (Miller, 1999b), there should be no need to label a GM food as such. In the United States, and in a handful of other countries including Canada, labeling of GM products is envisioned to be only on a voluntary basis and subject to some restrictions on the possible claims (U.S. FDA, 2001).

The labeling of GM products seems to make possible the emergence of differentiated demand for agricultural products that have been traded, to date, in commodity markets. But to be able to tap the underlying differentiated demand, it is necessary to keep GM products and non-GM products segregated at all stages of production, marketing, and processing, that is, an “identity preservation” (IP) system is needed. IP systems have emerged independently of GM crop adoption, as part of a pre-existing trend of specialty crops (such as high-oil corn and synchrony-treated soybeans) and organic farming that tries to tap specific niche markets. But a crucial element of IP systems is the specified “tolerance” level, that is, the acceptable percentage deviation from purity for the trait of interest. The notion of GM-free food sets the highest level of purity; even the 1% threshold level proposed by the EU is unusually strict (compared with pre-existing IP systems) and may be challenging. Hence, it may be very costly and difficult to keep GM and traditional products strictly separated (Bullock, Desquilbet and Nitsi, 2000; Desquilbet and Bullock, 2001).

Also, somewhat paradoxically, innovation here is bringing about goods that are considered by some consumers to be weakly inferior. At best, consumers may be indifferent between GM and non-GM food, and some consumers may in fact strictly prefer non-GM food. Indeed, even the mere presence of trace amounts of an unwanted product may be unacceptable, as illustrated by the recent StarLink fiasco.[3] Thus, the premium good in this setting is the pre-existing traditional (non-GM) food. It follows that, unlike the case of existing specialty crops mentioned earlier, adopters of new GM crops have no incentive to set up an IP system to keep their output segregated from non-GM crops.

Finally, it is necessary to note that the new GM crops in agriculture have been developed by the seed and chemical industries that supply inputs to agriculture, are protected by intellectual property rights (IPRs), and are being marketed by a small number of seed companies that can exploit the market power endowed by their ownership of this intellectual property. Patents and other IPRs of course play a fundamental role in the development and marketing of innovations in many industries, and since the landmark 1980 U.S. Supreme Court decision of *Diamond v. Chakrabarty,* utility patents increasingly have been used for biotechnology innovations (Heisey, Srinivasan and Thirtle, 2001). Effective IPRs essentially endow innovators with monopoly power, such that they can use their discovery exclusively or they can license it to others for a fee. The particular organization of agricultural production, distinguished by structural features typically leading to small production units (Allen and Lueck, 1998), makes the first option unworkable for the case of GM crop innovations, and the second solution applies. For example, the new Roundup Ready soybean technology has been transferred to U.S. farmers by written licenses in exchange for a "technology fee"—effectively a price premium that, in the last few years, has entailed a 40% markup on the corresponding conventional crop seed prices (U.S. GAO, 2000). The market power of GM seed suppliers influences the price that can be charged for these innovated inputs, and the pricing of the innovations in turn affects their adoption and the resulting private and social benefits and costs. To accurately model the production, trade, and welfare effects of new GM crop introduction, it is therefore

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[3] Starlink is an insect-resistant GM corn variety developed by Aventis that, in 1998, was approved by the Environmental Protection Agency for animal feed use but not for human consumption. But in September 2000 it was discovered that flour from this corn variety had found its way into many food products. Apparently, Aventis had failed to enforce a suitable IP system to segregate this corn variety. The incident led to the recall of over 300 food products and the implementation of a massive Starlink corn buyback program (led by the USDA), as well as numerous lawsuits, at a cost estimated in the hundreds of millions.

necessary to explicitly model the particular structure that characterizes these privately produced innovations in agriculture (Moschini and Lapan, 1997).

III. The Model

We develop a two-country, partial equilibrium model of an agricultural industry. Initially, both countries produce and consume the traditional non-GM product, and there is free trade, with the home country being the exporter and the foreign country being the importer. For simplicity, and to gain a modicum of real-world relevance, we will label the home country as "United States" and the foreign country as "Europe." The GM product is developed by a U.S. firm that, by virtue of having secured IPRs on this discovery, behaves as a monopolist for the seed of the new GM crop. The exercise of the monopoly power is constrained by availability of non-GM seed, which is competitively supplied. The GM product is adopted only in the United States,[4] which then can conceivably export both GM and non-GM output to Europe. Whether that will be the case in equilibrium depends, in addition to the decisions of the monopolist seed supplier, on consumer preferences for the new product and on possible regulations and/or protectionist policies by the importing country. Whereas consumers in the United States are assumed to be indifferent between the old non-GM product and the new GM product, consumers in Europe view the two products as imperfect substitutes and, in particular, treat the new GM product as a weakly inferior product. More details on the specification of demand and supply functions follow.

A. Supply

In the United States there is a fixed amount of land L that can be allocated either to producing the non-GM crop or the GM crop (presently we will discuss how the model can be generalized to make

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[4] Although here we limit our analysis to this setting, it is of course possible to contemplate the case where the GM product is adopted both at home and abroad. The additional complication (and interesting feature) of such an extension is that the United States would then export both the final agricultural products as well as the intermediate input (the GM seeds) that make foreign GM production competitive with the domestic GM output. Such an international spillover of technological innovation of course has welfare effects for the innovating country, as well as implications for appropriate commercial policy.

this amount of land endogenous). All variables pertaining to the traditional non-GM good are superscripted by n, whereas those pertaining to the new GM product are superscripted by g. It is assumed that there is a continuum of land quality, indexed by *z*, with density function $\theta(z)$.[5] By convention, land quality decreases with *z,* so that the total amount of land at least as good as type z (i.e., with index no larger than *z*) is

$$(1) \qquad \Theta(z) \equiv \int_{q=0}^{z} \theta(q)\,dq \ .$$

Because we are assuming that the amount of land available for production in this industry is fixed, we normalize $z \in [0,1]$, and thus $\Theta(1) = L$ denotes the total available land.

Land of type z allocated to the production of non-GM products yields a per-acre profit of $\pi\left(p^n, z\right)$, where p^n is the price farmers receive for their non-GM output. This profit is net of the cost of non-GM seeds, which are assumed to be produced under competitive conditions with constant unit cost. Production of GM crop requires improved seeds sold by a monopolist. To simplify the analysis that follows, as in Moschini, Lapan and Sobolevsky (2000), we assume that farmers use a constant seed density. Thus, if α denotes the amount of seed per acre, and τ denotes the premium of GM seed price over the price of non-GM seeds (the "technology fee" that is charged by the monopolist seed supplier), the per-acre profit for the GM crop on land of type *z* is written as $\tilde{\pi}\left(p^g, z\right) - \alpha\tau$, where p^g is the price of the GM output produced by farmers.

It is assumed that GM crops are a true technological innovation from the farmers' point of view—given the same seed prices and the same output prices, the GM technology would yield a higher per-acre profit. To capture farm heterogeneity with respect to the new GM technology, we also assume that the larger profit due to GM crops varies according to the land index. By convention, we assume that low indexed land is land on which GM crops are most productive. Furthermore, as a normalization, we

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[5] Alternatively, one can think of *z* as indexing farmers, whose farms are of a given acreage size.

assume that all land is equally productive in terms of the existing (non-GM) technology and therefore $\pi\left(p^n,z\right)=\pi\left(p^n\right),\forall z$. These two assumptions imply that

$$(2) \qquad \tilde{\pi}(p,z)>\pi(p) \qquad \forall z,p$$

$$(3) \qquad \tilde{\pi}\left(p^g,z\right)>\tilde{\pi}\left(p^g,k\right) \qquad \text{whenever } z<k .$$

Naturally, this does not necessarily imply that only GM crops are grown, because (i) the monopoly supplier of GM seeds will charge a premium for them; and (ii) if the two outputs are perceived as imperfect substitutes in consumption, then it may be that $p^g<p^n$.

The adoption of GM crops by a competitive farmer of type z will be profitable if

$$(4) \qquad \tilde{\pi}\left(p^g,z\right)-\alpha\tau\geq\pi\left(p^n\right) .$$

If the inequality holds for all land types (i.e., if $\tilde{\pi}\left(p^g,1\right)-\alpha\tau\geq\pi\left(p^n\right)$), then adoption will be complete. Otherwise, the marginal adopter, indexed by $\hat{z}=\hat{z}\left(\tau,p^n,p^g\right)$, is determined by

$$(5) \qquad \tilde{\pi}\left(p^g,\hat{z}\right)-\alpha\tau=\pi\left(p^n\right) .$$

Hence, a monopolist choosing the seed price premium τ will sell a total amount of seed $\alpha\Theta\left(\hat{z}\right)$ and will determine the marginal adopting farm $\hat{z}$. Alternatively, we can think of the monopolist as choosing the marginal farmer $\hat{z}$ directly, with the seed price premium τ determined by equation (5). For modeling convenience, in what follows we opt for the latter approach. The profit of the monopolist supplying GM seeds is therefore given by

$$(6) \qquad \Pi^M\left(p^n,p^g,\hat{z}\right)=T\left(\hat{z},p^g,p^n\right)\Theta\left(\hat{z}\right)$$

where $T\left(\hat{z},p^g,p^n\right)\equiv\tilde{\pi}\left(p^g,\hat{z}\right)-\pi\left(p^n\right)$ is the per-acre premium on GM seed that the monopolist can obtain when it chooses the marginal farm $\hat{z}$.

Given $\hat{z}$ as determined by the innovator/monopolist's choice, the supplies of non-GM and GM products are

$$S^n\left(p^n,\hat{z}\right)=\int_{z=\hat{z}}^{1}\pi_p\left(p^n\right)\theta\left(z\right)dz \quad =\left[L-\Theta\left(\hat{z}\right)\right]\pi_p\left(p^n\right) \tag{7}$$

$$S^g\left(p^g,\hat{z}\right)=\int_{z=0}^{\hat{z}}\tilde{\pi}_p\left(p^g,z\right)\theta\left(z\right)dz \tag{8}$$

where, again, L is the exogenously given land, $\Theta\left(\hat{z}\right)$ is the amount of land allocated to the GM crop, and $L-\Theta\left(\hat{z}\right)$ is the amount of land allocated to the traditional crop.[6] The pre-innovation situation is obtained simply by letting $\hat{z}=0$.

Finally, the results of this paper can be made sharper under the assumption that GM and non-GM crops have the same yield (per-acre production) function, that is, when

$$\tilde{\pi}_p\left(p,z\right)=\pi_p\left(p\right) \quad \forall p,z \qquad \rightarrow \qquad \tilde{\pi}\left(p,z\right)=\pi\left(p\right)+\eta\left(z\right) . \tag{9}$$

From a modeling standpoint, this assumption allows us to ignore the welfare implications of changes in yield and the ensuing need to recognize that optimal trade policy depends on acreage allocation. But we note that this assumption of equal yields may be appropriate anyway for innovations that are essentially cost reducing (the most important attribute of GM crops that are herbicide-resistant, for example).

