Welfare Impacts of Cross-Country Research Spillovers

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Abstract: The present study focuses on the welfare implications of intellectual property protection (IPP) in agriculture, when the associated knowledge has commercial application in more than one country. Attention is paid to the realistic case where countries provide different IPP levels. A model is developed to determine who benefits from, and who should pay for the associated research. A key contribution is the acknowledgement that in many cases the technology used in agriculture is subject to spillovers. This fact has some important implications for welfare analysis and for policy prescriptions on where the burden of paying for the research should lie.

Keywords: Biotechnology, intellectual property, research spillover, welfare analysis.
I. Introduction

Advances in private sector plant and animal genetics often have applicability outside the country where the research was conducted. Historically, firms who conducted successful research have captured some of the international benefits by charging a premium for the resulting seedstock. For example, rents associated with improved performance of hybrid breeds and varieties can be captured by charging a premium price for these seeds, and this premium can be maintained for many generations by controlling access to the purebred parental lines. This premium pricing solution has had less relevance in breeds and varieties where the commercial traits are passed on in retained seed and in the offspring of commercial farm animals. Until relatively recently, the only way to capture any benefits associated on these breeds and varieties has been to charge a premium for the first generation knowing that the producer will replicate this improvement in future generations.

Governments have attempted to stimulate private sector agricultural research by providing legal protection for intellectual property on both domestic and international markets. However, the ability of countries to impose intellectual property rights on farmers in other countries has not been universally accepted (FAO (2001)). In some instances, the private sector has been willing to conduct research in response to incomplete intellectual property protection (IPP) afforded in one or two major markets. For example, work on Roundup Ready© soybeans progressed because of protection available in the U.S. domestic market and despite the relative lack of IPP for this technology in other soybean growing countries. Farmers who planted Roundup Ready© seeds in the U.S. paid a technology fee to the company that developed the technology, but this company was typically not able to collect this technology fee from producers in other countries.

In the present paper we focus on the welfare implications of legal IPP in agriculture when this research has commercial application in more than one country. Agricultural markets tend to be unique in that the customer is a farmer who sells the resulting crop or livestock product into competitive domestic and international markets. The farmer further may also have the option of
using unimproved genetics, or possibly the newly developed technology from crops and animals
grown in previous years.

The outcome of the present study is a model that allows policy makers and those who
design domestic ands international mechanisms to protect intellectual property to determine who
benefits from, and who should pay for the associated research.

Recent developments have generated public interest in this topic. First, there has been a
large reduction in research capacity in developing countries due in large part to a reduction in
international funding for this research. This suggests that these countries will rely more and
more on research spillover from more developed countries to remain competitive. Second, the
recent development of genetic use restriction technologies (GURTs) can be viewed as an
extreme form of intellectual property protection, and this technology has received criticism from
some less developed countries. Third, it has recently become possible to trace in a legally
acceptable way particular genetic improvements through to genetic lines sold by other
companies. This scientific development has provided a much stronger legal basis for cross-
country and cross-company IPP. Finally the topic of cross country protections of intellectual
property rights in agriculture continues to stimulate discussion and controversy at international
bodies such as the World Trade Organization via the 1994 Agreement on Trade-Related Aspects
of Intellectual Property Rights (TRIPS).

I.1. Related Research

The framework developed for the present study is based on a recent model by Lence et al.
(2004), who examine the welfare implications of stronger IPP levels in agricultural seeds
markets. The Lence et al. model is nested within the model proposed here and their results can
be replicated within the present model by restricting the number of countries to one. To avoid
duplication of the single-country results presented in Lence et al. (2004), here we focus on the
welfare implications of IPP when research spills over from one country to another. We pay
particular attention to the more interesting and relevant situation where the strength of the IPP regime is different across countries.

Other related work by Moschini and Lapan (1997) examines the welfare implications of IPP in a model with private sector research, but this work does not extend backwards to motivate the incentive structure that generated the innovation. Alston and Venner (2002) and Tongeren and Eaton (2002) incorporate the incentive structure for the R&D firms, but they do not incorporate the market for the crop or the welfare of those who produce the crop. Swanson and Goeschl (2000), and Goeschl and Swanson (2002) point out that GURTs are a way for innovators to protect their intellectual property and they recognize that this will enhance R&D. They also attempt to quantify the potential impact of GURTs on crop yields in developing countries by extrapolating the experience with hybrid seeds. Harhoff, Regibeau, and Rockett (2001) discuss GURTs as a means by which innovators can exert market power and conclude that GURTs may be beneficial because they improve market performance.

The Lence et al. model which we use as the foundation for our work is in turn based on Dixit (1988), Loury (1979), Lee and Wilde (1980), and on Srinivasan and Thirtle (2000). The structure of the Lence et al. model requires simultaneous equilibrium in three markets in each country. The seedstock industry must in equilibrium conduct an amount of research that can be justified by the expected earnings from that research, and each seedstock industry participant must respond to incentives and to competition from other companies in an optimal way. The market for seeds and breeding stock must also be in equilibrium and the farmers who purchase the improved product should do so only if the premium charged is less than the additional profits they can expect. Finally, the domestic and international markets for the final product must be in equilibrium, and changes in costs and farm productivity must eventually impact market prices. A key innovation in the present model is that we allow research conducted and funded in one country to have potential applicability in another country. We parameterize the model and simulate the impact of changes in these three factors on consumer, producer and R&D company welfare in both countries.
II. A Model of Investment in Agricultural R&D

Following Lence et al. (2004), the strength of the IPP regime is embedded in a parameter $\mu_{q,IPP} \equiv \mu_{q,right} + \mu_{cost} \geq 0$, which measures the degree to which the developer of an improved farm input can appropriate the benefits associated with the innovation in country $q$. The level of $\mu_{q,IPP}$ determines the degree of market power that the developer of the improved input can exercise when selling it to farmers in country $q$. Parameter $\mu_{q,right} \geq 0$ is assumed to be increasing with the extent up to which the developer is granted IPP rights on the innovation in country $q$, and with the level of enforcement of such IPP rights in $q$. Appropriability $\mu_{q,IPP}$ also increases with parameter $\mu_{cost} \geq 0$, which reflects the costs of transferring or copying the output-enhancing innovation.

