



AgEcon SEARCH
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search

<http://ageconsearch.umn.edu>

aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

Innovation of Agricultural Biotechnology with Experimental Use Licensing

Jeremy Jackson and Jason Smith

Innovation in agricultural biotechnology seed products can be characterized as a non-drastic innovative process with product differentiation. We model this innovation and examine the pricing and purchase decisions for experimental use licensing. In equilibrium, a technologically advantaged firm will purchase a license, while a technologically disadvantaged firm will not. This is the case regardless of the order of pricing decisions.

Key words: non-drastic innovation, product differentiation, quality ladder

New plant varieties are created either through traditional breeding techniques or through advanced genetic modification. Both routes to innovation require access to a diversity of high-quality germplasm. Traditional breeders need a diversity of germplasm so that new traits can be identified and bred. Genotyping and induced mutation have enabled breeders to create and identify traits for breeding with greater accuracy and at a more rapid pace. Likewise, modern genetic engineering requires high-quality germplasm for trait insertion as well as initial identification of traits for development. Germplasm serves as a basic building block in the innovation and development of new seed varieties in either paradigm.

Innovations in the agricultural biotechnology industry, under either traditional or genetic engineering, can be characterized as having a cumulative element, derived from the development of high-quality germplasm, in the presence of product differentiation, as varying genetic traits are targeted. Each firm controls certain seed varieties and germplasm with traits aimed at specific soil and climate targets, such as RoundupTM readiness or drought tolerance. Much research and development (R&D) effort is expended trying to improve the yield or quality of these varieties. Creating new varieties with higher yield (quality) requires the appropriate building blocks. This type of quality-improving innovation requires genetic diversity, yet most of the genetic building blocks in the industry have been inaccessible due to patents and intellectual property protections.

Prior to a recent expansion of widespread cross-licensing of GM traits, agricultural biotechnology and seed companies experienced widespread consolidations in the late 1990s and into the 2000s due to changes in intellectual property for biotechnology (Marco and Rausser, 2008; Howard, 2009). What was once an industry flush with competition is now dominated by the “big six” life science conglomerates (Howard, 2009). In this period, consolidation was the key to gaining access to the intellectual property that innovations required. As intellectual property law for biotechnology has progressed to allow the stacking of multiple genetic traits into one variety, cross-licensing of proprietary traits has proliferated (Howard, 2009). Cross-licensing traits allows a firm that doesn’t own a genetically modified (GM) trait to insert it into their commercial product for sales by paying a royalty to the trait owner. This is a different phenomenon than experimental use

Jeremy Jackson is an associate professor in the Department of Agribusiness and Applied Economics at North Dakota State University. Jason Smith is an associate professor in the Department of Economics and Finance at Utah State University. The authors thank participants of seminars at North Dakota State University, the University of Manitoba, and Utah State University for many helpful comments. Special thanks to Bill Wilson and Scott Schaefer for conversations and comments that guided our thinking in this project.

Review coordinated by Darren Hudson.

licensing, which is the topic of this paper. An experimental use license grants a competitor access to a firm's technology (i.e., germplasm) for use in R&D. The positive result of this R&D is new biotech, potentially subject to its own intellectual property protections.

Galushko, Gray, and Oikonomou (2012, p. 296) note, "Access to prior knowledge could be more important in crop research because genetic advancement tends to be sequential in nature where new varieties are bred from the best of previous varieties." Such sequential innovation is amenable to the quality ladder model of cumulative innovation reviewed nicely in Scotchmer (2004). Traditionally, the quality ladder model is used to characterize patent races whereby firms compete to improve the existing product (moving to the next rung on the quality ladder) and garner the resultant monopoly profits, which are held for as long as the patent for the product currently at the highest rung on the quality ladder is possessed.

Our assessment of innovation in the agbiotech seed industry is that the traditional quality ladder model, which Moschini and Yerokhin (2008b) applied to agricultural biotechnology in a dynamic context, is not sufficiently descriptive of reality. We borrow the framework developed by Jackson and Smith (2015), which builds on models from Malla and Gray (2005) and Tangerås (2009), to construct a model of non-drastic innovation with two firms each moving along their own quality ladder as they produce outputs that compete in a Hotelling-style (1929) model of product differentiation. As one firm improves its quality and the other does not, the innovating firm is able to increase profits and market share but does not monopolize the entire market. Rather, innovated varieties compete with other varieties with different traits.

Farms in different regions with different climates and soil have very different needs and demand seed with different traits. However, individual farms deciding which seed variety to purchase ultimately do not care about the trait target of the variety itself but the yield (quality) of the variety for their particular soil/climate type. As one firm advances to a higher yield (quality) step on their quality ladder, some farms that had previously purchased the variety available from the other firm will switch to the innovated variety, which now provides a greater profit opportunity to the farmer. It is very unlikely that the yield improvement is great enough for all farm types to demand the improved variety; many will still purchase the unimproved variety. Because innovation does not lead to a monopolized market, innovation in agricultural biotechnology seed markets should be modeled as non-drastic.

Improved germplasm and its genetic information, which improves the yield of a seed variety targeted at one trait (or set of traits), may also improve the yield of another variety targeted at a different trait (or set of traits). Thus, one firm's genetic discovery could improve the quality of varieties owned and marketed by other firms. However, this can only occur if access to the genetic material is granted, either through a "research exemption" or the purchase of an experimental use license.

Moschini and Yerokhin (2008b) review at length the intellectual property right issues that permeate agricultural biotechnology. Additionally, Wright and Pardey (2006) and Smith (2008) detail the history of intellectual property for agricultural biotechnology.¹ In the United States and Canada, biotechnology is patentable and there is no applicable research exemption. If one biotechnology firm wants access to the patented intellectual property owned by a competitor for the purposes of R&D in the production of a new patentable seed variety, it must purchase a license for experimental use. Such experimental use licensing is the primary focus of this research.

In this paper, we provide a game-theoretic model of experimental use licensing that highlights the strategic aspects of pricing experimental use licenses, which has yet to be tackled in the literature. We demonstrate that prices will generally be set such that no experimental use licenses are actually purchased, limiting the sharing of intellectual property and inhibiting efficiency. This offers an explanation for the rapid consolidation that swept the industry in the 1990s and 2000s. Experimental

¹ Moschini and Yerokhin (2008a), Koo and Wright (2010), Galushko (2012), Galushko, Gray, and Oikonomou (2012), and Clancy and Moschini (2013) also examine innovation incentives and intellectual property rights for agricultural biotechnology.

use licenses can be bought and sold in equilibrium when both firms have an identical technological level (i.e., the rung on the quality ladder). As agricultural biotechnology firms converge on an equal technological footing, sharing intellectual property for the purposes of R&D becomes possible.

Literature Review

Our focus is similar to that of Moschini and Yerokhin (2008b) and Galushko, Gray, and Oikonomou (2012). Moschini and Yerokhin (2008b) focus on the effects of different intellectual property rights regimes on innovation: with and without a “research exemption” for experimental use in R&D. Under a regime of research exemption, a firm can use proprietary intellectual knowledge in its R&D activities to create a newly patentable product idea without infringement concerns. However, if no such exemption exists, then such use constitutes infringement and risks legal action. In this case, other firms’ intellectual property can only be used for R&D if a license for experimental use is purchased. This is an important issue in many industries in which the product and intellectual property produced and owned by one firm could be an important input into the R&D activities of a competing firm. This describes the agricultural biotechnology industry, as Moschini and Yerokhin (2008b) highlight. However, their model assumes that all market innovations move along *one* quality ladder, with the innovating firm capturing the entire market share and the monopoly profits that go with it. This is inconsistent with the agricultural biotechnology industry in that newly innovated seed strains do not monopolize the market. Rather, improved strains compete against existing strains for market share. Their structure neglects the reality that many innovations are quality improvements on existing products and not entirely new products. Their model makes sacrifices in the strategic environment in order to maintain the tractability requirements of Markov Perfect Equilibrium, which causes their analysis to underplay important aspects of the strategic environment that stem from licensing for experimental use.² Our approach allows the strategy involved in experimental use licensing to take center stage.

Galushko, Gray, and Oikonomou (2012) consider the sharing of intellectual property, through licensing and/or non-protection, between a public firm (university) and a private firm. They are effectively able to demonstrate that public institutions may have incentives to protect their intellectual property, even though this is seemingly against their mission to promote the “public good.” Our approach differs from theirs in several key ways: First, both firms in our environment operate under a profit-maximization motive. Second, and more importantly, while licensing fees do appear in their model, they are taken as given from an exogenous (not modeled) bargaining process.