Supply conditions in Europe are modeled in a similar fashion under the assumption, mentioned earlier, that the foreign country produces only the non-GM product. Throughout, we use an overbar to denote variables pertaining to Europe (the foreign country). Specifically, if $\kappa(\overline{p}^n)$ denotes the per-acre

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[6] This analytic framework can be readily generalized to make the total amount of land allocated to GM and non-GM crops endogenous. That can be accomplished by specifying an upward-sloping supply of land to this industry that depends on the profitability of the industry, $L(r)$, say, where r is the unit rent (the per-acre profit). Because of our assumption of heterogeneous land quality, what matters here is the rent on the marginal land (the quality of which makes its use in this industry indifferent to its next best use). Hence, the index of land quality in this industry satisfies $z\in[0,z^u]$, where z^u denotes the upper limit on the quality of land in this industry, and total land used is $\Theta(z^u)$. When some land in this industry is allocated to non-GM product, land rent on marginal land is $r=\pi(p^n)$. Thus, given p^n, the quantity of land used in this industry satisfies $L\left(\pi(p^n)\right)=\Theta(z^u)$. This relation determines $z^u=z^u(p^n)$, which defines the upper bound of the distribution of land under cultivation in this industry.

profit in production of non-GM output and $\bar{L}$ is the land allocated to this industry in Europe, the supply of non-GM product in this region is

$$\bar{S}^n\left(p^n\right)=\bar{L}\kappa_p\left(\bar{p}^n\right) \quad . \tag{10}$$

The assumption that the GM good is produced only in the United States is made so that the analysis can emphasize the trade implications of GM product introduction and of GM regulation by the importing country. If there were transportation costs in the model, then it is quite likely that Europe would not produce the GM crop if it had a strong preference for the non-GM variety.

B. Demand

In both countries we postulate a continuum of households with preferences defined over the consumption of the non-GM product N, of the GM product G, and of a composite (numéraire) good. But whereas we postulate that goods N and G are imperfect substitutes in Europe, we assume that these goods are perfect substitutes in the United States. Because of that, it is useful to consider the preferences of European consumers first. Assuming that the households' utility function is quasilinear in the numéraire good, individual preferences can be exactly aggregated, and the aggregate indirect utility function can be written as

$$\bar{V}\left(\bar{y},\bar{p}^g,\bar{p}^n\right)=\bar{y}+\bar{\phi}\left(\bar{p}^g,\bar{p}^n\right) \tag{11}$$

where $\bar{y}$ is aggregate income. Although exact aggregation holds here, there need not be any normative significance to this aggregate utility function.[7] But by Roy's identity, this aggregate utility function yields aggregate demands:

$$\begin{aligned}\bar{G}^* &= -\bar{\phi}_g\left(\bar{p}^g,\bar{p}^n\right)\equiv\bar{D}^g\left(\bar{p}^g,\bar{p}^n\right)\\ \bar{N}^* &= -\bar{\phi}_n\left(\bar{p}^g,\bar{p}^n\right)\equiv\bar{D}^n\left(\bar{p}^g,\bar{p}^n\right).\end{aligned} \tag{12}$$

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[7] A welfare interpretation is possible, however, if interpersonal transfers (through the numeraire good) are feasible, and that is what we will assume in the welfare analysis of this paper.

Throughout the paper we shall assume that good G is weakly inferior relative to N, such that $\overline{G}^* = 0$ if $\overline{p}^g \geq \overline{p}^n$. Furthermore, the assumption that the two goods are substitutes of course implies that $\left(\partial\overline{D}^g/\partial\overline{p}^n\right) = \left(\partial\overline{D}^n/\partial\overline{p}^g\right) \geq 0$. Convexity of the aggregate indirect utility function in prices guarantees that $\partial\overline{D}^n/\partial\overline{p}^n \leq 0$, $\partial\overline{D}^g/\partial\overline{p}^g \leq 0$, and $\left[\left(\partial\overline{D}^g/\partial\overline{p}^g\right)\left(\partial\overline{D}^n/\partial\overline{p}^n\right) - \left(\partial\overline{D}^g/\partial\overline{p}^n\right)\left(\partial\overline{D}^n/\partial\overline{p}^g\right)\right] \geq 0$. In the analysis that follows, we will find it convenient to appeal to one more assumption, which we state as:

CONDITION 1. For both GM and non-GM demands, the own-price effects are at least as large as the cross-price effects, i.e., $\left|\partial\overline{D}^n/\partial\overline{p}^n\right| \geq \left|\partial\overline{D}^n/\partial\overline{p}^g\right|$ and $\left|\partial\overline{D}^g/\partial\overline{p}^g\right| \geq \left|\partial\overline{D}^g/\partial\overline{p}^n\right|$.

Note that convexity of $\overline{\phi}$ implies that either $\left|\partial\overline{D}^n/\partial\overline{p}^n\right| \geq \left|\partial\overline{D}^n/\partial\overline{p}^g\right|$ or $\left|\partial\overline{D}^g/\partial\overline{p}^g\right| \geq \left|\partial\overline{D}^g/\partial\overline{p}^n\right|$ must hold. The additional bite of Condition 1 is to assume that both inequalities are satisfied, which can be interpreted as maintaining a notion of generalized substitutability among goods.[8]

For the United States, we similarly postulate a continuum of households with quasi-linear preferences, such that the aggregate indirect utility function would be written as

$$V\left(y, p^g, p^n\right) = y + \phi\left(p^g, p^n\right) . \tag{13}$$

But because we shall assume that consumers in the United States treat the GM and non-GM good as perfect substitutes, the aggregate indirect utility function specializes to

$$V\left(y, p\right) = y + \upsilon\left(p\right) \tag{14}$$

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[8] Let $\overline{p}^m$ denote the price of the numéraire good m, such that the demand for goods N and G are written as $\overline{D}^i\left(\overline{p}^n/\overline{p}^m, \overline{p}^g/\overline{p}^m\right)$, $i = \{n, g\}$. Then, $\partial\overline{D}^i/\partial\overline{p}^m = -\left(1/\overline{p}^m\right)\left[\left(\partial\overline{D}^i/\partial\overline{p}^i\right)\overline{p}^i + \left(\partial\overline{D}^i/\partial\overline{p}^j\right)\overline{p}^j\right]$, $i, j = \{n, g\}$ and $i \neq j$. Hence, Condition 1 ensures that $\partial\overline{D}^i/\partial\overline{p}^m \geq 0$, $i = \{n, g\}$, when evaluated at $\overline{p}^n = \overline{p}^g$ (i.e., at this point the GM and non-GM goods behave as substitutes with respect to the numeraire good).

where $\upsilon(p) \equiv \phi(p,p)$, and $p = \min\{p^g, p^n\}$. Thus, by Roy's identity, the aggregate demand in the United States is given by $D(p^g) = -\upsilon'(p^g)$ if $p^g \le p^n$, and $D(p^n) = -\upsilon'(p^n)$ if $p^g \ge p^n$.

IV. GMO Innovation and Trade with Costless Identity Preservation

To understand the effects of innovation when GM and non-GM products are seen as imperfect substitutes, it is useful to first analyze the situation where the two varieties can be segregated at zero cost. Intuitively, under the three assumptions that (i) yields are the same on the GM and non-GM product, (ii) identity preservation costs are zero, and (iii) U.S. consumers are indifferent between the two varieties, the introduction of the GM good should have no effect on market price provided that the output of the GM good is less than U.S. consumption. As GM production initially increases, all that happens is that U.S. consumers substitute the GM variety for the non-GM variety, while U.S. exports remain composed entirely of the non-GM variety. Provided that total GM output is smaller than total U.S. consumption, increased plantings of the GM variety will have no price effects. However, once the land allocated to the GM variety reaches that critical level where GM production just equals U.S. consumption, any further allocation of land to the GM variety will reduce the potential exports of the GM-free good to Europe, and prices must respond to ensure that markets clear. Thus, there is a critical value of land allocation (z^0) such that if the amount of land allocated to the GM variety is less than z^0, there are no price effects, whereas for land allocations above that level, the prices of the GM and non-GM products will differ and will change as GM plantings increase.

Turning to the formal analysis, the supply equations in the United States are as outlined in (7) and (8), whereas U.S. demands are derived from (14), with $p = p^g \le p^n$. Note that if $p^g = p^n$, U.S. consumers are strictly indifferent as to which good they buy, whereas for $p^g < p^n$ they will buy only the GM product. On the other hand, demands in Europe are given by (12), with the demand for the GM product equal to zero if $p^g \geq p^n$.[9] Given the aggregate sales of GM seeds chosen by the monopolist, the marginal farm $\hat{z}$ is determined, and final product supplies are given by equations (7), (8), and (10).

The U.S. excess demand for GM products $X^g\left(p^g, p^n, \hat{z}, \psi\right)$ can be written as[10]

$$X^g\left(p^g, p^n, \hat{z}, \psi\right) \equiv \psi D\left(p^g\right) - S^g\left(p^g, \hat{z}\right) \tag{15}$$

where $\psi = 1$ if $p^g < p^n$, $\psi \in [0,1]$ if $p^g = p^n$, and $D\left(p^g\right) = -\upsilon'\left(p^g\right)$. Similarly, the world excess demand for the non-GM output is given by

$$X^n\left(p^n, p^g, \bar{p}^n, \bar{p}^g, \hat{z}, \psi\right) \equiv \bar{D}^n\left(\bar{p}^n, \bar{p}^g\right) + (1-\psi) D\left(p^g\right) - S^n\left(p^n, \hat{z}\right) - \bar{S}^n\left(\bar{p}^n\right) . \tag{16}$$

Given that here we have no trade barriers, $p^n = \bar{p}^n$ and $p^g = \bar{p}^g$.

Suppose that $p^n = p^g = p$ (so that $\bar{p}^n = \bar{p}^g = p$). If there exists p^e and $\psi^e \in [0,1]$ such that $X^n\left(p^e, \psi^e, \hat{z}\right) = X^g\left(p^e, \psi^e, \hat{z}\right) = 0$, then this constitutes an equilibrium, with both goods being consumed in the United States for $\psi \in (0,1)$ and only the non-GM good being consumed in Europe.

PROPOSITION 1. Let p^0 denote the equilibrium price of the non-GM good prior to the introduction of the GM product, let z^0 be defined by $\Theta\left(z^0\right)\tilde{\pi}_p\left(p^0\right) = D\left(p^0\right)$, and assume that yields on the GM crop and on the traditional crop are identical. Then, for all levels of GM seeds sales such that $\hat{z} \leq z^0$, equilibrium prices are such that $p^g = p^n = p^0$. Hence, for all $\hat{z} \leq z^0$ the introduction (and adoption) of the GM crop does not affect domestic or foreign consumers, nor does it affect domestic or foreign producers of the non-GM crop. Economic efficiency and the profits of the GM crop producers increase as $\hat{z}$ increases.

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[9] In terms of modeling, it would make little difference if there were a mass of consumers in the foreign country who were indifferent between the two varieties.

[10] Clearly, no meaningful equilibrium, in which the GM crop is produced, occurs for $p^g > p^n$.