At time 0, R&D firms invest resources to compete in a race to develop $x_1$, a more productive version of an existing farm input (e.g., seed, or breed) $x_0$. A successful outcome ($x_1$) of the development process is random and the R&D competition ends at time $t$, when $x_1$ is first obtained. The first developer of $x_1$ is granted legal IPP for $T$ periods, so the successful innovator enjoys appropriability level $\mu_{q,right} + \mu_{cost}$ over the period $[t, t + T]$. During this period, the improved farm input $x_1$ is sold at the monopoly price if the innovator's appropriability level is high enough. Otherwise, the innovator will charge a markup of $\mu_{q,right} + \mu_{cost}$ over its marginal cost of producing $x_1 (c_1)$. Once the IPP rights expire at time $t + T$, $\mu_{q,right}$ is reduced to zero so that the innovator's appropriability level decreases to $\mu_{cost}$. This further restricts the innovator's ability to charge the monopoly price.

The previous discussion highlights the need to address the various components affecting the R&D investment decision at time 0. Such components include the derived demand for the improved farm input $x_1$ -- which in turn involves the end-demand for farm output, the monopoly pricing decision $w_1^m$, the nature of the R&D process, and the determination of equilibrium in the R&D market at time 0. Each of these components is the object of the following subsections.
II.1. Farm Production

The derived demand for the improved farm input $x_1$ depends on the type of technological improvement that $x_1$ represents with respect to the existing input $x_0$. Given limited space, rather than addressing all possible types of innovations, the following analysis will focus on the case where $x_1$ is a Hicks-neutral improvement in $x_0$, a variable input used by farmers to produce some crop or livestock product $y$. More specifically, let $f_q(x_{q0}, z_q)$ and $g_q(x_{q1}, z_q)$ denote the production functions of country $q$ under $x_{q0}$ and $x_{q1}$, respectively, where $z_q$ is a vector of other variable inputs. Then, the R&D improvement is represented by $g_q(x_{q1}, z_q) = (\alpha_q + 1) f_q(x_{q0}, z_q)$, with improvement factor $\alpha_q \geq -1$ and function $f_q(\cdot)$ assumed to satisfy standard regularity conditions.

The type of R&D improvement considered here is akin to a new crop or livestock variety with yield $\alpha_q \%$ higher than existing varieties. The improvement factor $\alpha_q$ will typically differ across countries, and may even be negative for some countries. However, $\alpha_{q\neq j} > 0$ if the new input was specifically developed to enhance output in country $j$. In this instance, $s_{qej} \equiv \alpha_{qej} / \alpha_{q=j}$ provides a measure of the new technology "spillover" to country $q \neq j$. For example, $s_{qej} < 0$ means that the new technology designed for country $j$ actually reduces output if employed in country $q \neq j$. In contrast, $s_{qej} > 1$ indicates that, even though the new technology was designed for country $j$, it leads to an even greater improvement on the production function of country $q \neq j$.

Given prices $p$, $w_0$, $w_1$, and $r$ associated with farm output $y$ and farm inputs $x_0$, $x_1$, and $z$, respectively, country $q$'s farm profit functions dual to the “traditional” and “new” technologies are (2.1) and (2.2), respectively:

1. $\pi_{q0}(p_q, w_{q0}, r_q) \equiv \max_{x_{q0}, z_q} [ p_q f_q(x_{q0}, z_q) - w_{q0} x_{q0} - r_q z_q ]$,

2. $\pi_{q1}(p_q, w_{q1}, r_q) \equiv \max_{x_{q1}, z_q} [ p_q g_q(x_{q1}, z_q) - w_{q1} x_{q1} - r_q z_q ]$.

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1A Hicks-neutral improvement seems the type of innovation that best represents seed improvements. However, as noted by an anonymous referee, innovations with IPP rights such as Roundup Ready or Liberty Link seeds are less clearly Hicks-neutral because they often have a single specific trait that changes one specific allocation (e.g., herbicide and herbicide application labor). It must be noted that non-Hicks-neutral innovations can be studied in an analogous manner (see Moschini and Lapan (1997) for an example).
If farmers can choose either technology, the unrestricted farmers' profit function is (2.3):

(2.3) \( \pi_q(p_q, w_{q0}, w_{q1}, r_q) \equiv \max[\pi_{q0}(p_q, w_{q0}, r_q), \pi_{q1}(p_q, w_{q1}, r_q)] \).

Profit functions (2.1) through (2.3) are used below to analyze equilibrium in the output and input markets. Note that farmers are assumed to behave as perfect competitors, so that they do not take into account the market impact (i.e., on industry production and overall prices) of the improved input.

II.2. Equilibrium in the Market for Farm Output

Using Hotelling’s lemma, country q’s farm supply \( y_q^* \equiv y_q(p_q, w_{q0}, w_{q1}, r_q) \) may be obtained by taking the partial derivatives of \( \pi_{q0}(p_q, w_{q0}, r_q) \) or \( \pi_{q1}(p_q, w_{q1}, r_q) \), as appropriate, with respect to the output price:

(2.4) \[
\begin{align*}
    y_q^* &= \begin{cases} \\
    \partial \pi_{q0}(p_q, w_{q0}, r_q) / \partial p_q & \text{if } \pi_{q0}(p_q, w_{q0}, r_q) > \pi_{q1}(p_q, w_{q1}, r_q), \\
    \partial \pi_{q1}(p_q, w_{q1}, r_q) / \partial p_q & \text{if } \pi_{q0}(p_q, w_{q0}, r_q) < \pi_{q1}(p_q, w_{q1}, r_q), \\
    \text{and a convex combination of } \partial \pi_{q0}(.) / \partial p_q \text{ and } \partial \pi_{q1}(.) / \partial p_q & \text{otherwise.}
    \end{cases}
\end{align*}
\]

Supply function (2.4) is increasing in \( p_q \) as long as \( \pi_{q0}(p_q, w_{q0}, r_q) \) and \( \pi_{q1}(p_q, w_{q1}, r_q) \) are increasing and convex in \( p_q \).

