# Endogenous R&D Investment and Market Structure: A Case Study of the Agricultural Biotechnology Industry

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**Abstract**
Over the past three decades, the agricultural biotechnology sector has been characterized by rapid innovation, market consolidation, and a more exhaustive definition of property rights. The industry attributes consistently identified by the literature and important to this analysis include: (i) endogenous sunk costs in the form of expenditures on R&D; (ii) seed and agricultural chemical technologies that potentially act as complements within firms and substitutes across firms; and (iii) property rights governing plant and seed varieties that have become more clearly defined since the 1970s. This paper adds to the stylized facts of the agricultural biotechnology industry to include the ability of firms to license technology, a phenomenon observed only recently in the market as licensing was previously precluded by high transactions costs and "anti-stacking" provisions. We extend Sutton's theoretical framework of endogenous sunk costs and market structure to incorporate the ability of firms to license technology under well-defined property rights, an observed characteristic not captured in previous analyses of the sector. Our model implies that technology licensing leads to lower levels of industry concentration then what would be found under Sutton's model, but that industry concentration remains bounded away from perfect competition as market size becomes large.

***Keywords:*** *licensing, market structure, R&D, agricultural biotechnology*

**JEL Codes:** L22, L24, Q16

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## I. Introduction

Over the past three decades, the agricultural biotechnology sector has been characterized by rapid innovation, market consolidation, and a more exhaustive definition of property rights. Concentration has occurred in both firm and patent ownership with the six-firm concentration ratios in patents reaching approximately 50% in the U.S. and the U.K. (Harhoff, et al., 2001) However, increased concentration has had ambiguous effects on R&D investment as the ratio of R&D expenditure to industry sales, 71.4%, remains relatively large. (Lavoie, 2004) Based upon the observed industry and patent ownership consolidation in the sector, Sheldon (2008) discusses the potential application of Sutton's "bounds" approach to the agricultural biotechnology industry and finds stylized facts that an exogenous technological shock led to an increase in both R&D expenditure and the number of innovating firms. We extend Sutton's theoretical framework of endogenous sunk costs and market structure to incorporate the ability of firms to license technology under well-defined property rights, an observed characteristic not captured in previous analyses of the sector. Our model implies that technology licensing leads to lower levels of industry concentration then what would be found under Sutton's model, but that industry concentration remains bounded away from perfect competition as market size becomes large.

The industry attributes consistently identified by the literature and important in the development of an endogenous market structure model include: (i) endogenous sunk costs in the form of expenditures on R&D; (ii) seed and agricultural chemical technologies that potentially act as complements within firms and substitutes across firms; and (iii) property rights governing plant and seed varieties that have become more clearly defined since the 1970s. Moreover, this paper adds to the stylized facts of the agricultural biotechnology industry to include the ability of firms to license technology, a phenomenon observed only recently in the market as licensing was previously precluded by high transactions costs and "anti-stacking" provisions.[1] We posit that complementarities between intellectual property assets and, to a certain extent, an increased willingness-to-pay and/or size of the market for agricultural biotechnology led to firm consolidation. The endogeneity of sunk cost R&D expenditure and consolidation of firms in agricultural biotechnology allowed the remaining firms to realize economies of scope in production and escalate their R&D expenditures.

Rapid technological innovation and observed firm consolidation has led to several empirical examinations of market structure in the agricultural biotechnology industry. Previous work has tested Schumpeterian hypotheses regarding the levels of industry concentration and innovation in biotechnology (Schimmelpfennig, Pray, and Brennan, 2004), assessed the role of complementary intellectual assets in merger and acquisition activity to diversify intellectual asset portfolios under significant transaction costs (Graff, Rausser, and Small, 2003), and analyzed patent rights in industry consolidation (Marco and Rausser, 2008). Additional stylized examinations of the agricultural biotechnology industry have identified an endogenous, cyclical relationship between industry concentration and R&D intensity (Oehmke, Wolf, and Raper, 2005), classified the firm characteristics and strategic incentives that affect the form of consolidation (Johnson and Melkonyan, 2003), and categorized the endogenous relationship between firm innovation strategies, including the role of complementary intellectual assets, and industry consolidation characteristics (Kalaitzandonakes and Bjornson, 1997). Empirical examinations have also identified economies of scope in firm R&D activity as well as the presence of both internal and external spillovers in R&D (Chen, Naseem, and Pray, 2004).

Relative to the current literature in agricultural biotechnology, our model is most closely related to the work of Shi (2009), Johnson and Melkonyan (2003), Goodhue, et al. (2002), and

[1] "Anti-stacking" in this context refers to contractual provisions, specified by the licensor of intellectual assets, which preclude licensee firms from incorporating multiple genetic traits from competitor firms into a single seed variety. (Graff, Rausser, and Small, 2003)

Kalaitzandonakes and Marks (2000) in its analysis of the choice of coordination strategy of intellectual property assets. Within a product life-cycle framework with uncertainty over the valuation of technical assets, Kalaitzandonakes and Marks (2000) argue for licensing arrangements with greater flexibility, rather than simple maximization of income streams based upon a comparative case study in agricultural biotechnology. Goodhue, et al. (2002) examine firm incentives to consolidate via mergers and acquisitions compared to exclusive and non-exclusive license agreements under differing intellectual property regimes given the nature of the product system. Building upon the model of Aghion and Tirole (1994), Johnson and Melkonyan (2003) find that choice of ownership structure and levels of R&D investment depend primarily upon the substitutability (complementarity) of assets across firms and/or the specificity of R&D investments. Adapting a Hotelling's spatial differentiation model and bundling theory to a game theoretic framework with farmer adoption decision, Shi (2009) finds incentives of firms to differentially integrate or license their technology depending upon whether genes are substitutes or complements.

Thus far, the empirical examinations in agricultural biotechnology have primarily focused upon levels of firm concentration and innovation activity measured via patent ownership, industry sales ratios, and field trial applications. With the exception of the comparative simulations of Johnson and Melkonyan (2003) and the stylized descriptions of Kalaitzanodakes and Bjornson (1997), little empirical attention has been paid to the differing mechanisms of firm consolidation in agricultural biotechnology. According to data on the four largest agricultural biotechnology firms reported by Johnson and Melkonyan (2003), nonexclusive and exclusive license agreements comprised nearly half (42 of 90) of the observed consolidation activities in the sector. Moreover, the collaborative agreements collected by Kalaitzanodakes and Bjornson (1997) imply that mergers and acquisitions, licensing, distribution, and production agreements became increasingly important in agricultural biotechnology relative to equity investments, R&D agreements, and joint ventures. Thus, a more rigorous examination of the nature of collaborative agreements in agricultural biotechnology under more clearly defined property rights is warranted, especially considering the role of licensing upon incentives for firms to innovate.

We extend Sutton's "capabilities" framework relating endogenous sunk costs and market structure to allow firms to consolidate via licensing and cross-licensing agreements. First, we present an illustrative example of the effect of licensing upon innovation and market structure in a quantity-quality choice framework under a Cournot duopoly. In these simulations, we find that there are incentives for low cost incumbent firms to license their (higher) level of technology to potential entrants even if firms compete along a single capability/quality and goods differentiated substitutes. Subsequently, we discuss Sutton's model and present our extensions as well as predictions on the effect of the ability of firms to license their technology upon market structure and innovation. In the final section we discuss the implications and conclude.

## II. Illustrative Example: Quality Choice in a Duopoly Model with Licensing

To illustrate the affect of the ability of firms to license product quality upon their incentives to innovate, we examine a simple two-stage game between firms with asymmetric returns to R&D that offer products differentiated by characteristics and quality. After determining the quantity/quality choices of firms in such a setting, we then incorporate the ability of firms engage in cross-product licensing agreements with their competitors and observe how the quantity/quality choices differ under licensing. Our primary concern is in determining the quality choices offered by each firm, which embeds the market entry decision, as well as the effects upon firm profit and consumer welfare as the timing of the entry decision and the cost elasticities of the firms vary.