Proofs are relegated to the Appendix. For low levels of GM adoption, output prices are unchanged, and thus neither consumers nor producers of the non-GM product are affected. Given that yields for the two varieties are equal, the price per acre to farmers of GM seeds is $T\left(p^n, p^g, \hat{z}\right) = \tilde{\pi}\left(p^g, \hat{z}\right) - \pi\left(p^n\right) = \eta\left(z\right)$, and since $\eta'\left(\hat{z}\right) < 0$, then $T_z < 0$, so that GM farmers gain as $\hat{z}$ increases. Further, aggregate (GM plus non-GM) output stays the same, but production costs decline as $\hat{z}$ increases. Thus, as long as we are in a domain where the goods are perfect substitutes to U.S. consumers, economic efficiency must increase.[11]

The optimal marketing decision for the monopolist seller of GM seeds depends upon the rate at which profitability declines as use expands and upon the density of users. *A priori*, it is not possible to specify whether the monopolist's optimal sales of seed will entail selling to producers beyond z^0. Assuming that Π^M is concave in z, then, from (6), $\left\{T_z\left(p^0, p^0, z^0\right)\Theta\left(z^0\right) + T\left(p^0, p^0, z^0\right)\theta\left(z^0\right)\right\} \le 0$ guarantees that $\hat{z} \le z^0$, such that the equilibrium output price will be unaffected by the introduction of the GM crop, and no GM product will be exported.

But it is quite possible that the optimal sales of GM seeds by the monopolist, absent trade barriers, is large enough such that $\hat{z} > z^0$. In that case, an equilibrium requires $p^n > p^g$. Furthermore, in this equilibrium some GM product will be exported if $\bar{D}^g\left(\bar{p}^g, \bar{p}^n\right) > 0$. For this case, equilibrium prices are determined from

$$(17) \qquad D\left(p^g\right) + \bar{D}^g\left(\bar{p}^g, \bar{p}^n\right) - S^g\left(p^g, \hat{z}\right) = 0$$

$$(18) \qquad \bar{D}^n\left(\bar{p}^n, \bar{p}^g\right) - S^n\left(p^n, \hat{z}\right) - \bar{S}^n\left(\bar{p}^n\right) = 0 \quad .$$

Totally differentiating (17) and (18) yields the comparative statics effects of a change in the adoption rate of the new technology on equilibrium prices. Because in this case we have $p^g < p^n$, actual yields per

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[11] Recall that we assume the economic (marginal) cost of producing GM and non-GM seeds is the same.

acre will be higher on non-GM lands and thus, given prices, total output (GM plus non-GM product) declines as land planted with the GM crop expands. Convexity assumptions by themselves, however, are not sufficient to determine the comparative static results, but Condition 1, stated earlier, permits the following conclusion.

PROPOSITION 2. Given Condition 1 and $\hat{z} > z_0$, (i) the equilibrium price of the non-GM product increases as GM crop cultivation increases, i.e., $\left(dp^n / d\hat{z}\right) > 0$; (ii) the price of the non-GM product must rise more than that of the GM product as cultivation increases, i.e., $\left(dp^n / d\hat{z}\right) > \left(dp^g / d\hat{z}\right)$.

Intuitively, one would think that the price of the GM product must fall as acreage allocated to it rises, but this is not necessarily true because, given prices, total output declines and because the GM and non-GM products are (potentially) close substitutes. Thus, one cannot rule out the possibility that $\left(dp^g / dz\right) \geq 0$. However, Proposition 2 ensures that, even if the price of the GM product increases, it increases less than the price of the non-GM product.

From a welfare perspective, efficiency would entail adoption of the GM product until profits per acre were the same for each type of crop. But it is clear that monopoly pricing of the innovation leads to lower levels of adoption. Thus, if the monopolist chooses to expand GM acreage (by selling more seeds), it must increase overall welfare. However, that does not mean that everyone gains from this expansion in GM acreage.

PROPOSITION 3. When $\hat{z} > z^0$, so that $p^g < p^n$, increased GM seed sales lower Europe's welfare if its imports of the non-GM product exceed those of the GM product.

Proposition 3 establishes that the foreign country is hurt—at least over some domain—through increased GM plantings in the United States. Note that this result occurs even though there are no market failures present (given that, at this point, identity preservation is assumed to be costless) and it can occur even if Europe imports no GM product. As is now apparent, the result here is due to the terms-of-trade impact on the foreign country's primary imports (non-GM product). The increased acreage of GM crop must increase the price of non-GM output, and this must hurt importers who predominantly buy this product. It is interesting to note, however, that European farmers actually gain from increased GM plantings in the United States. Also, note that Europe need not lose everywhere: when GM imports become important enough, Europe may benefit from the terms-of-trade changes.

V. The Impact of Costly Identity Preservation

As previously discussed, the introduction and adoption of a GM crop creates a situation whereby European consumers view GM and GM-free products as imperfect substitutes but cannot distinguish between the two products simply through taste or visual experience. To meet this differentiated demand, sellers must undertake a costly system of identity preservation (IP). Specifically, we assume that, if both GM and non-GM goods are produced in a given country, then establishing that a particular output is GM-free entails segregation and verification costs. If only the non-GM product is grown in a country, however, then verification costs are unnecessary. This framework implies that the introduction of GM production into a region involves an externality that imposes costs on the (verified) output of another good. However, because the externality depends on the simple presence of some GM output but is not monotonically related to the level of output of the GM product, conventional policies like Pigouvian taxes on GM production or GM seed sales are not the efficient solution.[12]

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[12] This is the case unless efficiency entails no output of the GM product, in which case a large enough per-unit tax could support that outcome. Note that the IP costs associated with the GM product introduce a non-convexity into the production set.

As in the prior section, if U.S. consumers consider the GM and GM-free goods to be perfect substitutes, there should be a range of GM plantings over which prices are independent of any *change* in the level of such plantings. However, because of the IP costs, the introduction of the GM product in the United States imposes costs on producing (and identifying) the GM-free product. Thus, if p^0 denotes the price of the (GM-free) product prior to the introduction of the GM good, we expect that the introduction of GM production in the United States will cause a discontinuous drop in (farm-level) prices in the United States and an increase in prices in Europe (where no IP costs are incurred on production). However, as long as U.S. GM production is less than U.S. consumption (i.e., for $\hat{z} \in \left(0, z^0(c)\right)$), increases in GM production will not affect prices. Beyond this critical level, we expect that increased GM production will cause the farm-level price of the GM-free good to increase relative to that of the GM product.

The formal analysis requires us to distinguish between the output of soybeans produced with non-GM seeds in a region and the availability of *verified* non-GM product from that region. Thus, we use the notation {*f,b*} to label the variables corresponding to the "verified GM-free" and "GM (or blend)" output, respectively, instead of the earlier notation of {*g,n*}. We do so to reflect, as described earlier, the extra step of verification that is required once the GM product is introduced. Thus, p^n and p^g now denote U.S. producer prices (farmgate prices), whereas p^f and p^b denote consumer prices. Clearly, $p^n \geq p^g$, because the non-GM product can always be sold without verification (to be marketed as part of the "blend" product), and $p^b \leq p^f$, because nobody strictly prefers the GM product (and the blend output is treated just like the GM product). Furthermore, if c denotes the unit segregation/verification cost, then $p^f = p^n + c$, and $p^g = p^b$. The absence of trade barriers (apart from IP costs) implies that $\overline{p}^f = p^f$ and $\overline{p}^b = p^b$. Since no GM product is grown in Europe, we assume that no IP costs are required for product grown in that region, and hence $\overline{p}^n = \overline{p}^f$ (of course, $\overline{p}^g$ is meaningless for this region).

With this introduction in place, we now analyze how identity preservation costs affect the equilibrium and conclusions of the previous section. As an initial reference point, consider the free trade pre-GM equilibrium. Assume demands are given from the indirect utility functions of section 3 with the price of the GM good set high enough so its demand is zero ($p^b \geq p^f$ suffices). Because in the pre-innovation equilibrium no GM good is produced, there are no verification costs, implying consumer and producer prices are equal, while free trade equates prices across the two countries. Thus, there is only one price, whose equilibrium level p^0 is determined by

(19) $$L\pi_p\left(p^0\right) + \bar{L}\kappa_p\left(p^0\right) - D^f\left(p^0\right) - \bar{D}^f\left(p^0\right) = 0$$

where $D^f\left(p\right) = -\upsilon'\left(p\right)$ and $\bar{D}^f\left(p\right) = -\bar{\phi}_f\left(p, p\right)$. As mentioned earlier, it is assumed that the United States is an exporter in this equilibrium, i.e., $L\pi_p\left(p^0\right) > D\left(p^0\right)$.

Now consider the introduction of the GM product, which we assume is grown only in the United States. Under our IP cost assumptions, segregation and verification costs in Europe are required only for imports, and these costs essentially act like an import tariff in which the tariff revenue is dissipated. The ensuing analysis needs to distinguish two cases, which depend on whether or not the farmgate prices of non-GM and GM products are equal in the United States, which in turn depends on the $\hat{z}$ determined by the monopolist's pricing of GM seed. Because verification costs are absent in the foreign country, the price received by foreign farmers for the non-GM product will differ from that received by U.S. farmers.

It is useful to break the analysis into stages, and take $\hat{z}$ as given initially. As discussed earlier, for a given GM acreage, there are two possibilities: (i) at $p^n = p^g$ the supply of non-GM product exceeds European (excess) demand; or (ii) at $p^n = p^g$ there is an excess demand for the GM-free product. In the first case, the U.S. farmgate prices for the two varieties will be the same, and consumer prices will differ only by the verification costs. In the second case, on the other hand, it must be that $p^n > p^g$. Turning to demand, recall that U.S. consumers are indifferent between the two varieties; thus, with verification costs, they will consume only the GM (or blend) product. An equilibrium in which U.S. farmgate prices are equal (i.e., $p^n = p^g$) occurs if

(20) $$S^g\left(p^g,\hat{z}\right)+S^n\left(p^n,\hat{z}\right)+\overline{S}^n\left(\overline{p}^n\right)+\upsilon'\left(p^b\right)+\overline{\phi}_f\left(p^f,\overline{p}^b\right)+\overline{\phi}_b\left(p^f,\overline{p}^b\right)=0$$

provided

(21) $$\left\{S^n\left(p^n,\hat{z}\right)+\overline{S}^n\left(\overline{p}^n\right)+\overline{\phi}_f\left(p^f,\overline{p}^b\right)\right\}\geq 0$$

where

(22) $$\begin{aligned}&p^f=\overline{p}^f=\overline{p}^n=p^b+c\\&\overline{p}^b=p^b=p^n=p^g\ .\end{aligned}$$

Equation (20) asserts the equality of supply and demand for all product, whereas (21) ensures that sufficient GM-free product is available to meet European demand. The pricing assumption in (22) reflects the verification costs on the U.S.-produced GM-free product, the absence of such costs on foreign production, and the assumed equality of farmgate prices in the United States. At $c=0$, this is the equilibrium that exists prior to the introduction of the GM crop, provided that GM acreage is small.

Define the equilibrium price from (20)-(22) as $p^b(c)$. From these equations we can determine the comparative statics effects $\left(dp^b/dc\right)$ and $\left(dp^f/dc\right)$. Given the assumption that the yield function is the same for the two varieties (equation (9)), and using Condition 1 (and the usual convexity properties of the profit function and indirect utility function), these comparative statics can be signed, yielding:

PROPOSITION 4. If GM plantings are not too large (so that farmgate prices of both varieties are the same), then (i) U.S. farmgate prices decrease as verification costs increase, (ii) EU farm prices rise, and (iii) consumer prices for GM-free products increase.