Equilibrium in the world market for farm output requires prices to equate the total quantity demanded for the crop with the total quantity produced:

(2.5) \[ \sum_{q=1}^{Q} D_q(p_q^*) = \sum_{q=1}^{Q} y_q(p_q^*, w_{q0}, w_{q1}, r_q) \]

where \( D_q(\cdot) \) denotes the Marshallian demand function for the crop in country \( q \). Further, market equilibrium implies no arbitrage opportunities, so that equilibrium output prices and net exports must also satisfy condition (2.6) for all countries \( q \) and \( j \neq q \):

(2.6) \[ p_j^* - p_q^* - \xi_{qj} \leq 0, \; v_{qj} \geq 0, \; (p_j^* - p_q^* - \xi_{qj}) \; v_{qj} = 0, \]
where $\xi_{qj}$ is the transportation cost between countries $q$ and $j$, and $\nu_{qj}$ are exports from country $q$ to country $j$. Conditions (2.5) and (2.6) define a vector of equilibrium prices for farm output $p^* \equiv [p_1^*, \ldots, p_Q^*]$, where $p_q^* \equiv p_q(\omega_0, w_1, r, \xi)$, $\omega_0 \equiv [w_{10}, \ldots, w_{Q0}]$, $w_1 \equiv [w_{11}, \ldots, w_{Q1}]$, and $\xi \equiv [\xi_{12}, \ldots, \xi_{Q-1,Q}]$.

II.3. The Innovation Supplier’s Pricing Decision and Equilibrium in the Input Market

Country $q$’s derived demands for the standard farm input $x_{q0}^* = x_q(p_q, w_{q0}, w_{q1}, r_q)$ and the improved farm input $x_{q1}^* = x_q(p_q, w_{q0}, w_{q1}, r_q)$ are also obtained from application of Hotelling’s lemma:

$$
x_{q0}^* = \begin{cases} 
-\partial \pi_{q0}(p_q, w_{q0}, r_q) / \partial w_{q0} & \text{if } \pi_{q0}(p_q, w_{q0}, r_q) > \pi_{q1}(p_q, w_{q1}, r_q), \\
0 & \text{if } \pi_{q0}(p_q, w_{q0}, r_q) < \pi_{q1}(p_q, w_{q1}, r_q), \\
\text{and a convex combination of 0 and } -\partial \pi_{q0}(p_q, w_{q0}, r_q) / \partial w_{q0} & \text{otherwise},
\end{cases}
$$

$$
x_{q1}^* = \begin{cases} 
-\partial \pi_{q1}(p_q, w_{q1}, r_q) / \partial w_{q1} & \text{if } \pi_{q0}(p_q, w_{q0}, r_q) < \pi_{q1}(p_q, w_{q1}, r_q), \\
0 & \text{if } \pi_{q0}(p_q, w_{q0}, r_q) > \pi_{q1}(p_q, w_{q1}, r_q), \\
\text{and a convex combination of 0 and } -\partial \pi_{q1}(p_q, w_{q1}, r_q) / \partial w_{q1} & \text{otherwise}.
\end{cases}
$$

Equilibrium in the farm output and input markets depends on the behavior of the producers of the farm inputs $x_0$ and $x_1$. In the interest of space, attention will be restricted to scenarios where $x_0$ is supplied by perfectly competitive firms. Also for simplicity, it will be assumed that $x_0$ is produced at constant marginal cost $c_0$, and that $x_1$ is produced by the innovator at constant marginal cost $c_1$. To make the problem interesting, it will also be assumed that $c_1$ and $c_0$ are such that the improved farm input $x_1$ represents a Pareto improvement over the standard farm input $x_0$. This requires that the marginal cost of producing $x_1$ not be “too large” relative to the marginal cost of producing $x_0$.

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The condition that $c_1 \leq [\max(\alpha_q) + 1] c_0$ ensures that $x_1$ is a Pareto improvement over $x_0$, but it is typically much more restrictive than necessary.
Under perfect competition and constant marginal costs \( c_0 \), the price of the standard farm input \( x_0 \) is \( w_{q0} = c_0 \) for all countries \( q \). Hence, if the innovator behaved as a monopoly in each country \( q \), it would set \( w_{q1} = w_{q1}^m( c_0, c_1, r, \xi) \) to maximize profits. That is:

\[
(2.9) \quad w_{q1}^m = \arg\max_{w_{q1}} \{ \sum_{q=1}^{Q} (w_q - c_1) x_q \{ p_q(c_0, w_{q1}, r, \xi), c_0, w_{q1}, r_q \} \}.
\]

Embedded in (2.9) is the pricing constraint imposed by the competition from the traditional input being supplied at price \( c_0 \). Expression (2.9) also assumes that potential arbitrageurs are not allowed to trade the new input across countries to take advantage of price differentials.

In contestable markets (Baumol, Panzar, and Willig (1982)), however, the optimal prices charged by the innovator for the improved farm input will be (2.10) instead of (2.9):

\[
(2.10) \quad w_{q1}^* = \arg\max_{w_{q1}} \{ \sum_{q=1}^{Q} (w_q - c_1) x_q \{ p_q(c_0, w_{q1}, r, \xi), c_0, w_{q1}, r_q \} \},
\]

subject to: \( w_{q1} \leq \mu_{q,IPP} + c_1, q = 1, \ldots, Q \).

In (2.10), \( \mu_{q,IPP} \equiv \mu_{q,right} + \mu_{cost} \) is the innovator’s effective IPP level in country \( q \). According to (2.10), the extent to which the innovator appropriates the rents from the improved input in country \( q \) may be limited by the extra marginal cost incurred by potential competitors to produce \( x_1(\mu_{q,IPP}) \).\(^3\) This extra cost arises from two sources, namely, competitors’ technological disadvantage (\( \mu_{cost} \)) and legal liability (\( \mu_{q,right} \)). For example, in the instance of a seed innovation, \( \mu_{cost} \) would represent the additional costs associated with transferring the trait without access to the original parent lines.\(^4\) This cost would obviously be greater for hybrid lines than for open pollinated varieties. Further, if the seed innovation has a utility patent, the legal liability cost

\(^3\)For example, \( x_1 \) may be produced illegally by firms other than the innovator, or some firms may be allowed to produce small quantities of \( x_1 \) without violating IPP rights. For the case of seeds, an example of the latter situation would be allowing farmers to save seed from an improved variety for their own usage.