While this paper focuses on experimental use licensing of germplasm, there are some similarities to the literature on cross-licensing genetically engineered traits that are worth mentioning. The proliferation of cross-licensing GM traits is well documented in the literature (Howard, 2009; Smyth and Gray, 2011; Galushko, Gray, and Oikonomou, 2012), but the theoretical literature on the topic is quite thin. Shi (2009) analyzes a model involving two traditional seed-breeding firms and one firm marketing a GM trait. They focus on explaining patterns of vertical and horizontal integration, treating the products of conventional seed producers as perfect substitutes. The licensing examined is purely from the firm possessing a GM trait to a conventional breeder for insertion and marketing. Their modeling strategy involves a three-stage game, which is solved for subgame perfect Nash equilibrium (NE).

Grossman and Helpman (1991) examine product differentiation with quality improvements along a quality ladder. In their model, each firm’s differentiated output follows its own stochastic progression along a quality ladder, bringing about quality improvements in existing products. However, their main concerns are the implications that such innovations have for the long-run rate of growth in the economy. As such, they ignore intellectual property rights and licensing issues.

² Comments about licensing in Moschini and Yerokhin (2008b) are relegated to a small section without formal analysis.

Innovation with Experimental Use Licensing

Our model suppresses issues of patentability and breadth of an innovation to focus on the competing interests of firms, which can increase their own probability of innovation when an experimental use license is purchased from their rivals.³ Likewise, a firm can sell an experimental use license of its own product to its competitor. Doing so results in a revenue gain from the sale but increases the probability that the rival will advance along its own quality ladder and compete away future profits.⁴ We model innovation as two firms moving along their respective quality ladders, as in Jackson and Smith (2015). Pricing and purchasing experimental use licenses follows a three-stage game⁵. In the first two stages, each firm successively sets the price of an experimental use license,⁶ and in the third stage both firms simultaneously decide to purchase or not purchase a license.

We derive both the pricing decision and the purchase decision for experimental use licensing and show that equilibrium will not result in the efficient exchange of experimental use licenses unless the competing firms have identical levels of initial quality. This is the case regardless of whether the technologically advantaged firm prices before or after the technologically disadvantaged firm. If the intellectual property rights regime were modified to include an experimental use exemption, the efficient exchange of intellectual property would occur.

The licensing game is dynamic, consisting of two periods, $t = 0, 1$. In period $t = 0$, the game begins with firms, indexed by $i = \{a, d\}$, producing and selling their current product with quality y_0^a and y_0^d . Each firm earns a profit that depends on the current product quality of both firms. Each firm may innovate, which improves the quality of its output in the following period.

Firms interact strategically both in the product market and in the purchase and sale of experimental use licensing. Possessing an experimental use license for a rival firm's product changes the distribution from which an innovation is stochastically drawn, increasing the probability of advancement along the quality ladder. Firm a gets profits from its sales in the product market based on the current product qualities of both firms and any revenue or expenses from experimental use license sales and purchases. Finally, based on license purchase decisions, nature will select whether each firm innovates in the next period, which in turn determines profits earned in the product market in the terminal period.

Let k_0 be the differential quality at the start of the game. We have purposefully labeled our two firms a and d to denote that firm a is the technologically advantaged firm and firm d is the technological disadvantaged firm. We adopt this convention so that $k_0 = y_0^a - y_0^d \geq 0$, with the inequality being strict if the two firms begin the game at differing steps along their respective quality ladders. Each firm earns a payoff from its sales in the product market, which depends on the differential quality at that point in time. Product market profits depend only on differential quality, k_0 and k , so we can write $\pi^i(k_0)$ and $\pi^i(k)$ for period $t = 0, 1$ profits, respectively.

Rather than recreate the underlying model of the seed market built up from farmer preferences, we refer to Jackson and Smith (2015)—who derive profit equations in a parametric model of non-drastic innovation such as we describe here—for in-depth description and derivation of the profit equations as they depend on differential quality. The analysis we provide here is more general; we maintain only that the product market profit functions, $\pi^a(k)$ and $\pi^d(k)$, are convex and symmetric

³ Issues of patentability and breadth have long been a focus of the literature. For examples, see Chang (1995), Green and Scotchmer (1995), O'Donoghue (1998), O'Donoghue, Scotchmer, and Thisse (1998), and Hopenhayn and Mitchell (2001).

⁴ Scotchmer (1991) considers the effects of licensing in sequential innovation in the standard quality ladder. Early innovators may license to later innovators who use their product in R&D. The possibility of such agreements being made depends on the breadth of patent protection afforded by law.

⁵ It is common for licensing games to be sequential in both the applied (Shi, 2009; Galushko, Gray, and Oikonomou, 2012) and the general (Kamien and Tauman, 1986; Wang, 1998; Hernandez-Murillo and Llobet, 2006; Sen and Tauman, 2007; Giebe and Wolfstetter, 2008) literatures.

⁶ For robustness, we demonstrate that our results do not depend on the order of pricing decisions. Further, when one firm has a technological advantage, it is quite natural to assume that some form of leader/follower relationship will result. Simultaneity of pricing decisions also eliminates the existence of pure strategy pricing in equilibrium.

in that we can write $-k = y_1^d - y_1^a$ and $\pi^d(k) = \pi^a(-k)$. Both of these properties are met by the Jackson and Smith (2015) parameterization.

We model innovation as a random process that depends on access to the rival's intellectual property. For notational simplicity, we model innovation as it influences the differential quality of the two firms. At time $t = 0$, \tilde{k} is a random variable with cumulative distribution F and density f and support $K \equiv \{k_0 - \Gamma, k_0, k_0 + \Gamma\}$. $\Gamma > 0$ is the distance between rungs on each firm's quality ladder. The realization, k , of the random variable \tilde{k} determines innovation at time $t = 1$ by yielding the difference between firm qualities at time $t = 1$ with $k = y_1^a - y_1^d$. If the quality differential narrows, as would happen when the advantaged firm does not innovate but the disadvantaged firm does, then $k = k_0 - \Gamma$. If the quality differential widens, as would happen when the advantaged firm innovates but the disadvantaged firm does not, then $k = k_0 + \Gamma$. Finally, if the quality differential stays the same, as would happen when either no firm innovates or both firms simultaneously innovate, then the differential quality is unchanged, with $k = k_0$.

In period $t = 0$, a three-stage game is played. In the first stage of period $t = 0$, one firm decides on a price to charge the other firm for an experimental use license to their product. Then, in the second stage, the other firm sets its price after observing the price set in stage one. Finally in the third stage each firm simultaneously decides whether or not to purchase the experimental use license from the other firm. The license has no effect on period $t = 0$ payoffs other than as a source of revenue or expenditure. Profits in period $t = 1$ are determined solely by k . However, nature will decide (probabilistically) whether each firm will innovate based upon the current value of k_0 and access to intellectual property as results from the combined license purchase decisions.

If i purchases a license from j , then the indicator function B^i returns a value of 1; if i does not purchase a license from j then the function B^i takes on a value of 0. Nature chooses k according to a known cumulative distribution function, $F(k|k_0, B^a, B^d) = \int_{-\infty}^k f(x|k_0, B^a, B^d) dx$. Period $t = 1$ is the terminal node, with no license pricing or purchase decisions made. Payoffs are simply awarded based on the realized value of k .

Holding one firm's license purchase decision constant, the probability that the other firm will innovate is larger when it purchases a license. If both (or neither) innovate, the technological gap (and product market profits) is unchanged. This has consequences for the distribution of the technological gap, as outlined in Assumption 1:

$$\text{ASSUMPTION 1. } F(k|k_0, 1, 0) > F(k|k_0, 0, 0) = F(k|k_0, 1, 1) > F(k|k_0, 0, 1).$$

Given the initial technology gap k_0 and license purchase decisions, the set-up of the model yields expected profits from the product market in period $t = 1$ as given in equation 1:

$$(1) \quad E[\pi^i(k)|k_0, B^a, B^d] = \int_{k \in K} \pi^i(k) f(k|k_0, B^a, B^d) dk.$$

As a direct result of Assumption 1, we can write $E[\pi^i(k)|k_0, 1, 1] = E[\pi^i(k)|k_0, 0, 0] = \pi^i$, for $i = \{a, d\}$. Convexity of the profit functions gives us the following inequalities:⁷

$$(2) \quad E[\pi^a(k)|k_0, 1, 0] > \pi^a > E[\pi^a(k)|k_0, 0, 1]$$

and

$$(3) \quad E[\pi^d(k)|k_0, 0, 1] > \pi^d > E[\pi^d(k)|k_0, 1, 0].$$

With δ as the common discount factor and ρ^i as the price i sets for its license, the discounted payoff to i is

$$(4) \quad \pi^i(k_0) + \delta \rho^i$$

⁷ These inequalities are a direct application of Jensen's inequality.

if neither purchases a license and

$$(5) \quad \pi^i(k_0) + \delta\pi^i + \rho^i - \rho^j$$

if both purchase a license.