As verification costs increase, European imports of the GM-free product decrease both because its domestic output rises and because its demand for the GM-free product falls. If verification costs are high enough, Europe's imports of the GM-free product may cease. Depending on preferences, Europe might start importing the GM product as *c* increases because the consumer prices of the two varieties move in opposite directions. But clearly, increases in *c* will not lead to excess demand for the GM-free product. If we define $z^0(c)$ such that $\left\{S^n\left(p^n, z^0\right)+\bar{S}^n\left(p^n+c\right)+\bar{\phi}_f\left(p^n+c, p^n\right)\right\}=0$ with $p^n=p^g$, then z^0 is a non-decreasing function of *c*. Hence, if the initial equilibrium at $c=0$ is such that U.S. farm prices are the same for both varieties, then, given $\hat{z}$, the equilibrium will remain so as c increases.

Finally, consider the monopolist's optimization problem. Its profits are given by

$$(23) \qquad \Pi^M\left(p^n, p^g, \hat{z}\right)=\left[\pi\left(p^g\right)+\eta(\hat{z})-\pi\left(p^n\right)\right]\Theta(\hat{z})$$

where we have used equation (9), the assumption that yields are independent of variety. Define z^0 as in the previous section, such that with costless verification there will be no price difference between GM and non-GM products for $\hat{z} \leq z^0$.

PROPOSITION 5. Assume the monopolist's profit function is concave in $\hat{z}$. If $\left[\eta'\left(z^0\right)\Theta\left(z^0\right)+\eta\left(z^0\right)\theta\left(z^0\right)\right]<0$, where $\Theta\left(z^0\right)\pi_p\left(p^0\right)=D\left(p^0\right)$, then the monopolist's optimal sales decision is unaffected by the verification costs.

Proposition 5 follows directly from Proposition 4, and from the fact that, as *c* increases, there remains sufficient excess supply of the non-GM product so that the foreign demand can be met. Thus, the residual U.S. production of non-GM product is sold in the home market at the same price as the GM product because U.S. consumers are indifferent between the GM and GM-free products. Furthermore, we have:

PROPOSITION 6. Provided Europe imports the GM-free product, increases in verification costs hurt the United States, lower world welfare, but have a potentially ambiguous effect on Europe's welfare.

U.S. welfare declines because it is a net exporter and the farm-gate price declines. World welfare declines because of increased verification costs. Europe's welfare decreases because of the effective cost increase for imports of the GM-free product (including verification costs), but it potentially benefits from the reduced price of the GM product, so the overall impact is ambiguous. Around $c = 0$, all parties are hurt.

Unlike the case of no verification costs, the introduction of GM products will affect producers and consumers even if $\hat{z} < z^0(c)$. Given verification costs, it is true that for $\hat{z} \in (0, z^0]$, equilibrium prices are unaffected by the level of *z* since some of the GM-free product is sold in the United States at the price of the GM product. However, the introduction of any GM product in the United States implies that verification costs become necessary in order to export the GM-free product, and hence there is a discontinuous drop in U.S. (and world) welfare with the introduction of the GM product. This situation is illustrated in Figure 1. Given $\hat{z} \in \left(0, z^0\right)$, increases in GM plantings do not affect equilibrium prices or Europe's welfare.

PROPOSITION 7. Assuming positive verification costs, and that the optimal level of GM sales for the monopolist is such that the GM and GM-free products sell at the same price in the United States, then (i) the introduction of the GM crop in the United States leads to a discontinuous drop in U.S. farm output prices and to an increase in the price of the GM-free product in the importing country; and (ii) the introduction of GM production may lead to a decline in U.S. welfare.

Part (i) follows from the previous section and the immediately preceding discussion, where we have shown that, given $\hat{z} \le z^0$, (a) if $c = 0$ then prices are independent of $\hat{z}$; whereas (b) given $\hat{z} \in (0, z^0)$, p^b is a declining function of *c,* while p^f is an increasing function of *c*. Part (ii) follows from the fact that the introduction of GM product leads to a decline in the U.S. terms of trade. If verification costs are small, then the gains will outweigh the losses; however, for large enough verification costs it is apparent that the introduction of the GM product may lower U.S. welfare.

VI. GMO Regulation: Consumer Protection or Protectionism?

As discussed in the introduction, one of the responses to the development and adoption of GM crops has been the imposition of an increasingly elaborate set of regulations aimed at the marketing of GM products. For example, such "regulation" may require importers of GM products to keep enhanced records about the origin of production of the imports (i.e., traceability), even if they are not labeled GM-free. Indeed, that seems to be a feature of the current EU labeling proposal, discussed in section 2, and perhaps it highlights the most important economic implications of "mandatory" labeling requirements relative to "voluntary" ones. Imposing such regulation-based costs on GM product marketing will lower GM imports into Europe, and a sufficiently high cost will be equivalent to a ban on imports. (If these administrative costs for GM products equal the verification costs for GM-free products, then, given equality of prices in the United States, this fee will be prohibitive with respect to GM imports.)

Let t denote the per-unit cost these regulations impose on GM imports, and assume $t < c$. Given equality of price in the United States, European prices for GM-free and GM products will be $\overline{p}^f = p^n + c;\ \overline{p}^b = p^b + t$ respectively, where $p^b = p^g = p^n$. Using these relations, equilibrium prices are determined from (20), provided the restriction on net supply of the GM-free product holds. Totally differentiating yields the comparative statics effects $\left(dp^b/dt\right)$ and $\left(d\overline{p}^b/dt\right)$. Given the identity of U.S. prices for the two varieties, $\left(d\overline{p}^f/dt\right) = \left(dp^b/dt\right)$. Under the assumption that the demand for each good is more sensitive to its own price (Condition 1), we have $\left(d\overline{p}^b/dt\right) > 0 > \left(dp^b/dt\right)$. It then follows:

*PROPOSITION 8***.** Assume the monopolist's decision on GM acreage is such that, in the United States, $p^g = p^n$. Also assume there are verification costs of c per unit on GM-free goods shipped from the United States to Europe. Then European regulations on the imported GM product that raise real handling costs will (i) lower the price of U.S. output, and thus lower U.S. welfare; (ii) raise the net cost to Europe of the imported GM product but lower the cost to Europe of the imported GM-free product; and thus (iii) may increase European welfare.

It is worth noting that the costs represented by t operate like a tariff on the GM product but with the tariff revenue dissipated through the regulatory costs (similar to the case of tariffs with rent-seeking behavior). Hence, the effects of GM regulations here are modeled as real costs due not to technology but to burdensome administrative rules, and hence these rules must reduce economic efficiency (i.e., the United States must lose more than Europe gains). The regulations do not correct an externality, provided that any GM goods are still produced in the United States; they merely serve as a (wasteful) device to manipulate the terms of trade. From proposition 8 we also have the following:

*Corollary 1***.** A European standard that prohibits the sale of GM products in Europe may raise European welfare.

Note that, unlike the "standards" literature where domestic standards are used as a strategic device to protect a local firm from a foreign competitor (who may appropriate local monopoly rents) (e.g., Fisher and Serra, 2000), there is no strategic game involved in this argument. Rather, the standard here serves as an indirect way to improve the terms of trade.

We turn now to the case in which the U.S. prices of GM and GM-free products differ. The U.S. price of the GM-free product will rise above the GM price when, at equal prices, exporting the entire U.S. GM-free crop is insufficient to meet European (excess) demand, given the arbitrage conditions. Equilibrium prices for this case, and the critical threshold for GM plantings are determined by:

$$(24)\qquad S^g\left(p^g,\hat{z}\right)+S^n\left(p^n,\hat{z}\right)+\overline{S}^n\left(\overline{p}^n\right)+\upsilon'\left(p^b\right)+\overline{\phi}_f\left(p^f,\overline{p}^b\right)+\overline{\phi}_b\left(p^f,\overline{p}^b\right)=0$$

$$(25)\qquad S^n\left(p^n,\hat{z}\right)+\overline{S}^n\left(\overline{p}^n\right)+\overline{\phi}_f\left(\overline{p}^f,\overline{p}^b\right)=0$$

$$
\begin{aligned}
&p^f = \overline{p}^n = p^n + c \\
(26)\qquad &\overline{p}^b = p^b + t \\
&p^b = p^g \\
&p^n \geq p^g\ .
\end{aligned}
$$

The equilibrium conditions in (24) and (25) determine $p^n\left(c,t,\hat{z}\right)$ and $p^g\left(c,t,\hat{z}\right)$, with European prices determined through the stated arbitrage conditions. For future reference, define $z^0(c,t)$ such that $p^n\left(c,t,z^0(c,t)\right) = p^g\left(c,t,z^0(c,t)\right)$. For $\hat{z} < z^0\left(c,t\right)$, $p^n = p^g$, and the preceding results apply. For $\hat{z} > z^0\left(c,t\right)$, $p^n > p^g$, as is assumed in this subsection. We will return to the case $\hat{z} = z^0\left(c,t\right)$ later.

Given $\hat{z}$, the comparative statics of prices can be determined. In particular, we find:

LEMMA 1. From equations (24)-(26) we find $\left(\partial p^n / \partial \hat{z}\right)$>0 and $\left(\partial p^n / \partial \hat{z}\right) > \left(\partial p^g / \partial \hat{z}\right)$, although the sign of $\left(\partial p^g / \partial \hat{z}\right)$ is indeterminate. Furthermore, $\left(\partial p^n / \partial c\right) < 0$, $\left(\partial p^f / \partial c\right) > 0$, $\left(\partial p^g / \partial c\right) = \left(\partial \overline{p}^b / \partial c\right) > 0$; and, $\left(\partial p^n / \partial t\right) = \left(\partial p^f / \partial t\right) > 0$, $\left(\partial p^g / \partial t\right) < 0$, $\left(\partial \overline{p}^b / \partial t\right) = \left[1 + \left(\partial p^g / \partial t\right)\right] > 0$.

Given $\hat{z}$, the incidences of the IP and regulation costs c and t act as one would expect both on own price and on the price of the substitute good. Thus, given $\hat{z}$, an increase in the unit verification costs *c* lowers the U.S. price of the GM-free product but raises the price of the GM product as European demand shifts; the European price of both varieties increases.[13] Similarly, given $\hat{z}$, an increase in administrative costs on the GM products (i.e., an increase in *t*) will lower the U.S. price of GM product but will raise the U.S. price of the GM-free variety while raising both prices in Europe. Thus, given (c,t), under the maintained demand assumption, an increase in $\hat{z}$ (the amount of the GM acreage cultivated) increases the

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[13] In the United States there is no substitution in demand by assumption, and no substitution in supply, given $\hat{z}$. If Europe does not consume the GM product, the increase in *c* will not affect the price of the GM product, given $\hat{z}$. Of course, in either case, the monopolist is likely to adjust his optimal $\hat{z}$ in response to these exogenous shifts in transaction costs.

price of natural soybeans but has a potentially ambiguous impact on the price of the GM product as total production in this industry declines (this cannot happen around $p^n = p^g$, where realized yields are equal across varieties). Because it must be that $\left(\partial p^n / \partial \hat{z}\right) > \left(\partial p^g / \partial \hat{z}\right)$, European welfare will be reduced by this increased GM acreage if European imports of GM-free soybeans are at least as large as those of GM product. Thus, it is apparent that Europe has an interest in adopting policies that could reduce the amount of acreage allocated to GM crops.

Similarly, given $\hat{z}$, an increase in European regulations on GMO imports (an increase in *t*) increases European prices for both varieties and thus must hurt Europe (as there is no tariff revenue), while it is conceivable that the United States benefits from this policy. Naturally, if $\hat{z}$ adjusts, then the qualitative results could change. We return to that point shortly, but first we want to consider the role of verification costs.