\(^4\)Note that \( \mu_{cost} \) is the same across countries. This assumption is adopted to focus on the impact of differential levels of property rights (\( \mu_{q,right} \)) across countries and can be justified if, for example, the costs of trading \( x_1 \) in the absence of legal restrictions were negligible.
faced by those violating the patent would be determined by the probability of being sued and found guilty, and by the fines imposed on them.

In summary, given production costs $c_0$ and $c_1$, the innovator’s degree of market power $\mu_{IPP} = [\mu_{1,IPP}, \ldots, \mu_{Q,IPP}]$, and the values of exogenous variables ($r$ and $\xi$), (2.10) yields the innovator’s optimal prices for input $x_1$ across countries $w_1^*$. In turn, $w_1^*$ determines equilibrium farm output prices $p^*$ from (2.5) and (2.6), total farm output $y^* = \sum q y_q^*$ from (2.4), and the amount of the new input bought by farmers $x_1^* = \sum q x_{q1}^*$ from (2.8).

II.4. A Firm’s Decision to Invest in R&D

The previous subsections address the farm input and farm output markets assuming that $x_1$ already exists. The R&D investment decision is concerned with such markets because they determine the rents accruing to the firm that first gets the innovation $x_1$.

More specifically, if the improved input $x_1$ is first obtained at time $t$ and the innovator is granted an effective level of IPP rights $\mu_{q,\text{right}}$ through the next $T$ periods, the innovator’s IPP levels will be $\mu_{q,IPP} = \mu_{q,\text{right}} + \mu_{cost}$ over the interval $(t, t + T)$ and $\mu_{q,IPP} = \mu_{cost}$ afterward.\textsuperscript{5} Hence, at time $t$ the present value of the rents extracted by the successful innovator are given by (2.11):\textsuperscript{6}

\[
(2.11) \quad v(c_0, c_1, r_1, \xi, \mu_{\text{right}}, \mu_{\text{cost}}, T, i) = \int_{t}^{t+T} \sum_{q=1}^{Q} \{[w_{q1}(\cdot) - c_1] x_{q1}(\cdot)\} |_{\mu_{q,IPP}=\mu_{q,\text{right}}+\mu_{\text{cost}}} \exp(-i \tau) d\tau
\]

\[
+ \int_{t+T}^{\infty} \sum_{q=1}^{Q} \{[w_{q1}(\cdot) - c_1] x_{q1}(\cdot)\} |_{\mu_{q,IPP}=\mu_{\text{cost}}} \exp(-i \tau) d\tau,
\]

\[
(2.11') \quad = i^{-1} [1 - \exp(-iT)] \sum_{q=1}^{Q} \{[w_{q1}(\cdot) - c_1] x_{q1}(\cdot)\} |_{\mu_{q,IPP}=\mu_{q,\text{right}}+\mu_{\text{cost}}}.
\]

\textsuperscript{5}The commercial life of successful corn hybrids in the U.S. market is surprisingly long. For example, Pioneer variety 3147 was introduced in 1969 and continued to sell until 1998, and Pioneer 3165 was introduced in 1982 and was not withdrawn until 2000. Some varieties that were for sale in the 2004 crop year and their respective introductory year are: Pioneer 3394 in 1991, Pioneer 3055 in 1983, Pioneer 3751 in 1988. Other varieties with commercial lives exceeding twenty years were Pioneer 3732 and Pioneer 3183, both of which were introduced in 1976 and withdrawn in the late nineties.

\textsuperscript{6}Expression (2.11') is derived by setting $t = 0$ in (2.11). This is not done explicitly in the latter expression to avoid confusion with the timing of the R&D investment decision, to be discussed later.
\[ + i^{-1} \exp(-iT) \sum_{q=1}^{Q} \{[w_{q1}(\cdot) - c_1] x_{q1}(\cdot) \} \mid \mu_{e,IPP} = \mu_{cost}, \]

where \( i \) is the continuously-compounded interest rate per unit of time and \( \tau \) is a variable of integration. The terms \( \sum_q \{[w_{q1}(\cdot) - c_1] x_{q1}(\cdot) \} \) represent the rents per unit of time accruing to the innovating firm. The present value of each period’s rents is obtained by discounting them at the appropriate discount rate \( i \) by means of \( \exp(-i\tau) \). Finally, the present value of the discounted rents over the entire period is obtained by integrating with respect to time. Expression (2.11) implies that only rents associated with \( \mu_{cost} \) accrue to the supplier of \( x_1 \) beyond the legal protection period (i.e., after time \( t + T \)).

R&D firms must decide whether to attempt to develop \( x_1 \) and obtain the associated IPP before \( x_1 \) exists. Here, such a decision is represented by means of the standard model of R&D competition advanced by Loury (1979), and Lee and Wilde (1980). This model postulates that there are \( N \) identical R&D firms. To participate in the competition to develop the improved farm input \( x_1 \), firm \( n \) must make a lump-sum R&D investment (e.g., physical capital) \( k_n \) and then incur a recurrent cost (e.g., labor) \( l_n \). R&D sunk cost \( k_n \) and recurrent cost \( l_n \) jointly determine the firm’s hazard rate \( h_n = h(k_n, l_n) \), where \( h(\cdot) \) is concave, twice continuously differentiable, strictly increasing, and satisfies \( h(0, 0) = \lim_{k \to \infty} h_1(\cdot) = \lim_{l \to \infty} h_2(\cdot) = 0 \). The firm’s hazard rate \( h_n \) is the conditional probability that it will succeed in developing the improved \( x_1 \) in the next small unit of time, given that no firm has succeeded so far. Individual firms’ hazard rates are thus functions of the respective lump-sum investments and recurrent costs, but are independent of the length of time elapsed since the R&D competition started.