We now proceed to solve for the best response functions for the license purchase decisions, which depend on the technology gap and license prices: k_0 , ρ^a , and ρ^d .

The Purchase Decision

Let $q^i \in [0, 1]$ be the probability that player i purchases a license, so that the payoff function can be written in the following general forms for each of the respective firms:⁸

$$(6) \quad \begin{aligned} &\Pi^a(\rho^a, \rho^d, q^a, q^d) = \\ &\pi^a(k_0) + q^d(\delta E^a(0, 1) - \delta E^a(0, 0)) + \delta\pi^a + q^d\rho^a - q^a\rho^d \\ &+ q^a q^d(\delta E^a(1, 1) - \delta E^a(0, 1)) + q^a(1 - q^d)(\delta E^a(1, 0) - \delta E^a(0, 0)) \end{aligned}$$

and

$$(7) \quad \begin{aligned} &\Pi^d(\rho^a, \rho^d, q^a, q^d) = \\ &\pi^d(k_0) + q^a(\delta E^d(1, 0) - \delta E^d(0, 0)) + \delta\pi^d + q^a\rho^d - q^d\rho^a \\ &+ q^d q^a(\delta E^d(1, 1) - \delta E^d(1, 0)) + q^d(1 - q^a)(\delta E^d(0, 1) - \delta E^d(0, 0)) \end{aligned}$$

The payoff functions simply represent the benefits and costs of a change in the technology gap combined with any license sales. From these payoff functions, the best response correspondence for the license purchase decision given license prices can be simply derived. We make use of some additional simplifying notation: Define $E_a^B(q^d)$ as the expected benefit to a from purchasing a license given the purchase decision of d , q^d .

$$(8) \quad E_a^B(q^d) = q^d \delta E^a(1, 1) - \delta E^a(0, 1) + (1 - q^d) \delta E^a(1, 0) - \delta E^a(0, 0)$$

The expected benefit to d from purchasing a license given the purchase decision of a is analogously written as

$$(9) \quad E_d^B(q^a) = q^a (\delta E^d(1, 1) - \delta E^d(1, 0)) + (1 - q^a) (\delta E^d(0, 1) - \delta E^d(0, 0)).$$

The best response correspondence for firm i , given below, demonstrates that a firm will only buy a license if the price is at or below its expected return.

$$(10) \quad q^i(q^j) = \begin{cases} q^i = 1 & \text{if } E_i^B(q^j) \geq \rho^j \\ q^i = 0 & \text{if } E_i^B(q^j) \leq \rho^j \\ q^i \in [0, 1] & \text{if } E_i^B(q^j) = \rho^j \end{cases}$$

The best response correspondences for the license purchase decisions are compact-valued and upper hemicontinuous, guaranteeing the existence of a Nash equilibrium to the third-stage license purchase game for any given prices $\rho^a \geq 0$ and $\rho^d \geq 0$. Proposition (1) describes these equilibria

⁸ Throughout, we use $E^i(1, 1)$ to represent $E(\pi^i(k)|k_0, 1, 1)$, suppressing both $\pi^i(k)$ and k_0 for ease of readability.

in detail. If the prices charged by both firms are small compared to the change in expected profits brought about by the license purchase, then there will be an equilibrium in which both firms purchase an experimental use license, as demonstrated by Case 1 in Proposition (1). When both firms charge too high a price, as in Case 2, neither firm will purchase a license in equilibrium. However, if either firm charges too high a price, the other firm will not purchase the license, as in Cases 3 and 4. Case 5 demonstrates that for intermediate levels of pricing, there is a mixed strategy equilibrium. There are many possible equilibrium outcomes dependent on the prices of both licenses relative to the expected profits from purchasing.

PROPOSITION 1. *Nash equilibrium to the license purchase game is characterized by the following conditions:*

1. *There is a pure strategy NE with $\{q^a, q^d\} = \{1, 1\} \iff$ both*

$$(a) \delta E^a(1, 1) - \delta E^a(0, 1) \geq \rho^d$$

$$(b) \delta E^d(1, 1) - \delta E^d(1, 0) \geq \rho^a$$

2. *There is a pure strategy NE with $\{q^a, q^d\} = \{0, 0\} \iff$ both*

$$(a) \delta E^a(1, 0) - \delta E^a(0, 0) \leq \rho^d$$

$$(b) \delta E^d(0, 1) - \delta E^d(0, 0) \leq \rho^a$$

3. *There is a pure strategy NE with $\{q^a, q^d\} = \{1, 0\} \iff$ both*

$$(a) \delta E^a(1, 0) - \delta E^a(0, 0) \geq \rho^d$$

$$(b) \delta E^d(1, 1) - \delta E^d(1, 0) \leq \rho^a$$

4. *There is a pure strategy NE with $\{q^a, q^d\} = \{0, 1\} \iff$ both*

$$(a) \delta E^a(1, 1) - \delta E^a(0, 1) \leq \rho^d$$

$$(b) \delta E^d(0, 1) - \delta E^d(0, 0) \geq \rho^a$$

5. *There is a mixed strategy NE with*

$$(11) \quad q^a = \frac{\rho^a - \delta E^d(0, 1) - \delta E^d(0, 0)}{\delta E^d(1, 1) - \delta E^d(1, 0) - \delta E^d(0, 1) - \delta E^d(0, 0)}$$

$$q^d = \frac{\rho^d - \delta E^a(1, 0) - \delta E^a(0, 0)}{\delta E^a(1, 1) - \delta E^a(0, 1) - \delta E^a(1, 0) - \delta E^a(0, 0)}$$

if both

$$(a) \delta E^d(1, 1) - \delta E^d(1, 0) < \rho^a < \delta E^d(0, 1) - \delta E^d(0, 0)$$

$$(b) \delta E^a(1, 1) - \delta E^a(0, 1) < \rho^d < \delta E^a(1, 0) - \delta E^a(0, 0)$$

Proof. Follows directly from the best response function specified in equation (10). ■

In the sections that follow, we consider three distinct games. First, we solve for equilibrium experimental use license prices for a game in which the technologically advantaged firm prices first. Then we consider a game in which the technologically disadvantaged firm prices first. Finally, we consider the case in which no firm has a technological advantage as both firms technology lie on equal rungs of their respective quality ladders.

License Pricing: Advantaged Prices First

We now consider the research-licensing game as a whole, taking into account the complication of license pricing. We model pricing as a two-stage process whereby one firm prices first with the other pricing subsequently after observing the price set by the other firm. In this section, we consider that the technologically advantaged firm, a , prices first. The definitions of firm strategy and equilibrium depend on the order of play.

A strategy for advantaged firm a , s^a , is a pair $s^a = (q^a(\rho^a, \rho^d(\rho^a)), \rho^a)$, where $q^a(\rho^a, \rho^d(\rho^a))$ is the probability that a purchases f 's license and ρ^a is the price a charges f for a 's license. A strategy for disadvantaged firm d , s^d , is a pair $s^d = (q^d(\rho^a, \rho^d(\rho^a)), \rho^d(\rho^a))$, where $q^d(\rho^a, \rho^d(\rho^a))$ is the probability that d purchases a 's license and ρ^d is the price d charges a for d 's license. Because we focus our solution on subgame perfect equilibrium, each player must believe that the other will always make purchase decisions according to her best response function, $q^i(\rho^i, \rho^j)$.

DEFINITION 1. *A subgame perfect equilibrium to the pricing game, with the advantaged firm pricing first, is a strategy profile, s , such that the following conditions are met:*

1. q^a and q^d are a Nash Equilibrium to the license purchase game given ρ^a and $\rho^d(\rho^a)$.
2. $\rho^d(\rho^a)$ must be optimal given purchase strategies q^a and q^d and the price ρ^a set by the advantaged firm.
3. ρ^a must be optimal given purchase strategies q^a and q^d and the pricing strategy of f , $\rho^d(\rho^a)$.

We proceed using backward induction to find subgame perfect equilibria by first finding the optimal pricing strategy for the disadvantaged firm given the price set by the advantaged firm. Proposition 2 shows that $\rho^d(\rho^a)$ will take one of two values depending on whether ρ^a is above or below a threshold. If ρ^a is sufficiently large, the disadvantaged firm sets a price for its license whereby only the technologically advantaged firm will purchase a license. However, with ρ^a sufficiently low, the disadvantaged firm will set its price at a level so that both purchase a license.