We find that incumbent firms only offer license arrangements when facing a 'low' cost elasticity and the product market is relatively differentiated (low degree of substitution). Licensing is never profitable in cases in which the cost elasticity on R&D expenditure is relatively 'high' for the incumbent, given the minimum setup cost, or if the goods are homogenous. The higher quality offerings under licensing are associated with higher incumbent and entrant firm profits as well as greater consumer utility under our linear demand example.

Consider the case of a single consumer and two firms, indexed by $\mathrm{i}$ and $\mathrm{j}$, that make deterministic investments in product quality, $(\mathrm{u_i}, \mathrm{u_j})$, in the first stage and then compete in quantities, $(\mathrm{x_i}, \mathrm{x_j})$, in the second stage. The information environment is such that product qualities are realized at the end of the first stage and are common knowledge to both firms as well as the consumer, regardless of the timing of actions in the first stage. Such an assumption simplifies potential concerns regarding asymmetric information that could arise in the second stage as well as provides some realism to the game in which introductions of new products can be divided into a development/design phase and production phase (Aoki and Prusa, 1996).

We assume in this simple case that the firms each offer a single good and face a consumer with a linear demand utility function in which the goods are indexed by their qualities such that consumer willingness-to-pay is increasing in product quality up to some maximum amount. The linear demand function thus takes the form:

$$\mathrm{U} = \left[\mathrm{x_i} - \frac{\mathrm{x_i^2}}{\mathrm{u_i^2}}\right] + \left[\mathrm{x_j} - \frac{\mathrm{x_j^2}}{\mathrm{u_j^2}}\right] - 2\sigma\left[\frac{\mathrm{x_i}}{\mathrm{u_i}} \cdot \frac{\mathrm{x_j}}{\mathrm{u_j}}\right] + \mathrm{V} \qquad (1),$$

where $\mathrm{V}$ is the utility that the consumer receives from consuming all outside goods and $\sigma$ is the parameter that captures the degree that the two goods are substitutes $(0 \leq \sigma \leq 1)$ and embeds the case in which the two goods are offered in independent submarkets (i.e. $\sigma = 0$).[2] The consumer's individual inverse-demand schedule for each good $\mathrm{i}$ is:

[2] In the most general cases, this parameter can take any values between negative one and one (i.e. $\sigma \in [0,1]$) such that any values less than zero captures the degree that the two goods are complements. Our assumption that goods are either

$$p_i = 1 - \frac{2x_i}{u_i^2} - 2\sigma\frac{x_j}{u_i u_j} \qquad (2).$$

As Sutton identifies, as the quality for any good $i$ approaches zero $(u_i \rightarrow 0)$, the demand for that good falls to zero for any nonnegative price.

The results thus far have been derived solely from consumer demand and are independent of the structure and timing of the quality-quantity choices by the firms. In the remainder of the illustrative example, we assume zero marginal costs in production such that firms compete in quantities in the second stage taking their own quality and competitor quality as given. Thus, Firm $i$ maximizes revenue such that:

$$\max_{x_i} R_i = \max_{x_i} p_i x_i = \max_{x_i}\left[1 - \frac{2x_i}{u_i^2} - 2\sigma\frac{x_j}{u_i u_j}\right]x_i \qquad (3).$$

Solving the first-order conditions yields the following reaction functions:

$$x_i^R = \frac{u_i^2}{4} - \frac{\sigma}{2}\left(\frac{u_i}{u_j}\right)x_j \qquad (4).$$

Substituting in the reaction function for the other firm and solving yields the Cournot equilibrium quantities for both firms as functions for the quality choice by each firm in the first stage. The optimal quantities can thus be expressed as:

$$x_i^* = \frac{1}{2}\left(\frac{2u_i^2 - \sigma u_i u_j}{4 - \sigma^2}\right) \qquad (5).$$

It can be observed that if goods are substitutes, then the amount of Firm $i$'s good demanded is increasing in own quality (i.e. $\frac{\partial x_i^*}{\partial u_i}>0$) only if the quality they offer is greater than or equal to a proportion of their competitor's quality offered, namely $\frac{\sigma u_j}{4}$. Additionally, the quantity demanded for

independent or substitutes is plausible in this illustrative example as we are limiting the market to only two goods. In the more general case, we relax this assumption to allow for demand-side complementarities which is consistent with an industry such as agricultural biotechnology in which greater utility can be derived from the final-stage consumption of complementary products such as between a herbicide-tolerant seed variety and a specific herbicide.

Firm $i$ is decreasing in the quality offered by their competitors (i.e. $\frac{\partial x_i^*}{\partial u_j}<0$). The revenue function for Firm $i$ can be written as:

$$R_i^* = \frac{1}{2}\left(\frac{2u_i - \sigma u_j}{4-\sigma^2}\right)^2 \qquad (6).$$

If the goods offered by the two firms are substitutes, then Firm $i$'s revenue is non-decreasing (i.e. $\frac{\partial R_i^*}{\partial u_i}\geq 0$) in own quality only if the quality they offer is greater than or equal to a proportion of their competitors quality, namely $\frac{\sigma u_j}{2}$, and is also non-increasing (i.e. $\frac{\partial R_i^*}{\partial u_j}\leq 0$) in the quality offered by their competitors.[3]

The previous results hold regardless of the timing of quality choices (i.e. irretrievable R&D investment decisions) in the first stage. The profit function that firms maximize in choosing the quality that they offer is equivalent to the revenue function net of the fixed costs associated with attaining quality $u_i$. This cost function can be specified as consisting of a fixed setup cost that all firms must pay in order to enter a particular trajectory $F_0$ as well as an additional cost parameter that is strictly increasing in quality by an elasticity equal to $\beta_i$. We assume that there is a minimum level of quality associated with entry ($u_i \in [1, \infty)$) and that the elasticity of the fixed cost schedule increases with quality at least as rapidly as firm profit ($\beta_i > 2$). Thus, the fixed cost schedule for Firm $i$ can be specified as:

$$F(u_i) = F_0(u_i)^{\beta_i} \qquad (7),$$

such that Firm $i$ maximizes the profit function:

$$\max_{u_i \in \{0,[1,\infty]\}} \pi_i = R(u_i) - F(u_i), \qquad (8)$$

[3] It is interesting to note that if the goods are complements $(-1 \leq \sigma \leq 0)$, then the quantity demanded for Firm $i$'s good is always increasing in both their own and competitor's quality (i.e. $\frac{\partial x_i^*}{\partial u_i}>0$ & $\frac{\partial x_i^*}{\partial u_j}>0$). Additionally, the revenue of Firm $i$ is always increasing in own and other firm quality (i.e. $\frac{\partial R_i^*}{\partial u_i}>0$ & $\frac{\partial R_i^*}{\partial u_j}>0$).

or explicitly:

$$\max_{u_i \in \{0,[1,\infty]\}} \frac{1}{2}\left(\frac{2u_i - \sigma u_j}{4-\sigma^2}\right)^2 - F_0(u_i)^{\beta_i} \qquad (9).$$

Each firm maximizes profit by choosing own quality $u_i$ taking other firm quality as given. Moreover, as quality-choice is constrained in the maximization problem to allow for both a minimum quality level as well as non-entry (i.e. $u_i = 0$), the first-order complementary slackness conditions can be specified as:

$$u_i\left[\frac{2(2u_i - \sigma u_j)}{(4-\sigma^2)^2} - \beta_i F_0 u_i^{\beta_i - 1}\right] = 0 \qquad (10).$$

Thus, for cases in which there exists an interior solution with quality choices that are greater than or equal to one, the solution to the optimal quality choice reaction functions is a non-linear function such that $u_i^R$ satisfies:

$$4u_i^R - 2\sigma u_j - (4-\sigma^2)^2 \beta_i F_0 u_i^{R^{\beta_i - 1}} = 0 \qquad (11).$$

In order to further analyze the illustrative example on quality-quantity choice in a duopoly, we first set a value for the minimum setup cost at which firms will always find it optimal to choose minimum quality compared to inactivity, given that the other firm is producing at minimum quality. This assumption precludes the possibility that the setup cost is prohibitively expensive such that only a single, minimum quality firm is sustainable in equilibrium. This implicitly excludes the possibility that there exists a natural monopoly in which the monopolist produces at a minimum level of quality. However, it does not exclude the possibility that a monopolist producing high quality can be sustained in equilibrium.