The hazard rate for the R&D industry as a whole (\( H \)) is obtained by adding up the individual hazard rates:

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These conditions on \( h(\cdot) \) are sufficient but not necessary for the following analysis (e.g., Lee and Wilde (1980)). Dixit (1988) discusses the implications of assuming either sunk costs only or recurrent costs only. Succinctly, such polar assumptions yield different implications regarding the effect of alternative R&D policies (e.g., product subsidies and cost subsidies) and the impact of different numbers of firms on R&D levels.
Given that $H$ is the hazard rate for the R&D industry, the probability that no firm has won the race by time $t$ is $\exp(-Ht)$. Further, if no firm has won the race, the probability that firm $n$ (who invested $k_n$ at the starting time 0) will win the R&D race in the next infinitesimally small interval $(t + dt)$ is $h_n dt$. Hence, the unconditional probability that such a firm wins the R&D race over the interval $(t, t + dt)$ is $\exp(-Ht) h_n dt$, and the present value of the expected rents associated with such a victory equals $v(\cdot) \exp(-i t) \exp(-Ht) h_n dt$. As of time 0, the present value of the expected rents to firm $n$ from winning the R&D race is the sum of the latter expression over all future infinitesimal time intervals. That is:

$$
\int_0^\infty v(\cdot) \exp(-i \tau) \exp(-H \tau) h_n d\tau = v(\cdot) h_n/(i + H).
$$

In addition to the lump-sum $k_n$ invested at time 0, R&D firm $n$ will incur the recurrent cost $l_n$ until the race is over. The expected present value of the recurrent costs is (2.14):

$$
\int_0^\tau \int_0^{\tau_1} l_n \exp(-i \tau_0) d\tau_0 \exp(-H \tau_1) H d\tau_1 = \int_0^\infty l_n \left[1 - \exp(-i \tau_1)\right] \frac{i}{i} \exp(-H \tau_1) H d\tau_1,
$$

$$
= l_n/(i + H).
$$

The inner integral on the left-hand side of (2.14) represents the present value of the recurrent costs if the race finished at time $\tau_1$, whereas the term $[\exp(-H \tau_1) H d\tau_1]$ denotes the probability of such an event. The outer integral accounts for the fact that the race may finish at any time after the lump-sum investment is made.

With expected returns and expected recurrent costs given by (2.13) and (2.14'), respectively, the expected profits to firm $n$ from investing the lump-sum $k_n$ at time 0 to participate in the R&D race are:

$$
V(k_n, l_n, H_{(-n)}; \cdot) = v(\cdot) h(k_n, l_n)/[i + h(k_n, l_n) + H_{(-n)}] - k_n - l_n/[i + h(k_n, l_n) + H_{(-n)}],
$$
where $H_{(-n)} \equiv \Sigma_{j \neq n} h(k_j, l_j)$. The decision problem for expected-profit-maximizing R&D firm $n$ consists of choosing $k_n^*$ and $l_n^*$ so as to maximize $V(k_n, l_n, H_{(-n)}; \cdot)$, given the hazard rate $H_{(-n)}$ for the rest of the industry. Optimal values $k_n^* = k^*(H_{(-n)}; \cdot)$ and $l_n^* = l^*(H_{(-n)}; \cdot)$ are obtained from the first-order necessary conditions for the maximization of (2.15).

II.5. Equilibrium in the R&D Market

Optimal lump-sum investment and recurrent costs for each of the R&D entrants are obtained as indicated in the preceding subsection. Because firms are identical, equilibrium in the R&D industry is postulated to be the symmetric Nash equilibrium. That is, the equilibrium optimal capital and labor levels for each of the $N$ R&D firms must satisfy conditions (2.16) and (2.17):

(2.16) $k^e = k^e[(N - 1) h(k^e, l^e); \cdot],$

(2.17) $l^e = l^e[(N - 1) h(k^e, l^e); \cdot].$

Therefore, the equilibrium aggregate lump-sum investment and recurrent costs are given by $K^e = N k^e$ and $L^e = N l^e$, respectively.

From (2.12), (2.16) and (2.17), the equilibrium aggregate industry hazard rate is:

(2.18) $H^e = N h(k^e, l^e).$

Quantification of the equilibrium industry hazard rate $H^e$ is essential to analyze R&D scenarios under alternative parameterizations, as $H^e$ represents the equilibrium probability that the innovation will occur in the next unit of time. In addition, the quantity $1/H^e$ is the equilibrium average time that it takes to obtain the innovation. Given $K^e, L^e,$ and $H^e$, the present value of the aggregate total expected R&D costs in equilibrium is $K^e + L^e/(i + H^e)$. 
II.6. Welfare Analysis

Let $\pi_q^e(\cdot)$, $\pi_q^e(\cdot)|_{\mu_{q,ipp}=\mu_{q,rig}+\mu_{cost}}$, and $\pi_q^e(\cdot)|_{\mu_{q,ipp}=\mu_{cost}}$ denote farmers' equilibrium profits in country $q$ before the innovation, after the innovation but under IPP rights, and after expiration of IPP rights, respectively. Then, if the innovation occurred at time $\tau$, the change in country $q$'s producer surplus per unit of time would be zero up to time $\tau$, $[\pi_q^e(\cdot)|_{\mu_{q,ipp}=\mu_{q,rig}+\mu_{cost}} - \pi_{q,0}^e(\cdot)]$ from time $\tau$ until time $\tau + T$, and $[\pi_q^e(\cdot)|_{\mu_{q,ipp}=\mu_{cost}} - \pi_{q,0}^e(\cdot)]$ afterward. Discounting such changes up to time zero and adding them up yields the present value of the change in producer surplus if the innovation happened at time $\tau$, which is the term within curly brackets in (2.19):

$$\Delta PS_q = \int_0^{\tau_1 + T} \left\{ \int_{\tau_1}^{\infty} [\pi_q^e(\cdot)|_{\mu_{q,ipp}=\mu_{q,rig}+\mu_{cost}} - \pi_{q,0}^e(\cdot)] \exp(-i\tau_0) \, d\tau_0 \right\} \exp(-H^e \tau_1) \, H^e \, d\tau_1,$$

$$= \frac{H^e}{i(i+H^e)} \{ \pi_q^e(\cdot)|_{\mu_{q,ipp}=\mu_{q,rig}+\mu_{cost}} \left[ 1 - \exp(-iT) \right] + \pi_q^e(\cdot)|_{\mu_{q,ipp}=\mu_{cost}} \exp(-iT) - \pi_q^e(\cdot) \}.$$  

The present value of the expected change in country $q$'s producer surplus due to the introduction of the improved input $x_1$ ($\Delta PS_q$) is computed as in (2.19) because $[\exp(-H^e \tau_1) \, H^e]$ is the probability of the innovation occurring during the interval $(\tau_1, \tau_1 + d\tau_1)$.