From Lemma 1 it is readily seen that increased verification costs decrease U.S. prices for the GM-free product and increase prices for the GM product, provided Europe imports some GM output. European prices rise for both varieties, and European welfare must fall. Depending on the composition of exports, U.S. welfare could rise, because of the increased price of the GM product. The result that the United States may gain from the increased verification costs can be understood in the context of an "optimal" U.S. trade policy (which is precluded in this model).

Using (23), the impact of a verification cost increase on the monopolist's profits is determined by

$$(27) \qquad \partial \Pi^M \left(c, t, \hat{z}\right) / \partial c = \left[\tilde{\pi}_p \left(p^g\right)\left(\partial p^g / \partial c\right) - \pi_p \left(p^n\right)\left(\partial p^n / \partial c\right)\right]\Theta\left(\hat{z}\right).$$

Because $\left(\partial p^g / \partial c\right) > 0 > \left(\partial p^n / \partial c\right)$, as shown earlier, it follows that $\partial \Pi^M \left(c, t, \hat{z}\right) / \partial c > 0$. Hence:

PROPOSITION 9. Increased verification costs raise the monopolist's maximized profits, even though they reduce economic efficiency and may lower U.S. welfare.

The interest in this result arises because IP costs may not be entirely exogenous. A sizeable portion of these costs are likely to take the form of testing costs at various junctures of the production and marketing chain where commingling can take place (Bullock, Desquilbet and Nitsi, 2000). Conceivably such testing costs could be influenced by the actions of the GM seed producer (say, by inserting an easily detectable and common marker on the many GM varieties that are being marketed). If the innovating monopolist may be able to manipulate the product in such a way as to make the GM product more readily distinguishable from the GM-free product, that can reduce verification costs. But, as Proposition 9 illustrates, such actions, while welfare-improving, may not be in the innovating firm's interest.

Finally, consider how changes in *c* or *t* affect the monopolist's *optimal* acreage decision. In doing so, we must consider the possibility that (i) $\hat{z} > z^0\left(c,t\right)$ so that $p^n\left(c,t,\hat{z}\right) > p^g\left(c,t,\hat{z}\right)$; (ii) $\hat{z} < z^0\left(c,t\right)$ so that $p^n = p^g$; and (iii) $\hat{z} = z^0\left(c,t\right)$ (the borderline case). Although this last case might seem to be a singularity, in fact it is not, because the monopolist's marginal revenue curve is discontinuous at that point. Specifically, from the monopolist's profit function in (23), we have

$$(28) \qquad \frac{d\Pi^M}{d\hat{z}} = \begin{cases} \left[\eta'(\hat{z})\Theta(\hat{z}) + \eta(\hat{z})\theta(\hat{z})\right], & \text{for } \hat{z} < z^0 \\ \left[\pi_p\left(p^g\right)\dfrac{\partial p^g}{\partial \hat{z}} + \eta'(\hat{z}) - \pi_p\left(p^n\right)\dfrac{\partial p^n}{\partial \hat{z}}\right]\Theta(\hat{z}) + \left[\pi\left(p^g\right) + \eta(\hat{z}) - \pi\left(p^n\right)\right]\theta(\hat{z}), & \text{for } \hat{z} > z^0. \end{cases}$$

As shown earlier, under the maintained demand assumptions, $\left(\partial p^n / \partial \hat{z}\right) > 0$, and $\left(\partial p^n / \partial \hat{z}\right) > \left(\partial p^g / \partial \hat{z}\right)$. Also, $\pi_p\left(p^n\right) \geq \tilde{\pi}_p\left(p^g\right)$, and $\lim_{\hat{z}\to z^0}\left[\pi_p\left(p^n\right) - \tilde{\pi}_p\left(p^g\right)\right] = 0$. Thus, it follows that

$$(29) \qquad \lim_{\hat{z}\to\left(z^0\right)^+}\left(\partial\Pi^M / \partial z\right) < \lim_{\hat{z}\to\left(z^0\right)^-}\left(\partial\Pi^M / \partial z\right).$$

In other words, the monopolist's marginal revenue curve is discontinuous at z^0, with a discrete downward jump at that point.

This discontinuity in the marginal revenue curve is illustrated in Figure 2. The curve ABD shows the inverse demand curve for GM seeds, which is the difference in profits on the marginal land

$T\left(p^n, p^g, \hat{z}\right)$. Along segment AB, $p^n = p^g$, and the demand curve is negatively sloped only because the cost savings due to GM production decline as $\hat{z}$ increases (if all land were identical, the demand curve would be horizontal over this domain). However, along segment BD ($\hat{z} > z^0$), GM output is sufficiently large (non-GM output is sufficiently small) so that the U.S. farm price of non-GM output exceeds that of GM output. The negative slope of the demand curve along BD reflects not only the change in cost savings on the marginal land but also the change in output prices. Even if all land were homogenous, the demand curve would be negatively sloped over this domain. Thus, the demand curve is continuous but has a kink, at B. The marginal revenue curve is represented by AB"CD", with the discontinuity in the marginal revenue curve at z^0 (the vertical segment B"C) reflecting the kink in the demand curve. The monopolist's optimal decision depends, of course, upon where the marginal revenue curve crosses the horizontal axis. While any of the three cases could occur, the figure represents the case in which the discontinuity in the marginal revenue curve encompasses the horizontal axis. Clearly, the possibility of the monopolist's optimal decision being z^0 is more than a singularity.

We have discussed previously how, if the monopolist's optimal choice $\hat{z}$ is in the domain $\hat{z} < z^0\left(c,t\right)$, then (marginal) changes in *c* or *t* will not affect acreage allocations. On the other hand, for the case in which $\hat{z} > z^0\left(c,t\right)$, the optimal decision will be affected by these parameters. Specifically, in such a case $\hat{z}$ solves

$$(30) \qquad \left[\pi_p\left(p^g\right)\frac{\partial p^g}{\partial \hat{z}} + \eta'\left(\hat{z}\right) - \pi_p\left(p^n\right)\frac{\partial p^n}{\partial \hat{z}}\right]\Theta\left(\hat{z}\right) + \left[\pi\left(p^g\right) + \eta\left(\hat{z}\right) - \pi\left(p^n\right)\right]\theta\left(\hat{z}\right) = 0 \ .$$

Let $K\left(z,c,t\right)$ denote the left-hand side of equation (30). From the second-order condition, $K_z < 0$. But, as occurs with comparative static analysis in situations of imperfect competition, the impact of the parameter shift depends on the curvatures of demand and cost curves. In particular,

$$
(31)\quad \begin{aligned}\frac{\partial K(c,t,\hat{z})}{\partial j} &= \left[\pi_{pp}\left(p^{g}\right)\frac{\partial p^{g}}{\partial j}\frac{\partial p^{g}}{\partial \hat{z}} + \pi_{p}\left(p^{g}\right)\frac{\partial^{2} p^{g}}{\partial j \partial \hat{z}} - \pi_{pp}\left(p^{n}\right)\frac{\partial p^{n}}{\partial j}\frac{\partial p^{n}}{\partial \hat{z}} - \pi_{p}\left(p^{n}\right)\frac{\partial^{2} p^{n}}{\partial j \partial \hat{z}}\right]\Theta(z) \\ &+ \left[\pi_{p}\left(p^{g}\right)\frac{\partial p^{g}}{\partial j} - \pi_{p}\left(p^{n}\right)\frac{\partial p^{n}}{\partial j}\right]\theta(\hat{z}) \quad , \qquad j = c,t\,.\end{aligned}
$$

The terms $\left(\partial p^{i}/\partial j\right),\ i = g,n;\ \ j = c,t$ have been signed earlier. However, the sign of the term in brackets on the first line of (31) depends on a comparison of the slopes of the supply curve at different prices (hence, on its curvature), and on the second-order partial derivatives, $\left(\partial^{2} p^{i}/\partial j \partial \hat{z}\right)$, which also depend on the curvatures of demand or supply curves. On the other hand, the sign of the expression on the second line of (31) can be determined without making assumptions about curvature; specifically, it is positive for *j=c* and negative for *j=t*. We will assume that the sign of $\left(\partial K/\partial j\right)$ is determined by the sign of the expression on the second line.[14] Specifically, we have the following:

CONDITION 2. The sign of $\left(\partial K/\partial c\right)$ and $\left(\partial K/\partial t\right)$ is determined by the impact of (c,t) on prices p^{n} and p^{g}. In particular, $\left(\partial K/\partial c\right)>0$ and $\left(\partial K/\partial t\right)<0$.

We have shown previously that European welfare is decreasing in *c*, given $\hat{z}$, and that European welfare is decreasing in $\hat{z}$ if GM-free imports exceed GM imports. Given that, and Condition 2, we obtain:

PROPOSITION 10. Assuming the optimal monopoly acreage decision is such that $\hat{z} > z^{0}(c,t)$ then increases in verification costs not only increase monopoly profits but also lead to increased GM acreage. Thus, European welfare must fall as verification costs increase, provided that their GM-free imports exceed GM imports.

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[14] Similar assumptions are often made in strategic games in which whether the strategies are substitutes or complements often depends on terms that cannot be signed unambiguously by economic theory.

The results for regulations (limitations) on GM imports into Europe are less clear-cut. We know that increasing t, given $\hat{z}$, hurts Europe. On the other hand, by virtue of Condition 2, increasing the administrative burden will decrease the monopolist's optimal choice of GM acreage, which can benefit Europe. Thus, we have the following:

PROPOSITION 11. Restrictions limiting GM imports (or raising their costs) have an ambiguous impact on Europe, as the direct effect (given GM acreage) increases domestic prices of both goods. However, the induced impact of reduced GM acreage is to lower the price of GM-free product and to raise the price of the GM product. Thus, if the amount of GM imports is relatively small, Europe can gain by restrictions on these imports.

Finally, as noted previously, there is a positive probability that the monopolist's optimal decision will be to choose GM acreage so that the prices of the two varieties are "just" equal; i.e., $\hat{z} = z^0(c,t)$. The impact on price and GM acreage for this case is readily demonstrated. Specifically, we find:

$$(32) \qquad \begin{array}{l} \left(dp(c,t)/dc\right) \in (-1,0) \\ \left(dp(c,t)/dt\right) \in (-1,0) \end{array} \quad \text{and} \quad \begin{array}{l} \left(dz^0(c,t)/dc\right) > 0 \\ \left(dz^0(c,t)/dt\right) < 0 \end{array}$$

where $p^n = p^g = p$, whereas European prices are such that $p^f = (p+c)$ and $\overline{p}^b = (p+t)$. These results reflect the endogeneity of GM acreage to the stated variables. Hence, we have the following:

*PROPOSITION 12***.** Assuming it is optimal for the monopolist to choose acreage such that the GM and non-GM varieties in the United States have just the same output price, then an increase in the IP cost c leads to (i) more acreage allocated to GM crops; (ii) lower U.S. prices for both goods; (iii) higher European prices for GM-free imports, but lower prices for GM imports; (iv) lower overall efficiency and lower welfare in the United States; (v) lower welfare in Europe if its primary imports are GM-free; but

(vi) an increase in the monopolist's profits. Similarly, an increase in the GM regulation cost t imposed on imports of the GM product leads to (i) less acreage allocated to the GM product; (ii) lower U.S. prices for both goods; (iii) higher European prices for GM imports but lower prices for GM-free imports; (iv) lower overall efficiency and lower welfare in the United States; (v) potentially higher welfare in Europe, especially if GM-free imports exceed GM imports; and (vi) a decline in monopoly profits.