Assuming Firm $j$ is producing at minimum quality (i.e. $u_j = 1$), for all feasible values of $\sigma \in [0,1]$, and independent of the cost parameter $\beta_i$, we find that it will be profitable for Firm $i$ to produce at minimum quality, versus inactivity, if the minimum setup cost $F_0$ is less than or equal to

$\frac{1}{18}$. This condition arises directly from the profit function (Eq. 12) for Firm $\mathrm{i}$ such that for any minimum setup cost $F_0 \leq \frac{1}{18}$, firms will find it (weakly) preferable to produce at minimum quality compared to remaining inactive. Although this parameterization may appear to be somewhat innocuous as all firms face the same setup cost, it will become a factor into subsequent analysis when we compare the incentives of firms to select own R&D expenditures versus licensing the technology from other firms.

In order to get a clearer understanding of the tradeoff between sunk cost investment, the quality offered by firms, and firm profitability, we solve the illustrative example assuming that firms face an exogenously determined elasticity of the fixed-cost R&D schedule that take a value that is either 'high' or 'low' cost. Until this point, we have placed only a single, theoretical assumption on the cost parameter, namely $\beta > 2$. To determine possible candidate values, we first solve the case in which firms offer products in independent submarkets (i.e. $\sigma = 0$), such that own quality choice does not affect, and in turn is unaffected by, the quality choice of the other firm.

Firm $\mathrm{i}$ chooses quality according to equation (Eq. 13) such that:

$$u_i = \begin{cases} \left[\dfrac{1}{4F_0\beta_i}\right]^{\frac{1}{\beta_i-2}}, & \forall\, 2 < \beta_i < \dfrac{9}{2} \\ 1, & \forall\, \beta_i \geq \dfrac{9}{2} \end{cases} \qquad (12),$$

and the profit for Firm $\mathrm{i}$ can be expressed as:

$$\pi_i = \begin{cases} \dfrac{1}{2}\left[\dfrac{1}{(4\beta_i)^{\beta_i}{F_0}^2}\right]^{\frac{1}{\beta_i-2}}[\beta_i - 2], & \forall\, 2 < \beta_i < \dfrac{9}{2} \\ \dfrac{5}{72}, & \forall\, \beta_i \geq \dfrac{9}{2} \end{cases} \qquad (13).$$

For 'large' values of the cost parameter, specifically for $\beta_i \geq \frac{9}{2}$, the firm will always find it optimal to choose minimum quality, $u_i = 1$, and earn a positive profit of $\frac{5}{72}$. Moreover, these results imply that if the goods are offered are in independent submarkets, inactivity, $u_i = 0$, is strictly dominated by choosing minimum quality, $u_i = 1$. As $\beta = \frac{9}{2}$ is the infimum of the set of 'large' values for the cost parameter such that it is optimal for firms to offer minimal quality in independent submarkets, we use this value to parameterize the 'high' cost value in the illustrative example and set $\beta = 3$ as the 'low' cost value as it satisfies the only assumption we have thus far made over the cost parameter (i.e. $\beta > 2$).

In the analysis of the first-stage quality choice games that follow, we are primary concerned with examining how the quality choice of each firm changes as we change: (i) the framework and timing of the first-stage quality choice game; (ii) firms face either symmetric cost elasticities or a cost (dis)advantage relative to the other firm; and (iii) the parameter over the degree to which the goods are substitutes. The three frameworks on the timing of the first-stage quality choice that we are interested in are: (i) simultaneous quality choice; (ii) sequential quality choice in which Firm $i$ has 'first-mover' advantage in choosing their own quality; and (iii) a sequential quality choice framework in which Firm $i$ has a 'first-mover' advantage and can offer a licensing agreement over their chosen level of quality. In this final framework, Firm $j$ chooses either their own optimal level of quality via expenditure on their own sunk cost R&D or the level of quality offered by Firm $i$ in the licensing agreement. For each of the first-stage quality choice games, we examine four cases for the possible cost parameters faced by each firm. There are two cases in which firms face symmetric elasticities of the fixed-cost schedule (low/low and high/high) as well as two cases in which the firms face asymmetric elasticities (low/high and high/low) and thus have an implicit cost (dis)advantage in R&D.

### *A. Simultaneous Quality Choice*

In the first quality choice framework, the two firms choose their level of quality simultaneously given the cost parameters for each firm as well as an exogenously determined degree of substitution between the goods. The firms solve nonlinear reaction functions to determine optimal quality conditional on this level of quality being greater than or equal to the minimum level and that each firm earns non-negative profits given the other firm's level of quality. Thus, we have a system of two nonlinear root-finding equations in two unknown quality variables such that:

$$4u_i - 2\sigma u_j - (4-\sigma^2)^2 \beta_i F_0 u_i^{\beta_i - 1} = 0$$

$$4u_j - 2\sigma u_i - (4-\sigma^2)^2 \beta_j F_0 u_j^{\beta_j - 1} = 0 \qquad (14).$$

$$\text{subject to:} \quad u_i, u_j \in \{0, [1, \infty)\}$$

$$\pi_i, \pi_j \geq 0$$

The results on both quality and firm profit under the simultaneous quality choice framework are illustrated graphically in Figures 1 and 2 for the four possible cost regimes as a function of the degree of substitution between goods in the product market.

Figure 1: Simultaneous Quality Choice

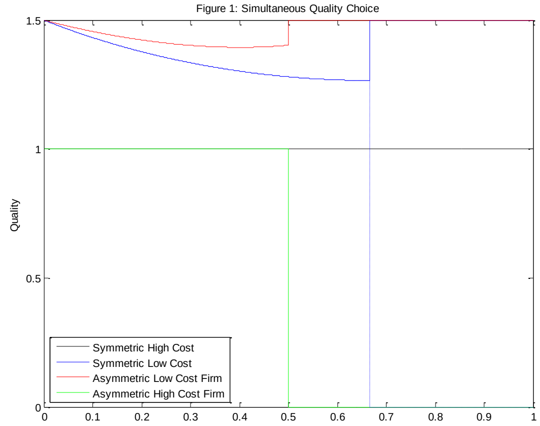
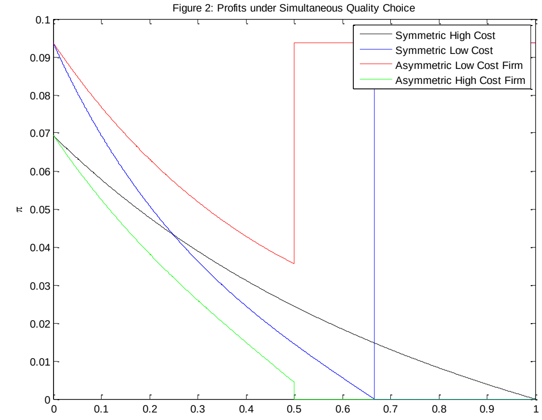



Figure 2: Profits under Simultaneous Quality Choice




For the case in which both firms have 'low' cost parameters ($\beta_i = \beta_j = 3$), there exists an interior solution in which firms choose symmetric quality levels that are greater than the minimum quality when the two goods have a 'low' to 'moderate' degree of substitution (i.e. $\sigma \in \left[0, \frac{2}{3}\right)$). As the degree of substitution between the two goods increases, the symmetric outcome with quality greater than the minimum does not satisfy the non-negative profit condition. Moreover, the collusive outcome in which both firms produce at minimum quality cannot be sustained in equilibrium as both firms have incentive to deviate and increase quality. Thus, for a 'high' degree of substitution (i.e. $\sigma \in \left[\frac{2}{3}, 1\right]$), there exist only corner solutions in which one firm offers the 'monopolistic' level of quality, in our case this is equivalent to $u_i = \frac{3}{2}$ for the given values of the cost parameter and minimum setup cost, and the other firms remain inactive as well as the trivial case in which both firms choose inactivity.