More specifically, when the price of the advantaged firm's license exceeds the discounted change in expected profits to the disadvantaged firm (calculated as the difference between expected profits when both firms purchase a license compared to the case where the advantaged firm purchases but disadvantaged does not), the disadvantaged firm will price at the highest amount possible that will induce the advantaged firm to purchase its license. Conversely, when the advantaged firm prices at or below the same value, the disadvantaged firm will price at the highest level possible that will induce both firms to purchase an experimental use license from the other.

PROPOSITION 2. *The best response function for the disadvantaged firm when the advantaged firm prices first is*

$$(12) \quad \rho^d(\rho^a) = \begin{cases} \delta E^a(1,0) - \delta E^a(0,0) & \text{if } \rho^a > \delta E^d(1,1) - \delta E^d(1,0) \\ \delta E^a(1,1) - \delta E^a(0,1) & \text{if } \rho^a \leq \delta E^d(1,1) - \delta E^d(1,0) \end{cases}$$

Proof. See Appendix. ■

Given this best response function for the disadvantaged firm, the technologically advantaged firm can choose to either price low so that both end up purchasing a license or price high so that only the advantaged firm purchases, having effectively priced the disadvantaged firm out of the license market. Proposition 3 shows that it is in the advantaged firm's best interest to price at a high level that prevents the disadvantaged firm from purchasing a license.

PROPOSITION 3. *The optimal price for the advantaged firm, when pricing first, is any $\rho^a(k_0)$ such that $\rho^a(k_0) > \delta E^d(1,1) - \delta E^d(1,0)$.*

Proof. See Appendix. ■

Having derived the purchase and optimal pricing decisions of both firms when the advantaged firm prices first, we can focus on equilibrium. While this game has multiple prices the advantaged firm could set in equilibrium, all such equilibria produce the same equilibrium outcome and payoffs. The advantaged firm prices too high for the disadvantaged firm to purchase its license, while the disadvantaged firm sets its price at the highest possible level at which the advantaged firm is willing to purchase. Only the advantaged firm purchases an experimental use license in equilibrium. This is summarized in Theorem 1:

THEOREM 1. *If the technologically advantaged firm prices first, then all subgame perfect equilibria to this game have the same outcome: the advantaged firm purchases a license at price $\rho^d = \delta E^a(1,0) - \delta E^a(0,0)$ and sets a price of $\rho^a > \delta E^d(1,1) - \delta E^d(1,0)$ so that the disadvantaged firm does not purchase a license.*

Proof. Follows directly from Propositions 1, 2, and 3. ■

License Pricing: Disadvantaged Prices First

Next we consider the case in which the technologically disadvantaged prices in the first stage, with the advantaged firm pricing in the second stage after observing the price set by the disadvantaged firm. In the third stage, both players simultaneously make purchase decisions. Because the definitions of a firm strategy and equilibrium depend on the order of play, we offer new definitions of each.

A strategy for the advantaged firm, s^a , is a pair $s^a = (q^a(\rho^a(\rho^d), \rho^d), \rho^a(\rho^d))$, where $q^a(\rho^a(\rho^d), \rho^d)$ is the probability that a purchases d 's license and ρ^a is the price a charges d for its own license. A strategy for the disadvantaged firm, s^d , is a pair $s^d = (q^d(\rho^a(\rho^d), \rho^d), \rho^d)$, where $q^d(\rho^a(\rho^d), \rho^d)$ is the probability that d purchases a 's license and ρ^d is the price d charges a for its own license. Since we focus our solution on subgame perfect equilibrium, each player must believe that the other will always make purchase decisions according to her best response function, $q^i(\rho^i, \rho^j)$.

DEFINITION 2. *A subgame perfect equilibrium to the pricing game, with the disadvantaged firm pricing first, is a strategy profile, s , such that the following conditions are met:*

1. q^a and q^d are a Nash Equilibrium to the license purchase game given $\rho^a(\rho^d)$ and ρ^d .
2. ρ^d must be optimal given purchase strategies q^a and q^d and the pricing strategy of the advantaged firm, $\rho^a(\rho^d)$.
3. $\rho^a(\rho^d)$ must be optimal given purchase strategies q^a and q^d and the price ρ^d set by the disadvantaged firm.

Again, this game is solved using backward induction to find subgame perfect equilibrium. First, we find the optimal pricing strategy for the advantaged firm given the price set by the disadvantaged firm. If the disadvantaged firm has priced its license sufficiently low, then the advantaged firm will set a price that is high enough so that only the advantaged firm will purchase a license. However, if the disadvantaged firm has set a high price, the advantaged firm will set its price in such a manner that neither will purchase a license. This result is given in Proposition 4.

When the disadvantaged firm prices at an amount that is equal to or exceeds the discounted expected gain to the advantaged firm from buying a license, given that the disadvantaged firm has

not purchased a license, the advantaged firm will set the price for its experimental use license high enough to extract all the expected gains that the disadvantaged firm could gain by its purchase. Thus, the disadvantaged firm does not purchase an experimental use license. Likewise, if the disadvantaged firm prices below the same threshold, the advantaged firm will price in such a manner that it will preclude the purchase of a license by the disadvantaged firm, while purchasing an experimental use license for itself.

PROPOSITION 4. *When the disadvantaged firm prices first, the best response function for the advantaged firm is*

$$(13) \quad \rho^a(\rho^d) \begin{cases} \delta E^d(0,1) - \delta E^d(0,0) & \text{if } \rho^d \geq \delta E^a(1,0) - \delta E^a(0,0) \\ \delta E^d(1,1) - \delta E^d(1,0) & \text{if } \delta E^a(1,0) - \delta E^a(0,0) > \rho^d \end{cases}$$

Proof. See Appendix. ■

Given that the best response function of the advantaged firm’s license pricing as a function of the disadvantaged firm’s license price, the disadvantaged firm essentially has a decision to either set its price in a manner that will ultimately result in only the advantaged firm purchasing a license or setting its price such that neither firm purchases a license. The disadvantaged firm gets the higher payoff by pricing so that the advantaged firm will purchase its experimental use license. The price the disadvantaged firm sets is given in Proposition 5.

PROPOSITION 5. *The optimal price for the disadvantaged firm, when pricing first, is $\rho^d = \delta E^a(1,1) - \delta E^a(0,1)$.*

Proof. See Appendix. ■

We now have all of the components needed to make a statement about the subgame perfect equilibria to the license pricing game when the disadvantaged firm prices first. Again, there are many equilibria to this game, as there are many prices that the advantaged firm could set that would yield identical payoffs. However, each of these equilibria have the same outcome. In any subgame perfect equilibrium, only the advantaged firm purchases an experimental use license. This is summarized in Theorem 2.

THEOREM 2. *If the technologically disadvantaged firm prices first, then all subgame perfect equilibria to this game have the same outcome that involves the disadvantaged firm setting a price of $\rho^d = \delta E^a(1,1) - \delta E^a(0,1)$ and the advantaged firm setting a price $\rho^a > \delta E^d(1,1) - \delta E^d(1,0)$ so that the disadvantaged firm does not purchase a license but the advantaged firm will.*

Proof. Follows from propositions 1, 4, and 5. ■

Theorems 1 and 2 are strikingly similar. Whether the advantaged or disadvantaged firm prices first has no bearing on the final license purchase decisions other than the price paid by the advantaged firm for a license to use the technology of the disadvantaged firm. In both scenarios, only the advantaged firm purchases a license, and the advantaged firm actually pays a lower price for the license it purchases when the disadvantaged firm prices first.

A Technological Tie

Now suppose that both firms start the game at an identical rung on their respective quality ladder (i.e., $k_0 = 0$). In this case, neither can be characterized as advantaged or disadvantaged, so it is unnecessary to list identity in the order of play. Without loss of generality, we let player i price first,

followed by player j . Player j 's best response pricing correspondence (as it depends on the price set by player i) is the same as that found in Proposition 2, replacing a with i and d with j .

The next step is to identify player i 's optimal pricing strategy given j 's best response. The optimal pricing strategy for i is given in Proposition 6, which is similar to the result in Proposition 3 except that the inequality is now weak. The player pricing first can either set the price such that the equality is satisfied, resulting in both players purchasing a license, or it can set the price high so that the player pricing first is the only one that will purchase a license. The price set by the first mover will be equal to or greater than the discounted expected profits that the second mover could gain, given that the first mover purchases a license.

PROPOSITION 6. *When firms have a technological tie, the optimal price for player i is $\rho^i(k_0) \geq \delta E^i(1, 1) - \delta E^j(1, 0)$.*

Proof. See Appendix. ■

Using these optimal pricing strategies, it is now possible to characterize equilibrium for the case of a technological tie in theorem 3 below. The theorem shows that two possible outcomes could occur in a subgame perfect equilibrium. Either the equilibrium is practically identical to that in Theorem 2, with the player pricing first purchasing a license but the player pricing second not purchasing a license, or both players purchase a license.