A similar reasoning can be followed to measure the expected change in country $q$'s consumer surplus due to the innovation ($\Delta CS_q$). That is, define $p_{q,0}^e(\cdot)$, $p_q^e(\cdot)|_{\mu_{q,ipp}=\mu_{q,rig}+\mu_{cost}}$, and $p_q^e(\cdot)|_{\mu_{q,ipp}=\mu_{cost}}$ as the equilibrium crop prices in country $q$ before the innovation, after the innovation but under IPP rights, and after expiration of the IPP rights, respectively. Then, if the innovation occurred at time $\tau$, the change in consumer surplus per unit of time would be zero
until time $\tau_1$, \( \int_{\mu_q,IPP+P_q,\text{right}+P_{\text{cost}}}^{\nu_q} p^{(i)}_q(\zeta) D_q(\zeta) d\zeta \) from time $\tau_1$ until time $\tau_1 + T$, and

\[
\int_{\mu_q,IPP+P_q,\text{right}+P_{\text{cost}}}^{\nu_q} p^{(i)}_q(\zeta) D_q(\zeta) d\zeta \]

after time $\tau_1 + T$. Discounting and adding up such values yields the change in consumer surplus if the innovation occurred at time $\tau_1$, shown as the term within curly brackets in (2.20):

\[
\Delta CS_q = \left\{ \int_0^{\tau_1 + T} \int_{\mu_q,IPP+P_q,\text{right}+P_{\text{cost}}}^{\nu_q} p^{(i)}_q(\zeta) D_q(\zeta) d\zeta \right\} \exp(-i \tau_0) d\tau_0
\]

\[
+ \int_{\tau_1 + T}^{\infty} \int_{\mu_q,IPP+P_q,\text{right}+P_{\text{cost}}}^{\nu_q} p^{(i)}_q(\zeta) D_q(\zeta) d\zeta \right\} \exp(-i \tau_0) d\tau_0 \exp(-H^e \tau_1) H d\tau_1.
\]

(2.20')

\[
\frac{H^e}{i(i + H^e)} \left\{ [1 - \exp(-i T)] \sum_{q=1}^{Q} p^{(i)}_q(\zeta) D_q(\zeta) d\zeta
\]

\[
+ \exp(-i T) \sum_{q=1}^{Q} p^{(i)}_q(\zeta) D_q(\zeta) d\zeta \right\}.
\]

Expression (2.20) takes into account the probabilities associated with the innovation taking place at different times in the future.

Still another welfare measure is the equilibrium aggregate present value of expected profits for the R&D industry (RDS). This can be computed from (2.21):

(2.21) \( RDS = N V(k^e, l^e, (N - 1) h(k^e, l^e); \cdot). \)

That is, RDS is calculated by aggregating (2.15) across the $N$ R&D firms.

If individual utility functions are quasilinear, the aforementioned welfare measures (i.e., $\Delta PS_q$, $\Delta CS_q$, and $RDS$) can be added together to yield a total measure of society's welfare for any social welfare function that society may have (Mas-Colell, Whinston, and Green, Chapter 10.E (1995)).
III. Simulation Specification and Parameterization

We resort to simulations to analyze the implications of technological spillovers on equilibrium welfare and R&D. This requires specifying functional forms for each country’s crop production and demand, and for the hazard rates of the individual R&D firms. Crop production functions under the traditional input are postulated to exhibit constant elasticity of substitution between inputs and decreasing returns to scale (so as to yield upward-sloping crop supply curves):

\[(3.1) \quad f_q(x_{q0}, z_q) = F_q \{[a_{qx} x_{q0}^{(\sigma_q-1)/\sigma_q} + z_q^{(\sigma_q-1)/\sigma_q}]^{\eta_q/(1+\eta_q)}\},\]

where \(F_q \geq 0\) is a scaling parameter, \(\sigma_q \geq 0\) is the constant elasticity of substitution between inputs \(x_{q0}\) and \(z_q\), and \(\eta_q > 0\) is the constant elasticity of crop supply. Parameter \(a_{qx} > 0\) determines the share of total costs due to input \(x_{q0}\), as the cost share equals \(a_{qx} w_{q0}^{1-\sigma_q}/(a_{qx} w_{q0}^{1-\sigma_q} + r_q^{1-\sigma_q})\).

The farm profit function associated with (3.1) is:

\[(3.2) \quad \pi_q(p_q, w_{q0}, r_q) \equiv \eta_q^{\eta_q} (1 + \eta_q^{1+\eta_q}) F_q^{1+\eta_q} p_q^{1+\eta_q} (a_{qx} w_{q0}^{1-\sigma_q} + r_q^{1-\sigma_q})^{-\eta_q/(1-\sigma_q)}.\]

Technology and profits under the improved input \((g_q(x_{q1}, z_q)\) and \(\pi_q(p_q, w_{q1}, r_q),\) respectively) are straightforward to obtain from (3.1) and (3.2) by noting that \(g_q(x_{q1}, z_q) = (\alpha_q + 1) f_q(x_{q0}, z_q).\) Crop demand is assumed to be isoelastic for each country:

\[(3.3) \quad D_q(p_q) = D_q p_q^{-\varepsilon},\]

where \(D_q > 0\) is a scaling parameter and \(\varepsilon_q > 0\) is country \(q\) elasticity of demand for the crop.