For the case in which the two firms face asymmetric costs of R&D expenditure (i.e. $\beta_i = 3$ & $\beta_j = \frac{9}{2}$ or $\beta_i = \frac{9}{2}$ & $\beta_j = 3$), the best response for a firm that is at a cost disadvantage is to produce minimum quality for any 'low' values on the substitution parameter (i.e. $\sigma \in \left[0, \frac{1}{2}\right)$) and to remain inactive for any value of the substitution parameter that is greater than one-half. Correspondingly, the firm with the cost advantage chooses a quality greater than the minimum level to solve the nonlinear reaction function given the other firm will be producing minimum quality for $\sigma \in \left[0, \frac{1}{2}\right]$ and will choose the 'monopolistic' level of quality, here $u_i = \frac{3}{2}$, for all values of the degree of substitution greater than one-half.

When both firms face a 'high' cost parameter ($\beta_i = \beta_j = \frac{9}{2}$), the best response for each firm regardless of the value of the substitution parameter is to produce minimum quality. Both firms earn profits strictly greater than zero in this symmetric equilibrium except under the case in which the two goods are perfect substitutes on the demand side, $\sigma = 1$, and profits are equal to zero. Moreover, neither firm has incentive to deviate and increase their quality offered as profits under any positive deviation are strictly less than zero.

### *B. Sequential Quality Choice*

Suppose that firms choose quality sequentially such that Firm $i$ selects quality $u_i$ first and can thus be considered an 'incumbent firm' whereas Firm $j$ chooses quality $u_j$ second as an 'entrant' firm. Hence, Firm $i$ maximizes profit by choosing their own quality under the constraint that Firm $j$ responds optimally after quality $u_i$ is determined. Firm 's decision on quality level can be effectively narrowed down to a choice between offering a 'monopolistic' level of quality at which Firm would earn a non-positive profit from a choice of minimum quality, offering an 'optimal' level of quality at which Firm selects a profit maximizing quality level, offering a level of quality at which Firm cannot profitably enter the market, and choosing inactivity.

The 'monopolistic' level of quality offered is equivalent to the level of quality chosen under independent submarkets, namely:

$$= \begin{cases} \left[\frac{1}{4_0}\right]^{\frac{1}{-2}}, & \forall\, 2 < \ < \frac{9}{2} \\ 1, & \forall\ \geq \frac{9}{2} \end{cases} \qquad (15).$$

If the firm faces a 'low' cost parameter, $= 3$, the 'monopolistic' level of quality is $= \frac{3}{2}$, whereas if the firm has a 'high' cost parameter, $= \frac{9}{2}$, then this quality level falls to the minimum, $= 1$.

The 'optimal' level of quality offered is determined by maximizing Firm 's profit subject to a constraint derived from the reaction function from Firm . Firm chooses both quality levels, $^*$ and $^*$, to maximize the problem:

$$\underset{,\in\{0,[1,\infty]\}}{} \frac{1}{2}\left(\frac{2-}{4-{}^2}\right)^2 - {}_0() \qquad (16).$$
$$..\ 4 - 2 - (4 - {}^2)^2{}_0{}^{-1} \leq 0$$
$$,\ \in \{0, [1, \infty)\}$$
$$,\ \geq 0$$

Solving for the first-order conditions under a binding reaction function, we obtain a system of two nonlinear root-finding equations in the two unknown quality variables. Specifically,

$$4[1-(4-{}^{2})_{0}{}^{-2}]-2[1-(4-{}^{2})_{0}(-1)^{-2}]-(4-{}^{2})_{0}(-1)^{-1}[4-(4-{}^{2})^{2}{}_{0}{}^{-2-1}]$$

$$=0 \qquad (17).$$

$$4-2-(4-{}^{2})^{2}{}_{0}{}^{-1}=0$$

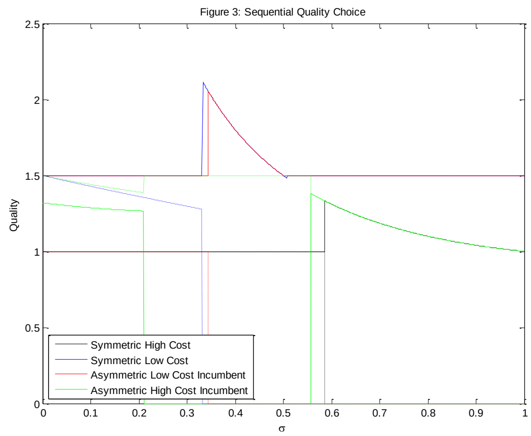
The level of quality at which Firm  can successfully preclude Firm  from entering is obtained by solving for the level of Firm  quality at which Firm  cannot profitably enter with minimum quality. Specifically, Firm  solves for ‾ such that the profit function for Firm  is less than (or equal to) zero if Firm  chooses minimum quality. Firm ’s problem is to solve for ‾ such that:

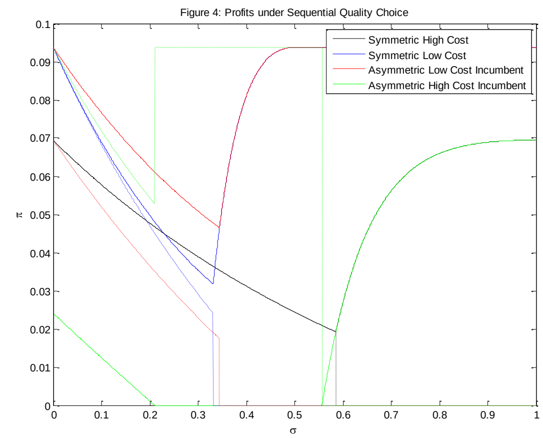
$$_{2}=\frac{1}{2}\left[\frac{2-\bar{}}{4-{}^{2}}\right]^{2}-{}_{0}\leq 0 \qquad (18).$$

Solving for ‾ yields:

$$\bar{}\geq{}^{-1}\left[2-(2_{0})^{\frac{1}{2}}(4-{}^{2})\right] \qquad (19).$$

Thus, in the sequential quality choice framework, Firm  chooses $\in\{,{}^{*},\bar{},0\}$ to maximize own profit given the cost parameters for both firms,  and $_j$, and the substitution parameter, $\sigma$. The results on both quality and firm profit under the sequential quality choice framework are illustrated graphically in Figures 3 and 4 for the four possible cost regimes as a function of the degree of substitution between goods in the product market.




For the case in which the incumbent firm faces a 'low' cost elasticity to R&D, there exist three possible quality choice regimes that govern the firm's decision depending upon the degree of substitution between goods and the cost elasticity to R&D of the potential entrant. The first regime holds under 'low' degrees of substitution between goods such that the incumbent offers a quality greater than the minimum and the potential entrant enters with quality greater than the minimum if it is also a 'low' cost firm and equal to the minimum if it is a 'high' cost firm. The incumbent firm offers a quality level that is lower in the second scenario relative to the first, but also switches to the next quality 'regime' at a lower value of $\sigma$.

The second quality regime holds for 'intermediate' values of the substitution parameter and corresponds to the case in which the incumbent firm can successfully prevent entry by increasing their own quality offered and the other firm cannot profitably enter. Within the first quality regime, the qualities offered, as well as firm profit, are decreasing in the substitution parameter. In this second regime, the quality offered continues to decrease from a higher absolute level, but the profit for the incumbent is increasing in the substitution parameter. As the potential entrant firm cannot profitably enter, it chooses inactivity and earns zero profit.

The final regime, which occurs approximately for values of the substitution parameter greater than one-half, consists of the entrant firm offering the 'monopolistic' level of quality at which profit is maximized and the entrant firm does not find it profitable to enter. This case holds regardless of the cost parameter of the potential entrant, although it occurs at a value for $\sigma$ that is slightly greater than one-half if the potential entrant is also a 'low' cost firm. Again, the potential entrant firm cannot profitably enter, chooses inactivity, and earns zero profit.