THEOREM 3. *When there is no technological advantage, $k_0 = 0$, and player i prices before j , there are two possible outcomes in a subgame perfect equilibrium:*

1. *Player i purchases a license at a price of $\rho^j = \delta E^i(1, 0) - \delta E^i(0, 0)$ and sets a price $\rho^i > \delta E^j(1, 1) - \delta E^j(1, 0)$ so that j does not purchase a license.*
2. *Player i purchases a license at a price of $\rho^j = \delta E^i(1, 0) - \delta E^i(0, 0)$ and sets a price $\rho^i = \delta E^j(1, 1) - \delta E^j(1, 0)$ so that both i and j purchase a license.*

Proof. Follows directly from Propositions 1, 2, and 6. ■

Extensions

Large Innovations

In the analysis presented above, we have considered the possibility of patentable innovations that are small in the sense that they do not allow the innovator to capture the entire market share. We now discuss the effect of a large innovation which *does* allow the innovator to capture the entire market on experimental use licensing.

In this case, the innovation is of such a large magnitude that all consumers will choose to purchase the product of the innovating firm. To keep matters simple, we assume that in this case the non-innovating firm will go out of business, resulting in profits of zero in the subsequent period, while the innovating firm captures monopoly profits of $M > \pi(k)$.

Whenever a license is sold in our model, the seller charges a price such that the entire discounted expected gain in profits from the innovation are appropriated to the seller. This leaves the purchaser indifferent between buying the license or not. The seller is only willing to make such a sale if this sales price is sufficient to cover the discounted expected loss it would suffer from falling behind technologically. Now that the sale of the license increases the probability of the advantaged firm innovating and thus the disadvantaged firm going out of business, the sale price of the license will have to be sufficiently large to cover all of the expected loss. Such a license will only be sold if the monopoly profits are sufficiently large. The advantaged firm will still find itself in a situation whereby it is unable to sell a license to the disadvantaged firm.

Innovation that leads to monopoly power decreases the parameter space for which any experimental use license can be sold and does not allow for both firms to buy a license from the other in any equilibrium.

Complementary Research and Development

A key limitation of the model presented here is that the decision about how much to invest in R&D itself is ignored. We hold R&D expenditure and effort constant, isolating only the marginal impact of experimental use licensing on innovation. This is not so different from the approach of Galushko, Gray, and Oikonomou (2012), in which research activities are determined *ex ante* and access to intellectual property reduces breeding cost, as opposed to our model, in which access to intellectual property increases the probability of innovation.

A richer model would make the R&D expenditures decision endogenous. A key question is whether complementarity between internal R&D efforts and possessing an experimental use license increases the incidence under which experimental use licenses can be sold. Allowing innovation to occur with increasing probability with increased internal R&D expenditure reduces a firm's reliance on possessing an experimental use license for the purposes of innovation, the price required by the seller of an experimental use license is likely to be lower. However, with high levels of complementarity between internal R&D and experimental use licensing (large investment in internal R&D can increase the degree to which an experimental use license increases the probability of innovation), the value of the license to the purchaser increases, as does the price required by a license seller. These effects cannot be intuited without additional modeling.

Efficient Licensing

The question of what licensing arrangement is efficient requires an analysis of the full economic welfare effects of licensing. This requires consideration not only of the profits gained by the firms purchasing and selling experimental use licenses but also of the welfare of agents in the product market.⁹ We reference the model of the product market found in Jackson and Smith (2015), which derives the welfare implications of innovation on both the firms and the agents that purchase their output in the product market. Proposition 4 in that paper shows that welfare increases the most when both firms innovate rather than only one firm innovating.

Simultaneous innovation by both firms increases total welfare by the largest amount, so that efficient experimental use licensing requires each firm to buy a license from the other. This maximizes the probability that both firms will innovate. Unfortunately, this pattern of licensing is rarely present in equilibrium. In fact, the only case in which both firms could simultaneously purchase an experimental use license is when both firms' initial products have identical quality. Even then, the equilibrium is not unique, as there is also an equilibrium in which the firm that prices its license first is the only firm that purchases an experimental use license.

What would be an appropriate policy to combat this lack of efficiency in innovation resulting from too little experimental use licensing? The main policy tool at play is the intellectual property rights regime itself. We considered the regime in which each firm has the right not only to sell its product exclusively but also possesses the exclusive right to use its product in R&D. An alternative property right regime is to maintain exclusivity in product sales but give a research exemption allowing the free use of existing products in the R&D activities of all firms. This regime allows R&D to move forward uninhibited by the sluggish sales of experimental use licenses and would thus be efficient.

This analysis of efficiency ignores the decision to conduct R&D itself, which is itself a limitation of the current research. With a research exemption, the incentive to conduct R&D in the first place

⁹ In our context, agents in the product market are farms that purchase seed.

would certainly be diminished and could substantially alter the efficiency result presented in this section.

Extended Time Horizon

Our model was created to focus attention on the strategic interaction stemming from experimental use license pricing and purchase decisions when access to a competing firm's output for experimental research increases the probability of innovation. In keeping with this focus, we only consider a world with two periods. One direction for future research is to consider the effect of a longer time horizon on the licensing decisions, which could have large consequences as it becomes possible for innovation to cause lead switching. If the disadvantaged firm is able to innovate in multiple periods while the advantaged firm fails to innovate, eventually the disadvantaged firm's quality level will overtake that of the advantaged firm. This possibility will increase the value of an experimental use license to the disadvantaged firm but simultaneously raise the price that the advantaged firm would require to make such a sale.

Conclusion

The nature of technological innovation for products in many markets (e.g., agricultural biotechnology) follows the model of sequential innovation as set forth by the quality ladder model. However, a limiting assumption of the quality ladder model is that when a firm that makes a patentable innovation is then able to monopolize the market. Yet most innovated products compete alongside older generations of products from other firms. Innovation gives the innovating firm an advantage, but it does not generally eliminate all competition.

We model sequential innovation whereby two firms produce differentiated products and compete for market share. Innovation by a firm results in a quality improvement of the existing product (e.g., increased yield for a strain of wheat targeted for land with specific traits). Additionally, firms may buy and sell a license for the experimental use of each others' products in R&D activities. Buying a license to use a competitor's product in R&D increases the probability of an innovation occurring. This complicates the strategic environment as selling a license has two effects: a direct increase in revenue due to the sale and an increased probability of the competitor innovating, which reduces profitability. Previous literature (Moschini and Yerokhin, 2008b; Galushko, Gray, and Oikonomou, 2012) was not able to focus attention on the endogenous pricing and purchase of experimental use licenses, while we explicitly derive these as they occur in equilibrium.

In equilibrium play with one firm having a technological advantage, the order of play has little bearing on the equilibrium. The technologically advantaged firm will purchase an experimental use license from the disadvantaged firm, but the disadvantaged firm will fail to purchase a license from the advantaged firm. This may seem counterintuitive, as it can be difficult to imagine why a firm with superior technology would have any need for inferior technology in R&D. Ours is not a model that can apply to every possible scenario but is descriptive of patterns of innovation in the agricultural biotechnology sector, where one of the key ingredients in creating new germplasm is the possession of genetic diversity. Even innovations created by inserting genetically engineered traits still depend on high-quality base germplasm to produce marketable seed.

While our modeling strategy has its limitations, the applicability of our framework extends beyond the confines of agricultural biotechnology. The cell phone industry provides another example of a market in which new product generations (quality improvements for an existing product) compete with older product generations. New products compete alongside newly innovated products. The cell phone market recently experienced a revolution with the introduction of third- and fourth-generation cellular networks, with fifth-generation networks coming soon. These high-speed networks have allowed cell phones to increasingly make use of data and internet connectivity, but not all customers value a data-driven phone. Some customers are content with voice-only services,

well after fourth-generation networks have proliferated. As such, when Verizon launched its fourth-generation cellular network in 2010, it still had to compete with other providers that only had third-generation networks. The innovation did not lead to a monopoly but certainly had an effect on consumers' purchase decisions and firm profitability. A similar dynamic is present in the video game console market, as Sony, Microsoft, and Nintendo all compete for market share. When one firm innovates, it may temporarily gain market share but, thus far, no firm has achieved complete market domination. This type of continued competition after a cumulative innovation also permeates many software development markets. Our modeling approach and conclusions regarding experimental use licensing extend to these markets as well.

[Received January 2018; final revision received May 2018.]