Finally, the hazard rate function of each individual R&D firm is represented by a Cobb-Douglas technology with decreasing returns to scale:

\[(3.4) \quad h(k, l) = A \ k^{\kappa_k} l^{\kappa_l},\]

where \(A\) is a scaling parameter, and \(\kappa_k > 0\) and \(\kappa_l > 0\) are constants such that \(\kappa_k + \kappa_l < 1.\)
Simulating the model for $Q$ countries entails specifying values for 2 $Q$ demand parameters ($\varepsilon_q$ and $D_q$), 6 $Q$ supply parameters and exogenous variables ($\eta_q$, $\sigma_q$, $a_{q*}$, $F_q$, $\alpha_q$, $r_q$), $Q$ legal liability parameters ($\mu_{q,\text{right}}$), and $Q$ $(Q - 1)/2$ transaction cost parameters ($\zeta_{qj}$). In addition, values must also be specified for the length of time during which IPP rights are enforced ($T$), the interest rate ($i$), the competitive disadvantage cost ($\mu_{\text{cost}}$), the cost of producing old seed ($c_0$) and new seed ($c_1$), the productivity of "labor" and capital in the R&D process ($\kappa_L$ and $\kappa_K$), and the number of R&D firms ($N$). Therefore, to simplify matters, we restrict attention to simulations involving just $Q = 2$ countries with frictionless crop trade ($\zeta_{qj} = 0$) and identical parameters except for improvement factors ($\alpha_q$) and legal liability parameters ($\mu_{q,\text{right}}$).

For the purpose of reporting results, the parameterization chosen for the benchmark scenario was $\eta = 1.5$, $\varepsilon = 0.5$, $\sigma = 0.3$, cost share = 10%, $T = 20$ years, $i = 10\%$ per year, $\mu_{\text{cost}} = 0$, $\kappa_K = \kappa_L = 0.4$, and $N = 5$ firms. Other parameters of the model are normalized to unity; these are the price of other inputs ($r$), and the cost of producing old seed ($c_0$) and new seed ($c_1$). Letting $q = A$ denote the country for which the new input is developed and $q = B$ the country receiving the technological spillover, simulations were conducted by fixing $A$'s improvement factor at $\alpha_A = 10\%$ and $B$'s legal liability parameter at $\mu_{B,\text{right}} = 0$, and varying spillover from $A$ to $B$ ($s_B \equiv \alpha_B/\alpha_A$) and $A$'s legal liability parameter ($\mu_{A,\text{right}}$) over very large ranges of feasible values. In the reported simulations, countries $A$ and $B$ were assumed to have identical market shares in crop production and consumption. Comprehensive sensitivity analyses of alternative parameterizations were performed, in particular regarding market shares and elasticities. The results were generally very similar to those that are shown in the figures below, apart from some obvious differences in scaling.

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8As explained in Lence et al., the scaling parameter in the hazard rate function is set equal to $A = N^{\kappa_K + \kappa_L - 1}$ to yield meaningful comparisons across regimes with different numbers of R&D firms (i.e., $A$ is normalized to unity for $N = 1$).

9Different output (consumption) market shares are simulated by varying $F_A$ and $F_B$ ($D_A$ and $D_B$). Scaling factors are normalized so that $F_A + F_B = 1 = D_A + D_B$. Hence, for example, a 30% output (consumption) market share for $A$ is obtained by setting $F_A = 0.3$. 

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IV. Results and Discussion

Figure 1 shows the present value of the expected change in consumer surplus in country $A$, under a range of appropriability levels in country $A$ and spillover coefficients from $A$ to $B$. The graph shows that consumers in country $A$ always benefit from strictly positive appropriability ($\mu_{A,IPP} > 0$). When there is no spillover ($s_B = 0$), the change in welfare of consumers in country $A$ increases with additional appropriability up to a value of about $\mu_{A,IPP} = 1.3$. This increase in consumer welfare occurs because increased appropriability encourages R&D, and R&D reduces the crop price as the new technology enhances the output of farmers in country $A$. The reduction in consumer welfare change after this maximum point occurs because the owner of the new technology captures more and more of the benefits associated with it, leaving less room for a reduction in crop prices. However, at even higher appropriability levels ($\mu_{A,IPP} \geq 2.1$), rent extraction by the owner of the new technology is restricted by the possibility of country $A$ farmers reverting to the old technology. Hence, the welfare increase of consumers in $A$ reaches a plateau.

As the spillover level is increased from $s_B = 0$ to $s_B = 1$, the level of appropriability that maximizes the change in consumer welfare increases as well. The logic behind this result is that full spillover allows farmers in country $B$ to take full advantage of the new technology, but the absence of any legal IPP in country $B$ means that the owner of the technology cannot capture any benefit from its use by country $B$ farmers. In this situation, the leakage of rents associated with the spillover reduces the ability of R&D firms to capture the benefits associated with the new technology from all those who use it. This means that less R&D is done than is optimal from the consumers’ standpoint. This rent leakage can be partly offset by increasing the appropriability level in country $A$.

Consumer welfare in country $A$ increases monotonically with the level of spillover. Consumers gain from additional crop output and when R&D conducted in country $A$ leads to additional output from country $B$, consumers benefit regardless of their location. The welfare response surface of consumers in country $B$ is not shown because it is identical to the one shown
for country $A$. This is true because consumers in $A$ and $B$ are assumed to have the same share of world consumption (50% share for each country) in the baseline scenario, and all consumers are assumed to face the same prices regardless of where they live. In general, consumer welfare is greatest whenever spillover is highest and for appropriability $\mu_{A,IPP} \geq 2$. From the consumers’ perspective, a large amount of spillover increases the case for high appropriability in country $A$. This is true because higher appropriability in $A$ encourages R&D, and this enhances not only the production capability of farmers in country $A$ but also that of farmers in $B$. As country $B$ has no IPP, farmers in $B$ do not have to pay any rents to the innovator. In turn, this allows farmers in $B$ to offer their output to all consumers at a lower price.

Figure 2 shows the welfare surface for the R&D industry. This surface is from the same set of simulations used to generate the consumer surface described above, and again the shape of this surface is insensitive to alternative parameterizations. Starting with a spillover of $s_B = 0$, the welfare of R&D firms increases in the level of appropriability in country $A$, but this response flattens when the level of appropriability exceeds $\mu_{A,IPP} = 2.1$. This flattening occurs because farmers in country $A$ always have the choice of reverting to the unimproved breed or variety, and this option limits the monopoly pricing power of the successful R&D firm. The welfare of the R&D industry falls slightly as spillover grows. By assumption, the successful R&D firm cannot capture any rent from producers in country $B$. Research spillovers from country $A$ to country $B$ allow farmers in country $B$ to capture market share from producers in country $A$, because country $A$ farmers must pay a premium for the improved seed that is not charged in country $B$. As this change in the competitiveness of country $A$ farmers decreases the relative size of their crop, it reduces the ability of R&D firms to capture rents from them.