If the incumbent firm, Firm $i$, faces a 'high' parameter value for the elasticity of R&D cost, it finds it optimal to produce at minimum quality for all values of $\sigma$ less than one-half, regardless of the cost parameter for the potential entrant, Firm $j$. If Firm $j$ has a 'low' cost parameter, it enters with a quality level greater than the minimum, but if it faces a 'high' cost parameter it can only profitably enter with minimum quality. As $\sigma$ increases from a value in the range between one-half and three-fifths, Firm $i$ regains its first-mover advantage as it is successfully able to increase the quality of their own good such that Firm $j$ cannot profitably enter by offering minimum quality. There is a special case for a relatively small range of values ($\sigma \in [0.541, 0.557]$) in this illustrative example, in which the incumbent firm faces a cost disadvantage and cannot profitably remain in the market by offering minimum quality. Thus, the entrant chooses to offer the 'monopolistic' level of quality and the incumbent chooses inactivity and earns zero profit.

### *C. Sequential Quality Choice under Licensing*

In order to incorporate licensing under sequential quality choice, we assume that incumbent firms can license their technology (or quality) to potential entrants who, in turn, choose between the licensing agreement, expenditure in own R&D, or pursuing both licensing and sunk R&D investment simultaneously.[4] This basic framework is similar to the transactions costs framework developed by Arora and Fosfuri (2003) in their modeling of the market for technology, but for our

[4] In the duopoly case that we examine in our illustrated example, the incumbent firm always prefers to set a level of quality under licensing such that the entrant optimally chooses to forgo own R&D and for the remaining discussion we disregard this possibility from the entrant's choice set.

purposes in this illustrative example, we assume that license arrangements occurs in only a single direction from incumbent to entrant, an assumption that is relaxed in the general framework to allow for cross-licensing.

We assume that incumbent firms specify their own level of quality as well as a proportion of per-firm profit associated with each license that it grants. For the duopoly case examined here, this proportion is relatively large as the gains from entry via licensing by an incumbent, who is able to forgo costly R&D expenditure, can be significant. Transactions costs associated with licensing are incorporated in two forms: first, we assume that the licensee incurs a fixed, non-recoupable transactions cost $T_0$ associated with each license contract that the firm undertakes; and second, we allow for an imperfect transfer of technology between firms by weighting the licensed quality by a 'depreciation' parameter $\delta \in [0,1]$. These assumptions allow us to incorporate the ability of firms to license their technology and pursue license arrangements with competitors in a manner consistent with the endogenous sunk cost and market structure framework of Sutton.

The incumbent firm, Firm $i$, solves the following problem by choosing the R&D expenditure of each firm as well as the proportion of per-firm profits that it receives for each license granted. The first constraint is derived from the reaction function of the entrant firm, Firm $j$, maximizing its own profit via the choice of R&D expenditure. This constraint will not be binding in the duopoly example as the incumbent firm will set its own quality as well as the proportion of entrant profit such that entrant firms cannot profitably increase the quality level offered under licensing by undertaking their own R&D expenditure. Additionally, a participation constraint is incorporated that must be satisfied for entrant firms to choose entry via licensing. It implies that incumbent profit under licensing is no less than incumbent profit in the absence of an offered license on quality. Thus, the incumbent firm, Firm $i$, solves the following maximization problem:

$$\max_{u_i,v_j,\alpha} \frac{1}{2}\left(\frac{2u_i - \sigma\left(\delta u_i + v_j\right)}{4-\sigma^2}\right)^2 - F_0(u_i)^{\beta_i} + \frac{\alpha}{2}\left(\frac{2\left(\delta u_i + v_j\right) - \sigma u_i}{4-\sigma^2}\right)^2$$

$$\begin{gathered} s.t.\ (1-\alpha)\left(4\left(\delta u_i + v_j\right) - 2\sigma u_i\right) - (4-\sigma^2)^2 \beta_j F_0 {v_j}^{\beta_j - 1} \leq 0 \\ \frac{(1-\alpha)}{2}\left(\frac{2\left(\delta u_i + v_j\right) - \sigma u_i}{4-\sigma^2}\right)^2 - F_0 v_j^{\beta_j} - T_0 \geq \bar{\pi}_j \qquad (20). \\ u_i \in \{0, [1,\infty)\} \\ v_j \geq 0 \\ \alpha \in [0,1] \\ \pi_i, \pi_j \geq 0 \end{gathered}$$

As the incumbent firm will prefer the case in which the entrant does not augment its quality via its own R&D expenditure, the incumbent will set its own quality $u_i$ and the proportion of per-firm revenue for each license at a level such that the participation constraint is binding under Firm $j$ choosing to forgo own R&D expenditure (i.e. $v_j = 0$). Thus, we can solve for the proportion of per-firm revenue $\alpha^*$ from this binding participation constraint such that:

$$\alpha^* = 1 - 2\left(\frac{4-\sigma^2}{(2\delta - \sigma)u_i}\right)^2 \left[T_0 + \bar{\pi}_j\right] \qquad (21).$$

From the first-order condition on $u_i > 0$, given the entrant firm accepts the license without augmenting quality through their own R&D expenditure (i.e. $v_j = 0$), the quality offered by Firm $i$ under licensing $u_i^*$ can be specified as:

$$u_i^* = \left[\frac{(2-\sigma\delta)^2 + (2\delta - \sigma)^2}{(4-\sigma^2)^2 F_0 \beta_i}\right]^{\frac{1}{\beta_i - 1}} \qquad (22).$$

Thus, the quality offered by a licensor firm depends only upon their own cost parameter $\beta_i$, the degree of homogeneity in the product market $\sigma$, the fixed set-up cost to R&D $F_0$, and the 'depreciation' of transferred technology $\delta$. The proportion of per-firm profits that the licensor extracts also depends upon the fixed-fee transactions costs per license $T_0$ and the 'reservation' profits the firm receives in the absence of licensing.

In the two cases in which the incumbent firm is a high-cost firm (i.e. $\beta_i = \frac{9}{2}$), there is no feasible proportion of per-firm profits under which the incumbent firm can offers a license contract that is accepted by the entrant and profitably remain in the market. Thus, the incumbent firm does not offer a potential entrant a contract over its quality level and these two cases revert to the sequential quality choice problem examined in the previous section. Although no license is offered in these cases, they do not contradict the story of sunk R&D expenditures and incentives of firms to license technology. If the two firms face asymmetric costs to R&D and the potential entrant has a cost advantage, an incumbent firm cannot profitably offer a feasible license contract that the entrant firm would prefer relative to pursuing quality via its own R&D expenditures. If the two firms are symmetric, high-cost firms, the quality level associated with a license contract offered by the incumbent is not significantly greater than the quality that the entrant would choose in the sequential framework without licensing. Additionally, as there are no cost advantages to capitalize upon, the entrant firm prefers to pursue its own R&D expenditure rather than forgo the proportion of profits that a license contract implies are transferred to the licensor firm.

For the two cases in which the incumbent firm, Firm $i$, faces a low-cost elasticity to R&D, there is a range of feasible values for the degree of substitution in the goods market in which it is profitable for both the incumbent to offer a license contract and the entrant is no worse off compared to the sequential quality choice framework without licensing, provided that the transactions costs are not 'too large'. If there is a 'low' degree of substitution between the goods, and regardless of the entrant's elasticity of the cost of R&D, Firm $i$ chooses a quality level that is greater than under the sequential framework without licensing and earns profits under licensing that are strictly greater. Firm $j$ chooses licensing and also produces a quality greater than under the framework without licensing, but the binding participation constraint implies that its level of profits is equivalent to the case without licensing. However, as the degree of substitution between the goods increases (i.e. the goods become more homogenous), the incentives for Firm $i$ to license its quality level diminish and the Firm $i$ chooses a quality level at which Firm $j$ cannot profitably enter.

### *D. Discussion*

In order to get a more complete understanding of quality choice decisions across timing frameworks, we further separate the analysis along the varying cost regimes and present the graphical illustrations of these results in Appendix A. Several trends can be identified from graphical illustrations that will provide us with some *a priori* predictions upon which to formulate the theoretical model. Moreover, we can compute consumer utility from the assumed quality-indexed linear demand function in order to determine the welfare effects of varying the firm cost regimes and quality choice timing frameworks. Finally, it is interesting to note that in almost all cases as goods become more homogenous in the product market, the market generally supports only a single firm in equilibrium with the notable exception occurring when firms facing symmetric 'high' cost elasticities to R&D and simultaneous quality choice both enter with minimum quality.