References

- Chang, H. F. 1995. "Patent Scope, Antitrust Policy, Cumulative Innovation." *RAND Journal of Economics* 26: 34–57. doi:10.2307/2556034.
- Clancy, M. S., and G. Moschini. 2013. "Incentives for Innovation: Patents, Prizes, and Research Contracts." *Applied Economic Perspectives and Policy* 35(2)(2): 206–241. doi:10.1093/aapp/ppt012.
- Galushko, V. 2012. "Do Stronger Intellectual Property Rights Promote Seed Exchange: Evidence from U.S. Seed Exports?" *Agricultural Economics* 43: 59–71. doi:10.1111/j.1574-0862.2012.00620.x.
- Galushko, V., R. Gray, and E. Oikonomou. 2012. "Operating in an Intellectual Property World: Knowledge Sharing among Plant Breeders in Canada." *Canadian Journal of Agricultural Economics* 60: 295–316. doi:10.1111/j.1744-7976.2011.01235.x.
- Giebe, T., and E. Wolfstetter. 2008. "License Auctions with Royalty Contracts for (Winners and Losers)." *Games and Economic Behavior* 63: 91–106. doi:10.1016/j.geb.2007.08.010.
- Green, T. R., and S. Scotchmer. 1995. "On the Division of Profit in Sequential Innovation." *RAND Journal of Economics* 26: 20–33. doi:10.2307/2556033.
- Grossman, G. M., and E. Helpman. 1991. "Quality Ladders in the Theory of Growth." *Review of Economic Studies* 58: 43–61. doi:10.2307/2298044.
- Hernandez-Murillo, R., and G. Llobet. 2006. "Patent Licensing Revisited: Heterogeneous Firms and Product Differentiation." *International Journal of Industrial Organization* 24: 149–175. doi:10.1016/j.ijindorg.2005.03.008.
- Hopenhayn, H. A., and M. F. Mitchell. 2001. "Innovation Variety and Patent Breadth." *RAND Journal of Economics* 32: 152–166. doi:10.2307/2696402.
- Hotelling, H. 1929. "Stability in Competition." *Economic Journal* 39: 41–57. doi:10.2307/2224214.
- Howard, P. H. 2009. "Visualizing Consolidation in the Global Seed Industry: 1996–2008." *Sustainability* 1: 1266–1287. doi:10.3390/su1041266.
- Jackson, J., and J. Smith. 2015. "A Framework for Non-Drastic Innovation with Product Differentiation." *Economics Bulletin* 35: 259–269.
- Kamien, M. I., and Y. Tauman. 1986. "Fees versus Royalties and the Private Value of a Patent." *Quarterly Journal of Economics* 101: 471–492. doi:10.2307/1885693.
- Koo, B., and B. D. Wright. 2010. "Dynamic Effects of Patent Policy on Sequential Innovation." *Journal of Economics and Management Strategy* 19: 489–512. doi:10.1111/j.1530-9134.2010.00259.x.
- Malla, S., and R. Gray. 2005. "The Crowding Effect of Basic and Applied Research: A Theoretical and Empirical Analysis of an Agricultural Biotech Industry." *American Journal of Agricultural Economics* 87: 423–438. doi:10.1111/j.1467-8276.2005.00732.x.

- Marco, A. C., and G. C. Rausser. 2008. "The Role of Patent Rights in Mergers: Consolidation in Plant Biotechnology." *American Journal of Agricultural Economics* 90: 133–151. doi:10.1111/j.1467-8276.2007.01046.x.
- Moschini, G., and O. Yerokhin. 2008a. "Intellectual Property Rights and Crop-Improving R&D under Adaptive Destruction." *Environmental and Resource Economics* 40: 53–72. doi:10.1007/s10640-007-9140-5.
- . 2008b. "Patents, Research Exemption, and the Incentive for Sequential Innovation." *Journal of Economics and Management Strategy* 17: 379–412. doi:10.1111/j.1530-9134.2008.00182.x.
- O'Donoghue, T. 1998. "A Patentability Requirement for Sequential Innovation." *RAND Journal of Economics* 29: 654–679. doi:10.2307/2556088.
- O'Donoghue, T., S. Scotchmer, and J.-F. Thisse. 1998. "Patent Breadth, Patent Life, and the Pace of Technological Progress." *Journal of Economics and Management Strategy* 7: 1–32. doi:10.1111/j.1430-9134.1998.00001.x.
- Schotchmer, S. 1991. "Standing on the Shoulders of Giants: Cumulative Research and the Patent Law." *Journal of Economic Perspectives* 5: 29–41. doi:10.1257/jep.5.1.29.
- Scotchmer, S. 2004. *Innovation and Incentives*. Cambridge, MA: MIT Press.
- Sen, D., and Y. Tauman. 2007. "General Licensing Schemes for a Cost-Reducing Innovation." *Games and Economic Behavior* 59: 163–186. doi:10.1016/j.geb.2006.07.005.
- Shi, G. 2009. "Bundling and Licensing of Genes in Agricultural Biotechnology." *American Journal of Agricultural Economics* 91: 264–274. doi:10.1111/j.1467-8276.2008.01174.x.
- Smith, S. 2008. "Intellectual Property Protection for Plant Varieties in the 21st Century." *Crop Science* 48: 1277–1290. doi:10.2135/cropsci2007.07.0413.
- Smyth, S. J., and R. Gray. 2011. "Intellectual Property Sharing Agreements in Gene Technology: implications for Research and Commercialisation." *International Journal of Intellectual Property Management* 4: 179–190. doi:10.1504/IJIPM.2011.041082.
- Tangerås, T. P. 2009. "Yardstick Competition and Quality." *Journal of Economics and Management Strategy* 18: 589–613. doi:10.1111/j.1530-9134.2009.00223.x.
- Wang, X. H. 1998. "Fee versus Royalty Licensing in a Cournot Duopoly Model." *Economics Letters* 60: 55–62. doi:10.1016/S0165-1765(98)00092-5.
- Wright, B. D., and P. G. Pardey. 2006. "The Evolving Rights to Intellectual Property Protection in the Agricultural Biosciences." *International Journal of Technology and Globalisation* 2: 12–29. doi:10.1504/IJTG.2006.009124.

Online Supplement: Proofs

As we proceed we make use of some simplifying notation. Define the discounted expected change in profit for i as

$$(S1) \quad \Delta\pi^i(x, y, u, v) = \delta E(\pi^i(k)|k_0, x, u) - \delta E(\pi^i(k)|k_0, y, v),$$

where x and y represent the advantaged firm's, a , purchase decisions and u and v represent the disadvantaged firm's, d , purchase decisions. Now we define $\kappa = 1, 0$ and $P = 1, 1$ and, finally, $N = 0, 0$. We can succinctly analyze the four separate cases as

$$(S2) \quad \begin{array}{cc} \Delta\pi^i(\kappa, P) & \Delta\pi^i(\kappa, N) \\ \Delta\pi^i(P, \kappa) & \Delta\pi^i(N, \kappa), \end{array}$$

where κ represents the change from not purchasing to purchasing, P represents always purchasing, and N represents never purchasing.

Proof. Proof of Proposition 2

- Case 1: Let $\Delta\pi^d(N, \kappa) > \Delta\pi^d(P, \kappa) > \rho^a$. Because players must play a Nash equilibrium (NE) in the third stage of the game, we can look to Proposition 1 to see where play in the third stage will end up dependant on second-stage play. NE play in the purchase game will result in either equilibrium (1) or (4), from Proposition 1. It follows that the payoff in equilibrium (1) is larger than the payoff in equilibrium (4) if

$$(S3) \quad \rho^d \geq \delta \left(E(\pi^d(k)|k_0, 0, 1) - \pi^d \right) > 0.$$

From equilibrium 1(a) in Proposition 1, we know that $\Delta\pi^a(\kappa, P) \geq \rho^d$ is the upper bound on price ρ^d . We also know from the profit function that the disadvantaged firm prefers to sell the license at the largest price possible: the upper bound. Therefore, it remains to be shown that

$$(S4) \quad \rho^d = \Delta\pi^a(\kappa, P) \geq \delta \left(E(\pi^d(k)|k_0, 0, 1) - \pi^d \right).$$

This inequality can be rewritten as

$$(S5) \quad \pi^a - E(\pi^a(k)|k_0, 0, 1) \geq E(\pi^d(k)|k_0, 0, 1) - \pi^d.$$

It follows from Assumption 1 and the convexity of the profit functions, $\pi^i(k)$, that it must be true that $\pi^a - E(\pi^a(k)|k_0, 0, 1) > E(\pi^d(k)|k_0, 0, 1) - \pi^d$. Therefore the payoff to d must be greater in equilibrium (1) than in equilibrium (4).

We can then conclude that the disadvantaged firm optimally prices at $\rho^d = \Delta\pi^a(\kappa, P)$ whenever the advantaged firm has priced such that $\Delta\pi^d(P, \kappa) > \rho^a$.