In other simulations that are not reported here, the degree to which the welfare of R&D firms falls with respect to the spillover coefficient increases as the elasticity of supply increases, and as the elasticity of demand falls. However, the degree to which the welfare of R&D firms falls with respect to the spillover is not monotonic in the output share of country $B$; it increases with such a share when the latter is small, and decreases when $B$'s output share is large.
Figures 3 and 4 show the welfare change surfaces for producers in countries $A$ and $B$, respectively, under the same parameters as the consumer and R&D surpluses described above. Starting with a spillover of $s_B = 0$, we see that producers in country $A$ benefit from increased appropriability up to the point $\mu_{A,IPP} = 1.3$. This increase in welfare is surprising because we assume an inelastic demand of $\varepsilon = 0.5$. One would normally expect producers to lose from outward shifts in the supply curve when demand is inelastic. The result comes about because appropriability increases R&D that enhances the technology available to farmers in country $A$, but has no direct impact on the technology available to producers in country $B$. Therefore, such R&D allows farmers in country $A$ to capture market share from producers in country $B$.

However, when we introduce even small amounts of research spillovers (e.g., $s_B \geq 0.2$), the positive link between appropriability and the welfare of producers in country $A$ is broken. Producers in country $A$ are generally worse off when appropriability is high and spillovers are greatest. Figure 4 shows that the welfare change surface of producers in country $B$ tends to mirror the welfare change surface for producers in country $A$.

Figures 5 and 6 show the changes in producer welfare with a much higher demand elasticity of $\varepsilon = 1.5$, and all other parameters at the level used for Figures 3 and 4. These results are very similar to those shown in Figures 3 and 4 despite the large change in the demand elasticity. These results suggest that under a wide range of parameters, producers in country $A$ lose from IPP when spillover is positive.

Figure 7 shows the change in total surplus for country $A$ under the same set of parameters as used in Figures 1 through 4. Total welfare in country $A$ increases with the appropriability level up to a point, and eventually flattens out as R&D firms are allowed to capture rents. Total welfare in country $A$ achieves its maximum when appropriability equals $\mu_{A,IPP} = 1.6$ and spillover is $s_B = 0$. However, the total welfare of country $A$ is largely insensitive to the level of spillover. This is true because losses to country $A$ farmers caused by large spillovers are offset by gains to consumers in $A$. The socially optimal level of appropriability in country $A$ is slightly larger as the level of spillover increases.
Figure 8 shows the welfare change surface for producers, consumers and R&D firms in both countries. World welfare rises monotonically with the level of spillover. Further, except for small spillovers \( s_B \leq 0.3 \), world welfare also rises monotonically with the level of appropriability in country \( A \) up to the point where the ability of R&D firms to capture the benefits of the research is limited by the ability of farmers to revert to the unimproved technology.

V. Summary and Conclusions

The provision of intellectual property rights in agriculture has gained increased attention as governments have attempted to stimulate private sector research. The welfare implications of increased protection of intellectual property in agriculture are fundamentally different from those in the rest of the economy because the customer for the improved product is a farmer who uses the technology to produce a final product that is then sold into competitive markets. A key contribution of the model presented here has been the acknowledgement that in many cases the technology used in agriculture is subject to spillovers. For example, improvements to the genetic composition of plants and animals developed in one country are often captured to some extent by producers in other countries. This fact has some important implications for welfare analysis and for policy prescriptions on where the burden of paying for the research should lie. We have paid particular attention to the realistic case where some countries provide legal protection for intellectual property, while other countries do not offer such protection.

In general, world welfare rises as the amount of research spillover increases, and it increases up to an optimal point in the level of intellectual property protection (IPP) offered in countries that develop the new technologies. This optimal level of protection also increases as spillovers increase because spillovers magnify the benefits of research. In all of the cases we examined, the relationship between world welfare and the level of appropriability flattens at high levels of appropriability.
Producers and consumers in countries with no IPP generally benefit from IPP in other countries so long as some reasonable level of spillover exists. Producers in countries with strong IPP strong almost always lose when spillovers exist, whereas consumers in the country protecting intellectual property always gains from the existence of spillovers. Whether the latter gains are large enough to offset the former losses as spillovers increase, depends on the relative magnitudes of the sectors producing and consuming the crop in the country with high IPP appropriability. When the crop production sector is of similar or greater size than the crop consumption sector (i.e., when the country is an exporter of the crop), producer losses tend to exceed consumer gains as spillovers increase. This result calls into question the use of producer paid technology fees to fund and stimulate research, and suggests that some other mechanism be found to finance this research.
Figure 1. Present value of expected change in country $A$ consumer surplus ($\Delta CS_A$), for inelastic demand ($\varepsilon = 0.5$).

Figure 2. Present value of expected profits for the R&D industry ($RDS$), for inelastic demand ($\varepsilon = 0.5$).
Figure 3. Present value of expected change in country $A$ producer surplus ($\Delta PS_A$), for inelastic demand ($\varepsilon = 0.5$).

Figure 4. Present value of expected change in country $B$ producer surplus ($\Delta PS_B$), for inelastic demand ($\varepsilon = 0.5$).
Figure 5. Present value of expected change in country $A$ producer surplus ($\Delta PS_A$), for elastic demand ($\varepsilon = 1.5$).

Figure 6. Present value of expected change in country $B$ producer surplus ($\Delta PS_B$), for elastic demand ($\varepsilon = 1.5$).
Figure 7. Present value of expected change in country $A$ surplus ($\Delta CS_A + \Delta PS_A + RDS$), for inelastic demand ($\varepsilon = 0.5$).

Figure 8. Present value of expected change in world surplus ($\Delta CS_A + \Delta CS_B + \Delta PS_A + \Delta PS_B + RDS$), for inelastic demand ($\varepsilon = 0.5$).
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