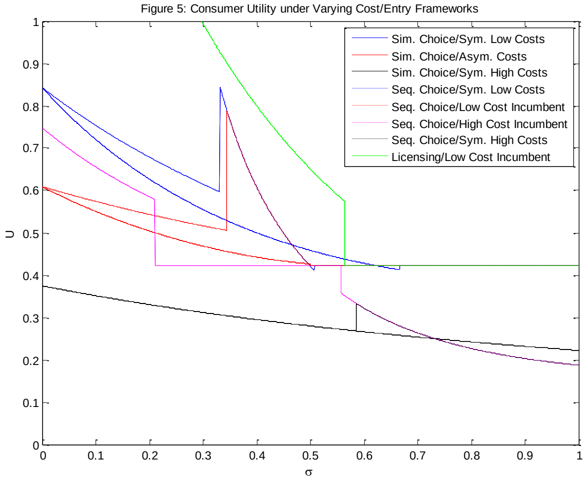
For the first case in which firms face symmetric, low cost parameters for R&D expenditure, the incumbent firm prefers to increase its offered quality and recoup the additional R&D expenditure via licensing for low degrees of substitution. Given the setup of the problem, the entrant firm earns profits under licensing that are no less than the profits it would receive under the sequential choice framework. Additionally, we observe that the level of quality offered by the market leader is (weakly) greater under sequential quality choice framework, with or without licensing, compared to the simultaneous choice framework. These general results remain unchanged when we alter the cost regimes to allow the incumbent firm to have a strict cost advantage with the primary differences arising for when the cost disadvantaged firm chooses to remain inactive.

For the cases in which the incumbent firm faces a high value for its cost parameter, a license in which the licensee transfers a proportion of its profits is infeasible and thus the sequential framework with and without licensing are equivalent. In the simultaneous, asymmetric cost framework, the cost disadvantaged firm can only profitably enter with minimum quality for values of the substitution parameter less than one-half. However, in the sequential framework, the cost disadvantaged incumbent can enter profitably and accommodate the potential entrant for a low degree of substitution, exits the market for intermediate values of the substitution parameter, and precludes entry by the firm with the cost advantage as the degree of substitution increases. The market-leading level of quality offered is greater under the simultaneous framework for all values of the substitution parameter except those for which the high cost incumbent exits. There is an easily visible correspondence between the offered level of quality and firm profit in this scenario.

If firms face symmetric, high cost elasticities of R&D expenditure, the optimal choice for both firms under a simultaneous quality choice decision is to enter with minimum quality regardless of the degree of product homogeneity. Firm profits are monotonically decreasing, but remain strictly positive for all values of the substitution parameter, a result that follows directly from our assumption on the minimum setup cost. For the sequential choice with and without licensing, the incumbent firm accommodates the entrant by offering minimum quality for low degrees of substitution, but precludes entry with increasing profits as the products become greater substitutes.

The welfare implications of the various cost regimes and timing frameworks are illustrated graphically in Figure 5 as we examine consumer utility derived from the assumed linear demand function. The results indicate that consumers receive the (weakly) greatest possible utility for almost any degree of substitution when low cost incumbents choose accommodate entry via licensing. The one exception being a range of values under which symmetric, low cost firms choose quality simultaneously. Moreover, consumers would prefer firms to choose quality sequentially for lower degrees of substitution; a general rule being consumer utility is no less under sequential choice for values of $\sigma < \frac{1}{2}$. The notable exception to this case occurs when there is a high cost incumbent and a low cost entrant and consumers would get greater utility under simultaneous quality choice for values of $\sigma > \sim\frac{1}{5}$. Finally, as products become more homogenous such that the market supports only a single firm, the level of consumer welfare converges across cost regimes and timing frameworks at a level that is less than what is observed if products are differentiated.

Figure 5: Consumer Utility under Varying Cost/Entry Frameworks




### III. Theoretical Model: Extending Sutton's "Capabilities" Approach

#### *A. Framework*

As Sheldon (2008) identifies, Sutton's (1997, 1998, 2008) "bounds" approach to the analysis of market structure and innovation is a natural candidate to the examination of the agricultural biotechnology sector. The "capabilities" approach considers firm concentration to be a function of endogenous sunk costs in R&D investment rather than as being deterministically driven by exogenous sunk costs. As the level of firm concentration will affect the incentives to innovate, the endogenous sunk cost framework provides the opportunity for some firms to outspend rivals in R&D and still profitably recover their sunk cost expenditures. The effectiveness with which firms can successfully recoup their sunk cost outlays depends upon demand side linkages across products, supply side economies of scope in R&D expenditure, the patterns of technology and consumer preferences, and the nature of price competition.

Our initial extension to Sutton's model considers a very general case in which firms choose a R&D program consisting not only of sunk investments along $M$ possible research trajectories, but also including the choice of whether to pursue the specific research trajectory via their own R&D or to license existing technology from the market leader in the specific trajectory. Consider some industry with $K$ submarkets indexed by $k$ such that a quantity of good in submarket $k$ is identified by $x_k$. Let there be $N_0$ total (and $N$ active) firms indexed by $i$.

Firms choose a R&D program consisting of investment in $M$ potential research trajectories, indexed by $m$. Along each trajectory, firms can achieve some competence (capability) $u_{im}$ from one of two sources: (i) own R&D competence $v_{im}$ and (ii) licensed competence $w_{im}$. A firm chooses some value $u_{im} \in \{0, [1, \infty]\}$ along each trajectory where $u_{im} = 0$ corresponds to inactivity along the trajectory and $u_{im} = 1$ corresponds to a minimum level of capability. As there may exist economies of scope in R&D and licensing expenditures, there exists a parameter $\sigma_2 \in [0,1]$ such that competence achieved along other trajectories $M_{-m}$ can increase capability realized along trajectory $m$. Therefore, capability $u_{im}$ can be written as:

$$u_{im} = v_{im} + \delta w_{im} + \sigma_2 \sum_{n \neq m} \{v_{in} + \delta w_{in}\},$$

where $\delta \in [0,1]$ is a parameter that captures (imperfect) substitution of licensed competence. Thus, overall capability that a firm achieves along any specific trajectory is a function of own R&D investment along the trajectory, licensed investment along the trajectory, and a discounted sum of investment along all other trajectories.

There exists a sunk (fixed) cost $F(v_{im}) = F_0[v_{im}]^{\beta_i}$ associated with R&D expenditure along with trajectory $m$ where $F_0$ is a (minimum) setup cost and the elasticity of the fixed cost schedule is characterized by the parameter $\beta_i > 2$, which can vary across firms so as to incorporate the possibility that incumbent and entrant firms face asymmetric cost schedules. Moreover, there exists a sunk (fixed) cost $T(w_{im}) = T_0[w_{im}]^{\gamma_i}$ associated with licensed expenditure along the trajectory $m$ where $T_0$ is a (fixed) transaction cost incurred by the licensee and the elasticity of the transaction cost schedule is characterized by the parameter $\gamma_i$. Thus, the total sunk (fixed) cost for firm $i$ can be written as:

$$TC_i = \sum_m \{F(v_{im}) + T(w_{im})\}.$$

Firm $i$ can enter products into some subset I of all possible submarkets. A product in submarket $k$, $x_k$, is defined by a production technology in submarket $k$, $x_k = f_k(\mathbf{u}_i)$, over a firm's set of capabilities $\mathbf{u}_i = (u_{i1}, \dots, u_{im}, \dots, u_{iM})$. Therefore, the firm's profit function can be written as:

$$\Pi_i = \sum_{k \in I} p_k x_k - TC_i + Z_i,$$

where $Z_i = \sum_m \sum_{j \neq i} z^j(v_{im})$ is licensing revenue for firm $i$ as a function of R&D competence along each trajectory $m$ and summed over all competitor firms that choose to license from firm $i$. Generally, we assume that firms will first set the total revenue for licensing they receive along each trajectory and then choose the number of licenses they issue to competitors.