VII. Conclusion

In this paper we have developed a model of an innovation that is produced and marketed by a home-country monopolist, is adopted by a competitive sector, and leads to tradable final products that are considered weakly inferior by consumers in the foreign country. This model fits the most important features of the current generation of agricultural GM products, and it allows us to investigate how the introduction of GMOs affects economic efficiency and the distribution of welfare across importers and exporters. We also have considered how policies limiting, or regulating, imports of GMOs will affect welfare in importing and exporting countries. We have explicitly accounted for the externality that the introduction of GMOs has on pre-existing non-GM products and have studied the role of segregation and verification costs in influencing the welfare effects associated with the introduction of GMOs. The analysis of the paper has been predicated on the assumption that consumers may rationally prefer, at least weakly, GM-free goods to GM goods. Whether that is in fact the case or whether claims to that effect are disguised protectionism, is perhaps not a settled issue, but we do not address that here.

Within this framework, we have shown that the introduction of GM products can lower welfare, because of the cost externality that arises if there are verification costs involved in certifying that a product is GM-free. Even if there is an overall welfare gain, the importing country (if it is the one that has the preference for the GM-free good) is likely to be harmed by the introduction of the GM product.

Moreover, we have shown that regulations on trade in GM-products will redistribute income among trading nations and may benefit the importing country. Some forms of such regulations may be thought of as imposing artificial costs on trade in GM-products—thus possibly reducing overall economic efficiency—and will harm the importing country if the regulations have no impact on planting decisions. However, by inducing the monopolist to reduce the amount of GM seeds sold, regulations restricting imports of GMOs can benefit the importing nation by lowering the price of GM-free goods. Thus, it may be difficult to determine whether these regulations are motivated by an attempt to "protect consumers" or simply "to protect." Recall that, within the context of our model, verification costs allow consumers to distinguish (and be able to choose) between GM and GM-free goods. But such costs only need to be incurred by the product wanting to claim "GM-free" status, and this verification can be delivered by a voluntary labeling system. The additional requirements of a "mandatory" labeling system can be interpreted as merely administrative burdens imposed on GM-trade. It is also interesting to note that both the verification costs and these administrative costs could induce some (or perhaps even all) exporters to ban production of GM products. This seems most likely in producing regions, such as South America, which likely do not retain the monopoly rents from GM-seed sales (and, perhaps, are subject to different political pressures).

We have also shown that verification costs—which obviously lower economic efficiency—are actually beneficial to the monopolist. Thus, there is a clear conflict between society's interest in reducing these costs and the firm's interest in preserving these costs. Note that such conflicts would be much less likely if consumers view the new product as being superior rather than inferior (or equivalent) to the existing good. This observation has direct implications for the effects of, and regulatory needs for, "output-trait" innovations (Miflin, 2000), which are expected to characterize the next wave of biotechnology innovations in agriculture.

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Table 1. Global area of transgenic crops, 1996-2001

Hectares (million)

By Country

	1996	1997	1998	1999	2000	2001	Percent (2001)
United States	1.5	8.1	20.5	28.7	30.3	35.7	67.9 %
Argentina	0.1	1.4	4.3	6.7	10.0	11.8	22.4 %
Canada	0.1	1.3	2.8	4.0	3.0	3.2	6.1 %
China	…	<0.1	<0.1	0.3	0.5	1.5	2.8 %
other	…	0.1	0.1	0.2	0.4	0.4	0.8 %
World	**1.7**	**11.0**	**27.8**	**39.9**	**44.2**	**52.6**	

By Crop

	1996	1997	1998	1999	2000	2001	Percent (2001)
Soybeans	…	5.1	14.5	21.6	25.8	33.3	63.3 %
Corn	…	3.2	8.3	11.1	10.3	9.8	18.7 %
Cotton	…	1.4	2.5	3.7	5.3	6.8	12.9 %
Canola	…	1.2	2.4	3.4	2.8	2.7	5.1 %
Total	**1.7**	**11.0**	**27.8**	**39.9**	**44.2**	**52.6**	

Source: International Service for the Acquisition of Agri-Biotech Applications (ISAAA).

Figure 1. Identity Preservation Costs, Acreage, and Prices

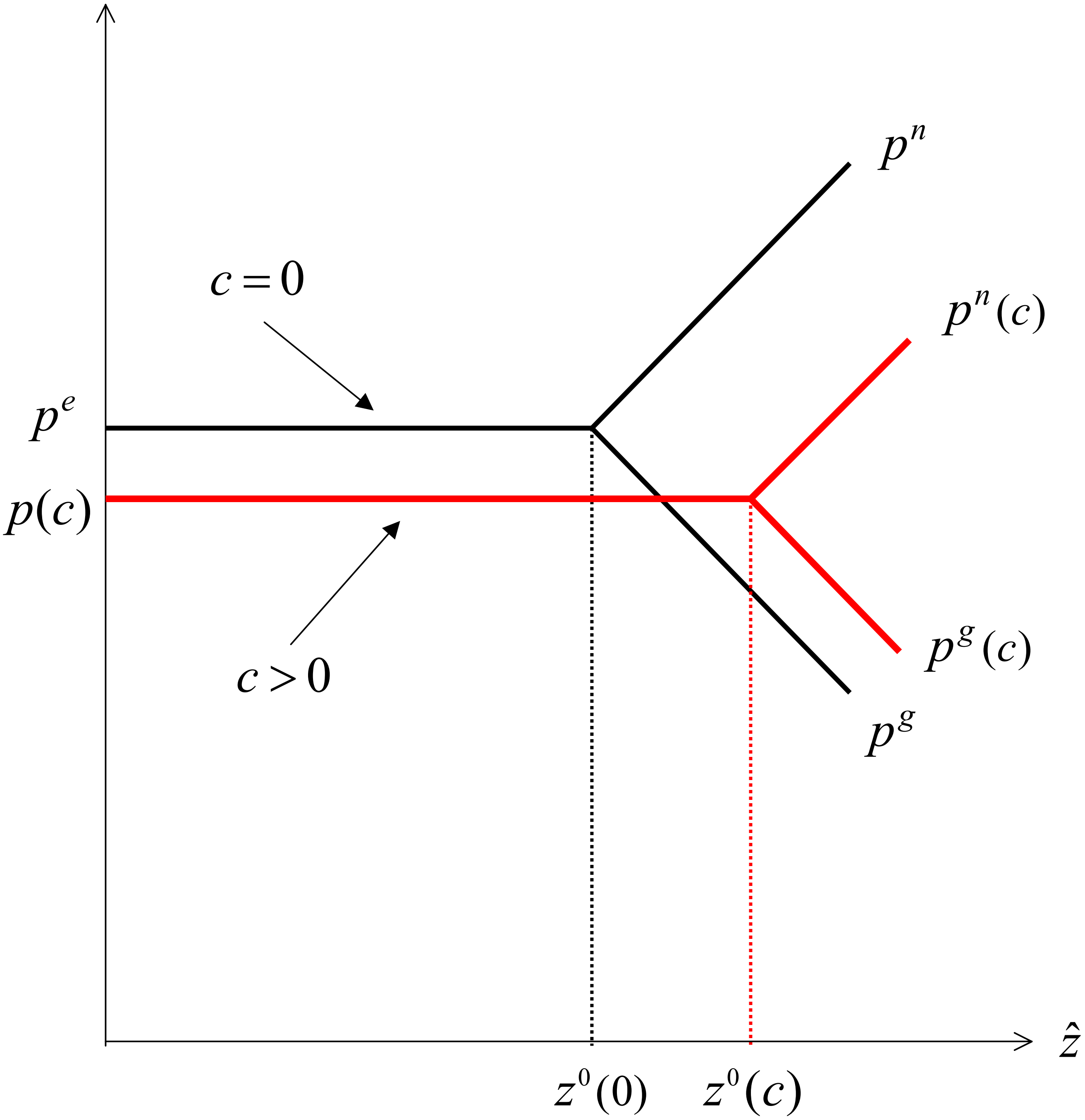
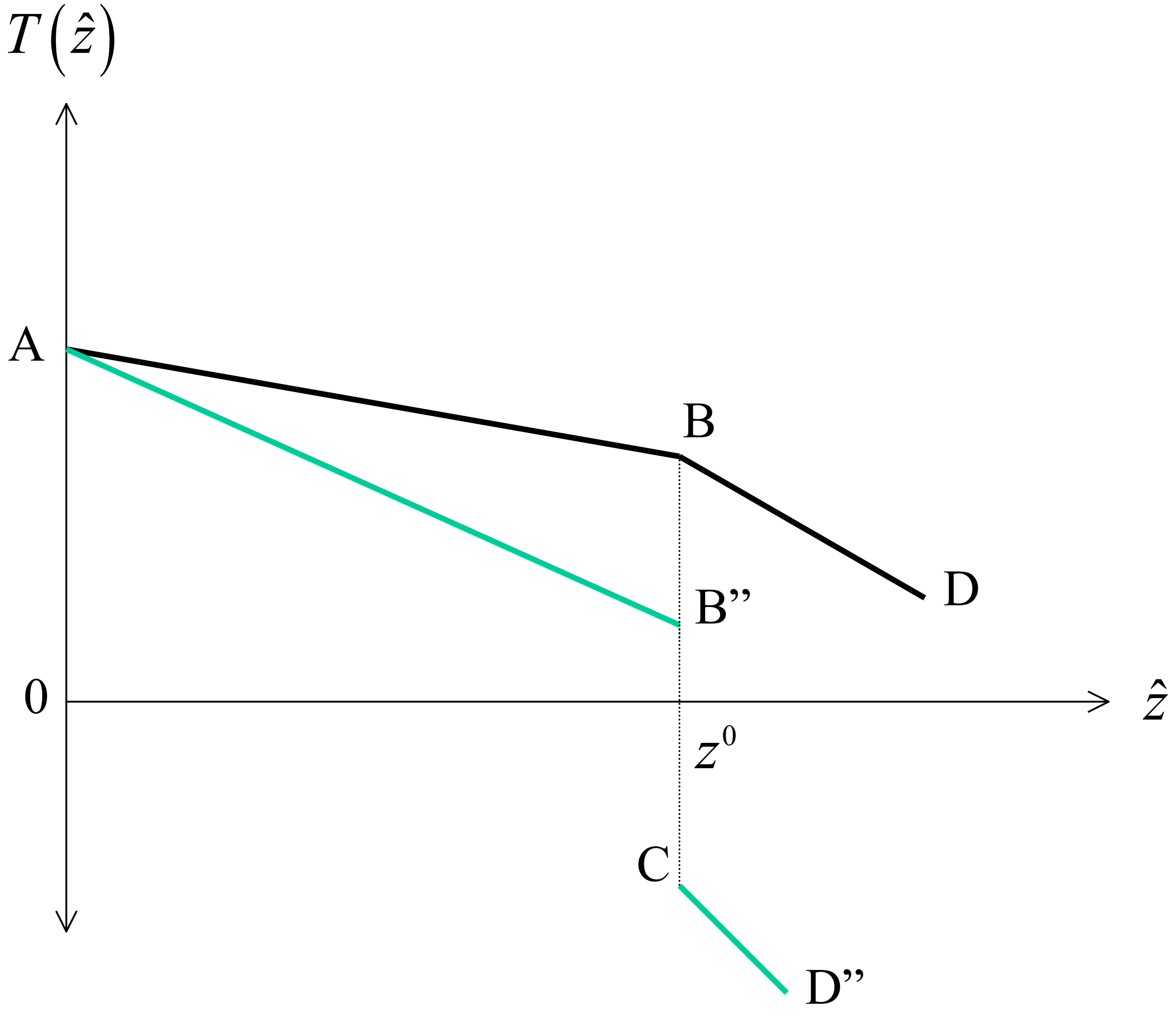