- Case 2: Let $\rho^a > \Delta\pi^d(N, \kappa) > \Delta\pi^d(P, \kappa)$. Nash strategies in the purchase game require the pricing by the disadvantaged firm to force the purchase equilibrium into either equilibrium (2) or (3) of Proposition 1. The payoff to equilibrium (3) is larger than that to equilibrium (2) if

$$(S6) \quad \rho^d \geq -\Delta\pi^d(\kappa, N).$$

In the Nash equilibrium (3), d wishes to make the price as large as possible, setting $\rho^d = \Delta\pi^a$. It remains to be shown that

$$(S7) \quad \rho^d = \Delta\pi^a(\kappa, N) \geq -\Delta\pi^d(\kappa, N),$$

which reduces to

$$(S8) \quad \pi^a(k_0) + \pi^d(k_0) \leq E(\pi^a(k)|k_0, 1, 0) + E(\pi^d(k)|k_0, 1, 0).$$

It follows from Assumption 1 and the convexity of the profit functions, $\pi^i(k)$, that it must be true that $\pi^a - E(\pi^a|1, 0) < E(\pi^d|1, 0) - \pi^d$, which proves the result.

- Case 3: Let $\Delta\pi^d(N, \kappa) \geq \rho^a > \Delta\pi^d(P, \kappa)$. NE play in the purchase game requires that the pricing decision of the disadvantaged firm forces the purchase equilibrium into either equilibrium (3), (4) or (5) of Proposition 1. First, we compare equilibria (3) and (4).

The payoff to the Nash equilibrium in equilibrium (3) is larger than that in equilibrium (4) if

$$(S9) \quad \rho^d \geq \Delta\pi^d(N, \kappa) - \Delta\pi^d(\kappa, N) - \rho^a.$$

Because $\Delta\pi^d(N, \kappa) \geq \rho^a > \Delta\pi^d(P, \kappa)$ it follows that

$$(S10) \quad \Delta\pi^d(N, \kappa) - \Delta\pi^d(\kappa, N) - \Delta\pi^d(P, \kappa) > \Delta\pi^d(N, \kappa) - \Delta\pi^d(\kappa, N) - \rho^a \geq -\Delta\pi^d(\kappa, N).$$

We also know that d will make the price as large as possible, $\rho^d = \Delta\pi^a(\kappa, N)$.

If we can show that

$$(S11) \quad \Delta\pi^a(\kappa, N) \geq \Delta\pi^d(N, \kappa) - \Delta\pi^d(\kappa, N) - \Delta\pi^d(P, \kappa),$$

then we will have proven that the payoff from equilibrium (3) is strictly greater than that of equilibrium (4). The equation above reduces to

$$(S12) \quad \Delta\pi^a(\kappa, N) \geq \delta E(\pi^d(k)|k_0, 0, 1) - \delta\pi^d = \Delta\pi^d(N, \kappa),$$

which must be true because a is the technologically advantaged firm (the inequality reduces to equality in the case of a technological tie), and the expected gain to the advantaged firm from buying a license when the disadvantaged firm does not purchase is larger than the expected gain to the disadvantaged firm from buying a licences when the advantaged firm does not due to Assumption 1 and the convexity of the profit functions, $\pi^i(k)$.

Next we compare the payoff to the disadvantaged firm from forcing the equilibrium into equilibrium (3) versus forcing the equilibrium into the mixed-strategy equilibrium (5). If the disadvantaged firm forces the equilibrium into equilibrium (3), she will do so, setting the price as high as possible with $\rho^d = \Delta\pi^a(\kappa, N)$. If the payoff to equilibrium (3) is to be larger, the following condition must hold, where ρ^d is the price the disadvantaged firm charges in equilibrium (5):

$$(S13) \quad \Delta\pi^a(\kappa, N) > (q^a - 1)\Delta\pi^d(\kappa, N) + q^a\rho^d - q^d\rho^a + q^a q^d \Delta\pi^d(P, \kappa) + q^d(1 - q^a)\Delta\pi^d(N, \kappa).$$

Because $\Delta\pi^d(N, \kappa) > \rho^a > \Delta\pi^d(P, \kappa)$, and if the disadvantaged firm pushes equilibrium into equilibrium (5), then $\rho^d > \Delta\pi^j(K, N)$. After some algebraic manipulation, the above equation will be shown to be true if we can show that

$$(S14) \quad \Delta\pi^a(\kappa, N) \geq -\Delta\pi^d(\kappa, N) + q^d(\Delta\pi^d(N, \kappa) - \Delta\pi^d(P, \kappa)).$$

Because $0 < q^j < 1$ in equilibrium (5), it follows that

$$(S15) \quad \Delta\pi^j(N, \kappa) - \Delta\pi^j(\kappa, N) - \Delta\pi^j(P, \kappa) = \Delta\pi^j(N, \kappa)$$

and

$$(S16) \quad \Delta\pi^j(N, \kappa) > -\Delta\pi^j(\kappa, N) + q^j(\Delta\pi^j(N, \kappa) - \Delta\pi^j(P, \kappa)).$$

We know that $\Delta\pi^a(\kappa, N) \geq \Delta\pi^d(N, \kappa)$, which establishes the result.

Therefore, it is optimal for the disadvantaged firm to price the license at $\rho^d = \Delta\pi^a(\kappa, N)$ when the advantaged firm has priced such that $\Delta\pi^d(N, \kappa) \geq \rho^a > \Delta\pi^d(P, \kappa)$.

■

Proof. Proof of Proposition 3

If the advantaged firm prices such that $\rho^a > \Delta\pi^d(P, \kappa)$, then (given Propositions 2 and 1) the NE of the buy game will end up in equilibrium (3) of Proposition 1. Using the disadvantaged firm's best response function, we see that $\rho^d = \Delta\pi^a(\kappa, N)$. This results in a payoff to the advantaged firm of

$$(S17) \quad \pi^a(k_0) + \delta\pi^a(k_0).$$

If the advantaged firm prices such that $\rho^d(k_0) \leq \Delta\pi^d(P, \kappa)$, then the NE of the buy game will be as in equilibrium (1) in Proposition 1, resulting in a payoff to the advantaged firm of

$$(S18) \quad \pi^a(k_0) + \Delta\pi^a(N, \kappa) + \delta\pi^a(k_0) + \rho^a.$$

The payoff to the advantaged firm is bigger in equilibrium (3) than in equilibrium (1) if

$$(S19) \quad -\Delta\pi^a(N, \kappa) > \rho^a.$$

Since the advantaged firm will always want to capture the largest price possible in equilibrium (1), we have $\rho^a = \Delta\pi^d(P, \kappa)$, which reduces our equation to $-\Delta\pi^a(N, \kappa) > \Delta\pi^d(P, \kappa)$ and even further to

$$(S20) \quad \pi^a - E(\pi^a(k)|k_0, 0, 1) > \pi^d - E(\pi^d(k)|k_0, 1, 0).$$

This must be true given Assumption 1 and the convexity of the profit functions, $\pi^i(k)$. ■

Proof. Proof of Proposition 4

- Let $\Delta\pi^a(\kappa, N) \geq \Delta\pi^a(\kappa, P) \geq \rho^d$.

Since $k_0 < 3t$, the convexity of the profit functions and Assumption 1 imply that the advantaged firm would like the technological gap to get larger, while the disadvantaged firm would like the gap to get smaller. However, the gain to the advantaged firm from making the gap larger is bigger than the gain to the disadvantaged firm from making the gap smaller. Likewise, the loss to the advantaged firm to falling behind is bigger than the gain to the disadvantaged firm from closing the gap. Therefore, the disadvantaged firm must trade off between income from a license purchase and the reduction in profit from the gap getting larger.

With a low price from the disadvantaged firm, the advantaged firm will buy regardless of the disadvantaged firm's purchase decision. This gives the advantaged firm a choice between equilibria (1) and (3) in Proposition 1.

Suppose that the payoff in equilibrium (1) is at least as large as the payoff in equilibrium (3) for the advantaged firm. Then

$$(S21) \quad \Delta\pi^a(\kappa, N) - \Delta\pi^a(\kappa, P) - \Delta\pi^a(N, \kappa) \leq \rho^a$$

and $\rho^a \leq \Delta\pi^d(P, \kappa)$, or, equivalently,

$$(S22) \quad \delta(E(\pi^a(k)|k_0, 1, 0) - E(\pi^a(k)|k_0, 1, 1)) \leq \rho^a \leq \delta(E(\pi^d(k)|k_0, 1, 1) - E(\pi^d(k)|k_0, 1, 0)).$$

There does not exist a ρ^a that can make this true, because the convexity of the profit functions and Assumption 1 imply that

$$(S23) \quad \delta(E(\pi^a(k)|k_0, 1, 0) - E(\pi^a(k)|k_0, 1, 1)) > \delta(E(\pi^d(k)|k_0, 1, 1) - E(\pi^d(k)|k_0, 1, 0)).$$

Therefore, the best response of the advantaged firm is to set the price high enough that the disadvantaged firm will not purchase a license. This requires a price such that $\rho^a > \Delta\pi^d(P, \kappa)$.