### *B. Equilibrium Configuration Conditions*

Preliminary results on equilibrium conditions $\mathbf{u}$, comparable to those derived by Sutton (1998, 2008) for his "capabilities" model, can be derived for a "capabilities" model with technology licensing with total market size S. The stability conditions, or "(no) arbitrage principle", imply that an entrant firm can neither profitably enter solely by outspending their competitors nor by only acquiring minimal levels of capability via licensing without any of their own expenditure in R&D. The first condition, equivalent to Sutton's "stability condition", implies that a high-spending entrant escalating the current maximum expenditure $\hat{u}$ by a factor of $\kappa$ cannot profitably enter with capability $\kappa\hat{u}$ without licensing. Condition $(S.1)$ can be written as:

$$\begin{aligned} &S\pi(\kappa\hat{u}|\mathbf{u}) - F(\kappa\hat{u}) \leq 0 \\ &\Rightarrow\ F_0\hat{v}^{\beta} \geq \frac{1}{\kappa^{\beta}} S\pi(\kappa\hat{u}|\mathbf{u}) \end{aligned} \qquad (S.1).$$

The second condition implies that, for any equilibrium condition $\acute{\mathbf{u}}$ in which an incumbent firm is willing to license its technology, a high-spending entrant cannot profitably enter by recouping its increased R&D expenditure solely via licensing. This condition eliminates the possibility of arbitrage by potential entrants via licensing arrangements in the technology market, but does not preclude a market-leading incumbent firm from successfully licensing its technology. The second condition can thus be written:

$$\begin{aligned} &S\pi(\kappa\hat{u}|\acute{\mathbf{u}}) - F(\kappa\hat{u}) + Z(\kappa\hat{v}) \leq 0 \\ &\Rightarrow\ F_0\hat{v}^{\beta} \geq \frac{1}{\kappa^{\beta}} S\pi(\kappa\hat{u}|\acute{\mathbf{u}}) + \frac{1}{\kappa^{\beta}} Z(\kappa\hat{v}) \end{aligned} \qquad (S.2).$$

The final stability condition implies that, for any equilibrium condition $\acute{\mathbf{u}}$, a low-spending entrant cannot profitably enter by acquiring a minimum-level of capability solely via licensing without also incurring any of their own R&D expenditure. This condition arises implicitly from our assumption that firms are able to only license their technology or competence imperfectly such that a license over the minimum competency would results in a realized competency less than the minimum. Condition $(S.3)$ can be written as:

$$\begin{aligned} &S\pi(\delta\hat{u}|\acute{\mathbf{u}}) - T(\hat{u}) \leq 0 \\ &\Rightarrow\ T_0\widehat{w}^{\gamma} \geq S\pi(\delta\hat{u}|\acute{\mathbf{u}}) \end{aligned} \qquad (S.3).$$

The viability conditions, or "survivor principle", imply that firms are able to recover their sunk cost outlays in both R&D expenditure and licensing for any sustainable equilibrium configuration. Condition $(\mathrm{V.1})$, equivalent to Sutton's "viability condition", implies that any equilibrium condition $\mathbf{u}$ must be such that each firm's final stage profit must cover its fixed outlay in the absence of licensing:

$$\begin{aligned} &S\pi(\hat{u}|\mathbf{u}) - F(\hat{u}) \geq 0 \\ &\Rightarrow \; S\pi(\hat{u}|\mathbf{u}) \geq F_0\hat{v}^{\beta} \end{aligned} \qquad (\mathrm{V.1}).$$

The second viability condition implies that, for any equilibrium condition $\acute{\mathbf{u}}$, a firm that licenses its technology (capability) to others must have final stage profits that cover its R&D expenditures. If this condition did not hold, firms would otherwise choose a different configuration of capabilities or would not license its technology to competitors. Condition $(\mathrm{V.2})$ can thus be written as:

$$\begin{aligned} &S\pi(\hat{u}|\acute{\mathbf{u}}) - F(\hat{u}) + Z(\hat{v}) \geq 0 \\ &\Rightarrow \; S\pi(\hat{u}|\acute{\mathbf{u}}) + Z(\hat{v}) \geq F_0\hat{v}^{\beta} \end{aligned} \qquad (\mathrm{V.2}).$$

The final viability condition implies that, for any equilibrium condition $\acute{\mathbf{u}}$, a firm that licenses its technology (capability) from other must have final stage profits that cover its fixed outlays in licensing. Thus, a firm that only licenses its capability from other firms must still have non-negative profits in equilibrium, a condition such that:

$$\begin{aligned} &S\pi(\kappa\delta\hat{u}|\acute{\mathbf{u}}) - T(\kappa\hat{u}) \geq 0 \\ &\Rightarrow \; \frac{1}{k^{\gamma}}S\pi(\kappa\delta\hat{u}|\acute{\mathbf{u}}) \geq T_0\widehat{w}^{\gamma} \end{aligned} \qquad (\mathrm{V.3}).$$

Equilibrium configuration conditions can be obtained from combining each of the corresponding viability and stability conditions. Thus, the condition proposed by Sutton is such that any equilibrium configuration $\mathbf{u}$ without licensing must satisfy:

$$S\pi(\hat{u}|\mathbf{u}) \geq \frac{1}{\kappa^{\beta}}S\pi(\kappa\hat{u}|\mathbf{u}) \quad \forall\kappa \qquad (\mathrm{E.1}).$$

Combining conditions $(S.2)$ and $(V.2)$ obtains a "Licensor Condition" that limits the compensation that firms that increase R&D expenditure are able to receive via licensing to competitors. Thus, for any equilibrium licensing configuration $\mathbf{ú}$, a firm that licenses its technology must satisfy:

$$S\pi(\hat{u}|\mathbf{ú}) \geq \frac{1}{\kappa^{\beta}} S\pi(\kappa\hat{u}|\mathbf{ú}) + \frac{1-\kappa^{\beta}}{\kappa^{\beta}} Z(\hat{v}) \quad \forall\kappa \qquad (E.2).$$

Finally, combining conditions (3) and (6) obtains a "Licensee Condition" that implies that, for any equilibrium configuration $\mathbf{ú}$, there is a limit to the amount that a firm that enters solely via licensing can profitably increase their capabilities such that:

$$S\pi(\kappa\delta\hat{u}|\mathbf{ú}) \geq \kappa^{\gamma} S\pi(\delta\hat{u}|\mathbf{ú}) \quad \forall\kappa \qquad (E.3).$$

### *C. Non-convergence and Licensing*

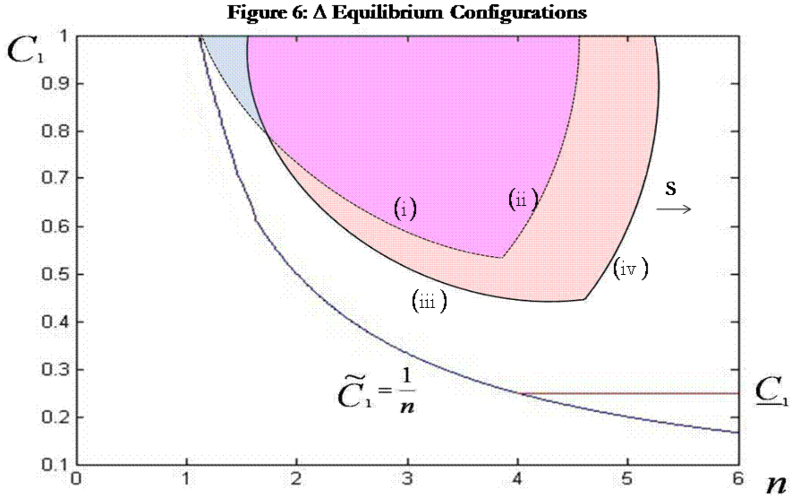
The proofs covering this section are not yet complete. However, preliminary results imply that allowing firms the ability to license their technology/capability greatly increases the set of feasible outcomes that will be observed in equilibrium. Moreover, the bound to concentration under licensing will be lower as the market leader will find it profitable to permit a greater number of competitors to enter the market with its technology. This result follows intuitively as we relax certain assumptions upon the general framework. The assumptions that we relax include the existence of economies of scope within firms, complementarities across goods in the product market, and a reduction in the transactions costs associated with licensing.