Figure 2. Marginal Revenue and Innovator's Acreage Choice



APPENDIX. Proofs

Proof of Proposition 1. By assumption, $\tilde{\pi}_p\left(p,z\right) = \pi_p\left(p\right)$ for all p,z. As $\hat{z}$ increases, more land is allocated to the GM crop and less to the non-GM crop, but total production of soybeans is unchanged provided that price is unchanged. Further, if $p^n = p^g = p^0$, then European demand for the non-GM product is unchanged, whereas U.S. demand is perfectly elastic and equal to $\left(1-\psi\right)D\left(p^0\right)$. Thus, if $\psi D\left(p^0\right) = \Theta\left(\hat{z}\right)\pi_p\left(p^0\right)$, both markets will clear at this price. In other words, if $\hat{z}$ is such that $\Theta\left(\hat{z}\right) \le D\left(p^0\right)/\pi_p\left(p^0\right)$, then equilibrium prices are unchanged.

Proof of Proposition 2. Totally differentiating (17) and (18) yields

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}\begin{bmatrix} dp^g \\ dp^n \end{bmatrix} = \begin{bmatrix} \tilde{\pi}_p\left(p^g\right)\theta\left(\hat{z}\right)d\hat{z} \\ -\pi_p\left(p^n\right)\theta\left(\hat{z}\right)d\hat{z} \end{bmatrix} \tag{33}$$

where

$$a_{11} \equiv -\left[\tilde{\pi}_{pp}\left(p^g\right)\Theta\left(\hat{z}\right) + \upsilon''\left(p^g\right) + \bar{\phi}_{gg}\left(\bar{p}^n, \bar{p}^g\right)\right] < 0$$
$$a_{12} = a_{21} \equiv -\bar{\phi}_{gn}\left(\bar{p}^n, \bar{p}^g\right) > 0$$
$$a_{22} \equiv -\left[\pi_{pp}\left(p^n\right)\left(L-\Theta\left(\hat{z}\right)\right) + \bar{L}\bar{\pi}_{pp}\left(\bar{p}^n\right) - \bar{\phi}_{nn}\left(\bar{p}^n, \bar{p}^g\right)\right] < 0.$$

The signs for a_{11} and a_{22} come from the convexity of the profit and indirect utility functions whereas the sign for $a_{12} = a_{21}$ comes from the final goods being substitutes in consumption. The argument "$\hat{z}$" is dropped from the supply function because yields on GM acreage are independent of land type. Also, because $p^g < p^n$, realized yields per acre will be higher on non-GM lands. Solving (33) yields

$$\begin{bmatrix} dp^g \\ dp^n \end{bmatrix} = \left(1/\Delta\right)\begin{bmatrix} a_{22} & -a_{12} \\ -a_{21} & a_{11} \end{bmatrix}\begin{bmatrix} \tilde{\pi}_p\left(p^g\right)\theta\left(\hat{z}\right)d\hat{z} \\ -\pi_p\left(p^n\right)\theta\left(\hat{z}\right)d\hat{z} \end{bmatrix} \tag{34}$$

where $\Delta = \left(a_{11}a_{22} - a_{12}a_{21}\right) > 0$. Because $p^g < p^n$ for $\hat{z} > z^0$, then, provided $\pi_{pp} > 0$ (i.e., yields are positively affected by output price), it follows that $\pi_p\left(p^n\right) > \tilde{\pi}_p\left(p^g\right)$. Thus, given price, total output (GM plus non-GM product) declines as land planted with the GM crop expands. From (34), $\left(dp^n/d\hat{z}\right) = \left(\theta(\hat{z})/\Delta\right)\left(-a_{11}\pi_p\left(p^n\right) - a_{21}\tilde{\pi}_p\left(p^g\right)\right)$. Because $p^n \geq p^g$, then $\pi_p\left(p^n\right) \geq \tilde{\pi}_p\left(p^g\right)$. Further, $a_{11} < 0$, and, by the assumed Condition 1, $\left(a_{11} + a_{12}\right) < 0$, provided that $\tilde{\pi}_{pp} > 0$ or $\upsilon'' > 0$. Thus: $\left(-a_{11}\pi_p\left(p^n\right) - a_{21}\tilde{\pi}_p\left(p^g\right)\right) > -\pi_p\left(p^g\right)\left(a_{11} + a_{21}\right) > 0$, proving $\left(dp^n/d\hat{z}\right) > 0$. And, from (34) $\left[\left(dp^n/d\hat{z}\right) - \left(dp^g/d\hat{z}\right)\right] = \left(-\theta(\hat{z})/\Delta\right)\left(\left(a_{11} + a_{12}\right)\pi_p\left(p^n\right) + \left(a_{22} + a_{21}\right)\tilde{\pi}_p\left(p^g\right)\right)$. Given convexity, Condition 1 guarantees $\left(a_{11} + a_{12}\right) < 0$ and $\left(a_{21} + a_{22}\right) < 0$, proving $\left(dp^n/d\hat{z}\right) > \left(dp^g/d\hat{z}\right)$.

Proof of Proposition 3 . Europe's welfare can be written as $\overline{W} = \overline{L}\overline{\pi}\left(p^n(\hat{z})\right) + \overline{\phi}\left(p^n(\hat{z}), p^g(\hat{z})\right)$. Thus, $\left(d\overline{W}/d\hat{z}\right) = \left[\overline{L}\overline{\pi}_p\left(p^n(\hat{z})\right) + \overline{\phi}_n\right]\left(dp^n/d\hat{z}\right) + \overline{\phi}_g\left(dp^g/d\hat{z}\right) = \left\{\left[\overline{S}^n - \overline{D}^n\right]\left(dp^n/d\hat{z}\right) - \overline{D}^g\left(dp^g/d\hat{z}\right)\right\}$, where $\left[\overline{D}^n - \overline{S}^n\right]$ is imports of the non-GM product and $\overline{D}^g$ is imports of the GM product. From Proposition 2, $\left(dp^n/d\hat{z}\right) > 0$ and $\left(dp^n/d\hat{z}\right) > \left(dp^g/d\hat{z}\right)$; thus, for $\left[\overline{D}^n - \overline{S}^n\right] > \overline{D}^g \geq 0$, the result is proven.

Proof of Proposition 4. From equation (9) we have $\tilde{\pi}\left(p^n, \hat{z}\right) = \pi\left(p^n\right) + \eta(\hat{z})$, and thus

$$
\begin{aligned}
& S^n = \pi_p\left(p^n\right)\Theta(\hat{z}) \\
(35) \qquad & S^g = \pi_p\left(p^n\right)\left[L - \Theta(\hat{z})\right] \\
& \overline{S}^n = \overline{L}\kappa_p\left(p^f\right).
\end{aligned}
$$

Define the equilibrium price from (20) as $p^b(c)$. Naturally, $p^b(0) = p^0$. From this equation we have

$$
\begin{aligned}
& \left(dp^b/dc\right) = -\left[\overline{L}\kappa_{pp}\left(p^f\right) + \overline{\phi}_{ff} + \overline{\phi}_{bf}\right]\Big/\Delta \\
(36) \qquad & \\
& \left(dp^f/dc\right) = \left[L\pi_{pp}\left(p^b\right) + \upsilon''\left(p^b\right) + \overline{\phi}_{bf} + \overline{\phi}_{bb}\right]\Big/\Delta
\end{aligned}
$$

where $\Delta \equiv \left[L\pi_{pp}\left(p^b\right) + \bar{L}\kappa_{pp}\left(p^f\right) + \upsilon''\left(p^b\right) + \bar{\phi}_{ff} + 2\bar{\phi}_{bf} + \bar{\phi}_{bb} \right]$ and $\bar{\phi}_{ij} \equiv \partial^2 \bar{\phi}\left(p^f, p^b\right) / \partial p^i \partial p^j$, $i, j \in \{f, b\}$. Convexity of the profit and indirect utility functions guarantee that Δ is positive (the excess supply function is positively sloped). If Europe does not consume the GM variety, the numerator of the first line in (36) must be negative, whereas that of the second must be positive. But if Europe does consume the GM product we cannot unambiguously sign both numerators (one must be positive). However, under the assumed Condition 1, the numerator of the first line must be negative, and that of the second positive.

Proof of Proposition 5. See text.

Proof of Proposition 6. We have shown previously that $\left(dp^b/dc\right) < 0$. The changes in home, foreign, and hence world welfare are

$$\left(dW/dc\right) = \left[L\pi_p\left(p^g\right) + \upsilon'\left(p^b\right) \right]\left(dp^b/dc\right) = \left[S^n + S^g - D \right]\left(dp^b/dc\right) < 0 \qquad \text{given: } p^b = p^g = p^n$$

$$\left(d\bar{W}/dc\right) = \left[\bar{L}\pi_p\left(p^f\right) + \bar{\phi}_f\left(p^f, p^b\right) \right]\left(dp^f/dc\right) + \left[\bar{\phi}_b\left(p^f, p^b\right) \right]\left(dp^b/dc\right) = \left[\bar{S}^n - \bar{D}^n \right]\left(dp^f/dc\right) - \bar{D}^g\left(dp^b/dc\right)$$

$$\left(d\left(\bar{W} + W\right)/dc\right) = \left[\bar{L}\pi_p\left(p^f\right) + \bar{\phi}_f\left(p^f, p^b\right) \right] = \left[\bar{S}^n - \bar{D}^n \right] < 0 \ .$$

U.S. welfare declines because it is a net exporter, and the farmgate price declines. World welfare declines because of the increased verification costs. Europe's welfare is reduced by the effective cost increase for imports of the GM-free product (including verification costs), but Europe may benefit from the reduced price of the GM product, so that the overall impact is ambiguous. Around $c = 0$, all parties are hurt.

Proof of Proposition 7. Part (i) follows from the previous section and the immediately preceding discussion where we have shown that, given $\hat{z} \le z^0$, (a) if *c=0*, then prices are independent of *z*; whereas (b) given $\hat{z} \in \left(0, z^0\right)$, p^b is a declining function of *c*, while p^f is an increasing function of *c*. Part (ii) follows from the fact that the introduction of the GM product leads to a decline in the U.S. terms of trade. The welfare gain to the United States due to the introduction of GM seeds is $\Delta W = \int_0^{\hat{z}} \eta(z)\theta(z)dz$, whereas the welfare loss in the United States depends upon the magnitude of the decline in the terms of trade. If verification costs are small, then the gains will outweigh the losses; however, for large enough verification costs the introduction of GM product may lower U.S. welfare.