- Suppose that $\Delta\pi^a(\kappa, N) \geq \rho^d > \Delta\pi^a(\kappa, P)$.

In this instance, the advantaged firm can force the game into a purchasing Nash equilibrium of equilibrium (3), (4) or (5) in Proposition 1 by choosing her price accordingly.

First, we compare the expected payoffs to the advantaged firm from forcing the game into either equilibrium (3) or (4). The expected payoff to the advantaged firm from pricing into equilibrium (3) is greater than from pricing into equilibrium (4) if

$$(S24) \quad \Delta\pi^a(\kappa, N) - \rho^d > \Delta\pi^a(N, \kappa) + \rho^a.$$

Since in equilibrium (3) we have $\Delta\pi^a(\kappa, N) \geq \rho^d$ and in equilibrium (4) we have $\Delta\pi^d(N, \kappa) \geq \rho^a$, we know that

$$(S25) \quad \Delta\pi^a(\kappa, N) + \Delta\pi^d(N, \kappa) \geq \rho^a + \rho^d.$$

If we can show that $\Delta\pi^a(\kappa, N) - \Delta\pi^d(N, \kappa) > \Delta\pi^a(\kappa, N) + \Delta\pi^d(N, \kappa)$, then we will have established that the payoff under equilibrium (3) is higher than that under equilibrium (4). This condition reduces to

$$(S26) \quad -\Delta\pi^d(N, \kappa) > \Delta\pi^d(N, \kappa).$$

This reduces further to

$$(S27) \quad \pi^a - E(\pi^a(k)|k_0, 0, 1) > E(\pi^d(k)|k_0, 0, 1) - \pi^d.$$

It follows from Assumption 1 and the convexity of the profit functions, $\pi^i(k)$, that this inequality must hold.

Now we compare the expected payoff to the advantaged firm from forcing the purchasing game into either equilibrium (3) or (5) in Proposition 1. The payoff to the technologically advantaged firm is bigger in equilibrium (3) than in equilibrium (5) if the following holds:

$$(S28) \quad \begin{aligned} \Delta\pi^a(\kappa, N) &\geq q^d \Delta\pi^a(N, \kappa) + q^d \rho^a + (1 - q^d) \rho^d \\ &+ q^a q^d \Delta\pi^a(\kappa, P) + q^a (1 - q^d) \Delta\pi^a(\kappa, N) \equiv (\star) \end{aligned}$$

Because both $\rho^d < \Delta\pi^a(\kappa, N)$ and $\rho^a < \Delta\pi^d(N, \kappa)$ in equilibrium (5), we have

$$(S29) \quad \begin{aligned} q^d \Delta\pi^a(N, \kappa) + q^d \Delta\pi^d(N, \kappa) + (1 - q^d) \Delta\pi^d(\kappa, N) \\ + q^a q^d \Delta\pi^a(\kappa, P) + q^a (1 - q^d) \Delta\pi^a(\kappa, N) > (\star). \end{aligned}$$

If we can show that

$$(S30) \quad -\Delta\pi^d(N, \kappa) \geq \Delta\pi^a(N, \kappa) + q^a (\Delta\pi^a(\kappa, P) - \Delta\pi^a(\kappa, N)),$$

then we will have established the result.

Because $0 < q^a < 1$, $-\Delta\pi^d(N, \kappa) \geq \Delta\pi^a(N, \kappa)$, and $\Delta\pi^a(\kappa, P) \leq \Delta\pi^a(\kappa, N)$, the inequality above holds and it is true that the payoff for the advantaged firm is greater in equilibrium (3) than in equilibrium (5).

Therefore, the best response in this case is to set the price at any price high enough to force the equilibrium into equilibrium (3), $\rho^a > \Delta\pi^d(P, \kappa)$.

- Suppose that $\rho^d \geq \Delta\pi^a(\kappa, N) \geq \Delta\pi^a(\kappa, P)$.

The advantaged firm's price strategy will cause NE purchase strategies to result in either equilibrium (2) or (4) in Proposition 1. The expected payoff to the advantaged firm from pricing into equilibrium (4) is greater than from pricing into equilibrium (2) if

$$(S31) \quad \rho^a \geq -\Delta\pi^a(N, \kappa).$$

If the pricing forces the buy game into equilibrium (4), then the advantaged firm will set the price such that $\rho^a = \Delta\pi^d(N, \kappa)$, as this is the upper bound on what the disadvantaged firm is willing to pay. Thus, the above condition can be rewritten as

$$(S32) \quad \delta \left(E(\pi^d(k)|k_0, 0, 1) - E(\pi^d(k)|k_0, 0, 0) \right) \geq \delta \left(E(\pi^a(k)|k_0, 0, 0) - E(\pi^a(k)|k_0, 0, 1) \right).$$

This can never be true as a result of the lead being strict, $k_0 > 0$, along with Assumption 1 and convexity of the profit functions. Therefore, it must be the case that the payoffs under equilibrium (2) are greater than those under equilibrium (4), and the advantaged firm will price so that neither party will purchase.

Therefore, the best response for the advantaged firm is to set the price high enough that the disadvantaged firm will not purchase; that is, any $\rho^a > \Delta\pi^d(N, \kappa)$. ■

Proof. Proof of Proposition 5

If the disadvantaged firm prices so that $\rho^d \geq \Delta\pi^a(\kappa, N)$, then the advantaged firm will price such that $\rho^a \geq \Delta\pi^d(N, \kappa)$. In this scenario, the buy equilibrium is as in equilibrium (2) in Proposition 1, in which neither buys a license. The payoff to the disadvantaged is

$$(S33) \quad \pi^d(k_0) + \delta E[\pi^d(k)|k_0, 0, 0].$$

If the disadvantaged firm prices so that $\rho^d < \Delta\pi^a(\kappa, P)$, then the advantaged firm will price such that $\rho^a > \Delta\pi^d(P, \kappa)$. In this scenario, the buy equilibrium is as in equilibrium (3) in Proposition 1, in which the advantaged firm buys but the disadvantaged does not. The disadvantaged firm will want the highest price possible and will hence set $\rho^d = \Delta\pi^a(\kappa, P)$. The payoff to the disadvantaged firm is

$$(S34) \quad \pi^d(k_0) + \delta E[\pi^d(k)|k_0, 0, 0] + \Delta\pi^d(\kappa, N) + \Delta\pi^a(\kappa, P).$$

Due to the convexity of the profit functions and Assumption 1, we know that $\Delta\pi^d(\kappa, N) + \Delta\pi^a(\kappa, P) > 0$, so that the payoff to the disadvantaged firm is largest when the disadvantaged firm prices such that equilibrium will end up in equilibrium (3) with $\rho^d = \Delta\pi^a(\kappa, P)$. ■

Proof. Proof of Proposition 6

If i prices such that $\rho^i(k_0) > \Delta\pi^j(P, \kappa)$, then the NE of the buy game will be as in equilibrium (3) in Proposition 1. From j 's best response function, we see that $\rho^j = \Delta\pi^i(\kappa, N)$. This results in a payoff to i of

$$(S35) \quad \pi^i(k_0) + \delta\pi^i(k_0).$$

If i prices such that $\rho^i(k_0) \leq \Delta\pi^j(P, \kappa)$, then the NE of the buy game will be as in equilibrium (1) in Proposition 1. This results in a payoff to i of

$$(S36) \quad \pi^i(k_0) + \Delta\pi^i(N, \kappa) + \delta\pi^i(k_0) + \rho^i.$$

The payoff to i is at least as big in equilibrium (3) as it is in equilibrium (1) if

$$(S37) \quad -\Delta\pi^i(N, \kappa) \geq \rho^i.$$

Since i will always want to capture the largest price possible in equilibrium (1), we have $\rho^i = \Delta\pi^j(P, \kappa)$, which reduces our equation to

$$(S38) \quad -\Delta\pi(N, \kappa) \geq \Delta\pi^j(P, \kappa).$$

After substituting, we have

$$(S39) \quad \pi^i(k_0) - E(\pi^i(k)|k_0, 0, 1) \geq \pi^j(k_0) - E(\pi^j(k)|k_0, 1, 0),$$

which holds with equality for the case of $k_0 = 0$. ■