Proof of Proposition 8. Totally differentiating yields the following comparative statics effects:

$$\textbf{(37)}\qquad \begin{aligned} \left(dp^b/dt\right) &= -\left[\bar{\phi}_{fb} + \bar{\phi}_{bb}\right]\Big/\Delta \\ \left(d\bar{p}^b/dt\right) &= \left[L\pi_{pp}\left(p^b\right) + \bar{L}\kappa_{pp} + \upsilon''\left(p^b\right) + \bar{\phi}_{ff} + \bar{\phi}_{fb}\right]\Big/\Delta \end{aligned}$$

where $\Delta \equiv \left[L\pi_{pp}\left(p^b\right) + \bar{L}\kappa_{pp}\left(p^f\right) + \upsilon''\left(p^b\right) + \bar{\phi}_{ff} + 2\bar{\phi}_{bf} + \bar{\phi}_{bb}\right]$ and

$\bar{\phi}_{ij} \equiv \partial^2\bar{\phi}\left(p^f, p^b\right)\Big/\partial p^i \partial p^j$, $(i, j) \in \{f, b\}$. Given the identity of U.S. prices for the two varieties,

$\left(d\bar{p}^f/dt\right) = \left(dp^b/dt\right)$. Under the assumption of Condition 1, we have $\left(d\bar{p}^b/dt\right) > 0 > \left(dp^b/dt\right)$. This establishes the proof of parts (i) and (ii). The proof of (iii) follows from

$$\left(d\bar{W}/dt\right) = \left(\bar{L}\kappa_{pp} + \bar{\phi}_f\right)\left(d\bar{p}^f/dt\right) + \left(\bar{\phi}_b\right)\left(d\bar{p}^b/dt\right) = \left(\bar{S}^n - \bar{D}^f\right)\left(d\bar{p}^f/dt\right) - \bar{D}^b\left(d\bar{p}^b/dt\right).$$

The first expression is the welfare gain due to the improved terms of trade on GM-free product imports (U.S. prices decline), whereas the second term measures the loss due to the worsened gross terms of trade on the GM product. Note that these costs operate like a tariff on the GM product, assuming the tariff revenue is thrown away. Clearly, if GM-free imports are large enough, or if imports of the GM product are low enough, the expression will be positive. Further, as *t* increases, net imports of GM-free goods will increase; those of the GM product will decrease, so the expression is even more likely to be positive.

Proof of Lemma 1. Totally differentiating (24)-(25) and rearranging yields

$$(38)\qquad \begin{bmatrix} dp^n \\ dp^g \end{bmatrix} = \left(\frac{1}{\Delta}\right)\begin{bmatrix} a_{22} & -a_{12} \\ -a_{21} & a_{11} \end{bmatrix}\begin{bmatrix} b_n \\ b_g \end{bmatrix}$$

where

$$\begin{aligned} a_{11} &= \left(\pi_{pp}\left(p^n\right)\left(L - \Theta(\hat{z})\right) + \bar{L}\bar{\pi}_{pp}\left(\bar{p}^n\right) + \bar{\phi}_{ff}\left(p^f, \bar{p}^b\right)\right) > 0 \\ a_{12} &= a_{21} = \bar{\phi}_{fb}\left(\bar{p}^n, \bar{p}^g\right) < 0 \\ a_{22} &= \left(\tilde{\pi}_{pp}\left(p^g\right)\Theta(\hat{z}) + \upsilon''\left(p^g\right) + \bar{\phi}_{bb}\left(p^f, \bar{p}^b\right)\right) > 0 \end{aligned}$$

$$\Delta = \left(a_{11}a_{22} - a_{12}^2\right) > 0$$
$$b_n = \left\{\theta(\hat{z})\pi_p\left(p^n\right)d\hat{z} - \left[\bar{L}\bar{\pi}_{pp}\left(\bar{p}^n\right) + \bar{\phi}_{ff}\left(p^f, \bar{p}^b\right)\right]dc - a_{12}dt\right\}$$
$$b_g = -\left\{\theta(\hat{z})\tilde{\pi}_p\left(p^g\right)d\hat{z} + a_{12}dc + \bar{\phi}_{bb}dt\right\}.$$

From (38) the following comparative statics are readily derived:

$$(39)\quad \begin{aligned} \left(\partial p^n/\partial\hat{z}\right) &= \left(\theta(\hat{z})/\Delta\right)\left\{\left[\tilde{\pi}_{pp}\left(p^g\right)\Theta(\hat{z}) + \upsilon''\left(p^g\right)\right]\pi_p\left(p^n\right) + \left[\bar{\phi}_{bb}\pi_p\left(p^n\right) + \bar{\phi}_{bf}\tilde{\pi}_p\left(p^g\right)\right]\right\} > 0 \\ \left(\partial p^g/\partial\hat{z}\right) &= \left(-\theta(\hat{z})/\Delta\right)\left\{\left[\pi_{pp}\left(p^n\right)\left(L - \Theta(\hat{z})\right) + \bar{L}\bar{\pi}_{pp}\left(\bar{p}^n\right)\right]\tilde{\pi}_p\left(p^g\right) + \left[\bar{\phi}_{ff}\tilde{\pi}_p\left(p^g\right) + \bar{\phi}_{bf}\pi_p\left(p^n\right)\right]\right\} \end{aligned}$$

where the sign of $\left(\partial p^n/\partial\hat{z}\right)$ is determined with the help of Condition 1 [i.e., $\left(\bar{\phi}_{bb} + \bar{\phi}_{bf}\right) > 0$]. Again, $\left(\partial p^g/\partial\hat{z}\right)$ cannot be unambiguously signed, except around $p^g = p^n$, in which case $\left(\bar{\phi}_{ff} + \bar{\phi}_{fb}\right) > 0$ suffices to imply $\left(\partial p^g/\partial\hat{z}\right)$<0. However, regardless of the sign of $\left(\partial p^g/\partial\hat{z}\right)$, it must be true that $\left(\partial p^n/\partial\hat{z}\right) > \left(\partial p^g/\partial\hat{z}\right)$, provided that the demand assumption holds.

Similarly, holding $\hat{z}$ constant, comparative statics for changes in *c* and *t* are

$$(40)\quad \begin{aligned} \left(\partial p^n/\partial c\right) &= (-1/\Delta)\left\{a_{22}\left(\bar{L}\bar{\pi}_{pp}\left(\bar{p}^n\right) + \bar{\phi}_{ff}\right) - a_{12}^2\right\} < 0 \\ \left(\partial p^f/\partial c\right) &= (1/\Delta)\left\{a_{22}\pi_{pp}\left(p^n\right)\left(L - \Theta(\hat{z})\right)\right\} > 0 \\ \left(\partial p^g/\partial c\right) &= \left(\partial\bar{p}^b/\partial c\right) = \left(-a_{12}/\Delta\right)\pi_{pp}\left(p^n\right)\left(L - \Theta(\hat{z})\right) > 0 \end{aligned}$$

$$(41)\quad \begin{aligned} \left(\partial p^n/\partial t\right) &= \left(\partial p^f/\partial t\right) = (-1/\Delta)\left\{a_{22}a_{12} - a_{12}\bar{\phi}_{bb}\right\} = \left(-a_{12}/\Delta\right)\left\{\tilde{\pi}_{pp}\left(p^g\right)\Theta(\hat{z}) + \upsilon''\left(p^g\right)\right\} > 0; \\ \left(\partial p^g/\partial t\right) &= (-1/\Delta)\left(a_{11}\bar{\phi}_{bb} - a_{12}^2\right) < 0 \\ \left(\partial\bar{p}^b/\partial t\right) &= \left(1 + \left(\partial p^g/\partial t\right)\right) = (1/\Delta)a_{11}\left[\tilde{\pi}_{pp}\left(p^g\right)\Theta(\hat{z}) + \upsilon''\left(p^g\right)\right] > 0. \end{aligned}$$

Proof of Proposition 9. The monopolist's maximized profits are

$$\Pi^{M*}(c,t) = \underset{\hat{z}}{Max}\left\{\widehat{\Pi}^M(\hat{z},c,t) = \left(\pi\left(p^g(\hat{z},c,t)\right) + \eta(\hat{z}) - \pi\left(p^n(\hat{z},c,t)\right)\right)\Theta(\hat{z})\right\}.$$

Let $\hat{z}(c,t) = \underset{\hat{z}}{Argmax}\left[\widehat{\Pi}^M(\hat{z},c,t)\right]$. By the envelope theorem

$$\left(d\Pi^{M*}/dc\right) = \left(\partial\widehat{\Pi}^M(\hat{z},c,t)/\partial c\right) + \left(\partial\widehat{\Pi}^M(\hat{z},c,t)/\partial\hat{z}\right)\left(\partial\hat{z}(c,t)/\partial c\right) = \left(\partial\widehat{\Pi}^M(\hat{z},c,t)/\partial c\right) > 0.$$

Proof of Proposition 10. See text.

Proof of Proposition 11. See text.

Proof of Proposition 12. The impact on price and GM acreage for the case when $\hat{z} = z^0(c,t)$ is readily demonstrated, using (38), by setting $p \equiv p^n = p^g$ (and hence $dp = dp^n = dp^g$), and by bringing $d\hat{z}$ to the left-hand side of the equation. Doing so, and inverting, yields

$$(42) \qquad \begin{bmatrix} dp \\ dz^0 \end{bmatrix} = \left(\frac{1}{\Delta'}\right) \begin{bmatrix} \theta(\hat{z})\pi_p(p) & \theta(\hat{z})\pi_p(p) \\ -(a_{22}+a_{12}) & (a_{11}+a_{12}) \end{bmatrix} \begin{bmatrix} h_p \\ h_{\hat{z}} \end{bmatrix}$$

where

$$\begin{aligned} &\Delta' \equiv \theta(\hat{z})\pi_p(p)(a_{11}+a_{22}+2a_{12}) > 0 \\ &h_p = -\left\{\left[\bar{L}\bar{\pi}_{pp}\left(\bar{p}^n\right) + \bar{\phi}_{ff}\left(p^f, \bar{p}^b\right)\right]dc + a_{12}dt\right\} \\ &h_{\hat{z}} = -\left\{a_{12}dc + \bar{\phi}_{bb}dt\right\} \end{aligned}$$

and where a_{ij} are as defined in the proof of Lemma 1. Proceeding as earlier, using the same demand assumptions, it is readily verified that

$$(43) \qquad \begin{matrix} \left(dp(c,t)/dc\right) \in (-1,0) \\ \left(dp(c,t)/dt\right) \in (-1,0) \end{matrix} \quad \text{and} \quad \begin{matrix} \left(dz^0(c,t)/dc\right) > 0 \\ \left(dz^0(c,t)/dt\right) < 0 \end{matrix}$$

where $p^n = p^g = p,$ whereas European prices are such that $p^f = (p+c)$ and $\bar{p}^b = (p+t)$. What remains to be shown is the impact of higher *t* on monopoly profits. The result follows because, given the corner solution, $\left(d\Pi^M/dt\right)\Big|_{z^0(c,t),\ p^n=p^g} = \left(d\Pi^M/d\hat{z}\right)\Big|_{z^0}\left(dz^0(c,t)/dt\right) < 0$, where the sign follows because, by virtue of the corner solution, $\left(d\Pi^M/d\hat{z}\right)\Big|_{z^0} > 0,$ and we have shown that $\left(dz^0(c,t)/dt\right) < 0$.