The existence of complementary intellectual assets has been shown to be a characteristic of the agricultural biotechnology sector. (Graff, Rausser, and Small, 2003) These complementary intellectual assets can be captured by allowing for economies of scope across capabilities and our licensing framework extends the methods by which firms can acquire these complementary assets.

By allowing for licensing and cross-licensing of technologies, industries can become more consolidated without drastically increasing the levels of concentration as smaller research labs are able to capitalize on their own R&D expenditure via licensing of their technology.

Secondly, the development of specific genetic traits in regards to nutritional content, yield, herbicide-, pesticide-, and/or fungicide-resistance opens the possibility of complementarities in the product market between an herbicide-resistant strain of germoplasm and a specific herbicide. If there are complementarities between consumer products, then firms across historically-segmented markets, such as the chemical industry and germoplasm producers, may find it more profitable to consolidate via licensing of a specific technology compared to a more costly integration of firms via mergers or acquisitions. Finally, as a clearer definition of property rights over genetic material in agricultural biotechnology has reduced the transactions costs associated with licensing of technology. A reduction in licensing-related transactions costs makes consolidation via licensing feasible in more circumstances as these costs become relatively less compared to the fixed costs associated with increasing capability via own R&D. We illustrate this change in feasible equilibrium configurations graphically in Figure 6 below:

**Figure 6: Δ Equilibrium Configurations**



If fixed costs in an industry are exogenous, then the lower bound on industry concentration $\tilde{C}_1 = \frac{1}{n}$ converges to zero as market size and the number of firms in the industry become large. The presence of endogenous sunk costs in the model creates a lower bound to industry concentration $\underline{C}_1$ which is a function of degree of substitutability (complementarity) on the demand side, economies of scope on the supply side, and the parameter on the elasticity of the R&D cost function.

Sutton's stability condition, condition (i) in graph and $(\mathrm{S.1})$ in model, implies that for $\mathbf{u}$ to constitute an equilibrium configuration of capabilities, an existing firm (or potential entrant) cannot profitably enter by escalating the 'maximum' level of some capability $\hat{u}$ by some positive value $\kappa$. Sutton refers to it as an "arbitrage principle" by positing that within an equilibrium configuration, all profitable opportunities along possible research trajectories will be exhausted. Profits from escalating are less than or equal to sunk costs associated with escalation of capability.

Sutton's viability condition, condition (ii) in graph and $(\mathrm{V.1})$ in model, implies that for $\mathbf{u}$ to constitute an equilibrium configuration of capabilities, firms that are active in equilibrium earn non-negative profits. Sutton refers to this as the "survivorship principle" as firms who fail this condition will exit from the industry. Profits in equilibrium from producing 'maximum' level of some capability are greater than or equal to the sunk costs associated with achieving that capability. Jointly, Sutton's viability and stability conditions imply that the stability condition intersects the viability condition and provides a lower bound on industry concentration as market size increases.

The licensing stability condition, condition (iii) in the graph and $(\mathrm{S.2})$ in model, implies that for $\mathbf{\acute{u}}$ to constitute an equilibrium configuration of capabilities under licensing, an existing firm (or potential entrant) cannot escalate the level of capability and fully recoup the difference in profits by licensing this capability to other firms. The interpretation of the viability condition, condition (iv) in graph and $(\mathrm{V.2})$ in model, is equivalent to the interpretation of Sutton's condition with the addition of the ability of firms to also earn additional revenue via licensing to other firms. Jointly, conditions (iii) and (iv) also imply that the stability condition under licensing intersects the viability condition, but that the lower bound on industry concentration is less than the case in which firms are unable to license.

The result under licensing holds under well-defined property rights as firms are now able to license their capability to competitors and receive compensation equivalent to the profits dissipated from licensing without the fear that the capability can be appropriated without compensation. Moreover, firms that choose to license a capability (and incur the transactions costs and license expenditure) can do so profitably if there are economies of scope across capabilities within a firm (i.e. within firm spillovers) $\sigma_2$, if there are demand-side complementarities between differentiated products $\sigma_1 \in [-1,0]$, or if a firm has a cost advantage in incurring additional R&D expenditure $\beta$. This is illustrated graphically as a rightward shift in both the stability and viability conditions such that a greater number of firms exist for a given equilibrium configuration. The stability condition now crosses Sutton's stability condition such that there are some cases under which an equilibrium configuration exists solely under Sutton's conditions as well as cases in which feasible equilibrium configurations exist only under licensing.

## IV. Conclusion

The agricultural biotechnology sector has been characterized by rapid innovation, market consolidation, and a more exhaustive definition of property rights over the past 30 years. In their review of the literature on the market structure in agricultural biotechnology, Fulton and Giannakas (2001) find that the sector has undergone a restructuring in the form of both horizontal and vertical integration over the past ten years. The industry attributes consistently identified by the literature and that factor into the analysis here include: (i) endogenous sunk costs in the form of expenditures on R&D that may create economies of scale and scope within firms; (ii) seed and agricultural chemical technologies that potentially act as complements within firms and substitutes across firms; and (iii) property rights governing plant and seed varieties that have become more clearly defined since the 1970s. We address these considerations in developing a theoretical model of endogenous sunk costs, licensing, and market structure in the presence of well-defined property rights.

The research presented here extends the "capabilities" approach developed by Sutton (1991; 1997; 1998; 2008) along three dimensions: allowing firms to consolidate via licensing arrangements and not solely via mergers and acquisitions; incorporating economies of scale within firms across capabilities; and complementarities in the product market. Simulation results from a Cournot duopoly quantity-quality choice framework and a linear demand function with quality indices imply that licensing is (weakly) preferred by low-cost incumbent firms, potential entrant firms regardless of their fixed cost schedule for R&D expenditure, as well as consumers that receive a level of quality that is greater under licensing compared to the cases where licensing is not feasible.

Additionally, we incorporate the ability of firms to license technology into the theoretical "capabilities" model and specify the necessary conditions on configurations of goods in equilibrium. The first additional condition on equilibrium configurations is of primary importance here as it suggests that the ability of firms to license their technology will decrease the lower bound to concentration in an industry. This is not to imply that licensing agreements are unprofitable; the construction of the model requires that any undertaken action is inherently profitable or at the very least does not diminish profit. It does imply that in some circumstances, license arrangements do not necessarily lead to an increase in concentration.

The results indicate that following the technological innovations and opening of markets in the 1970s, the sector did appear to be characterized by Sutton's model, but that the theoretical model allowing for licensing cannot be ruled out as a candidate model. Additionally, casual observation of the industry would suggest the latter as firms appear to have realized the most profitable synergies between seed and chemical manufacturers first in the form of costly mergers and acquisitions. As the profitable opportunities diminished, firms seem to have become more likely to engage in less costly licensing agreements over specific technologies more frequently. However, this leaves open the chance that future exogenous shocks to technology or to the size of the market could lead to additional entry, exit, and consolidation once again within the industry.

## References


Aghion, P. and J. Tirole. 1994. "On the Management of Innovation." Quarterly Journal of Economics 109(4): 1185-1209.

Aoki, R. and Prusa, T. "Sequential versus simultaneous choice with endogenous quality." International Journal of Industrial Organization, 15 (1), Feb. 1996, pp. 103-121.

Arora, A. and Fosfuri, A. "Licensing the market for technology." Journal of Economic Behavior and Organization, 52(2), Oct. 2003, pp. 277-295.

Chen, Q., A. Naseem, and C. Pray. 2004. "The Determinants of Research Productivity in the Agricultural Input Industry." Prepared for The American Agricultural Economics Association Annual Meeting, Denver, CO: Aug. 1-4, 2004.

Fulton, M. and K. Giannakos. 2001. "Agricultural Biotechnology and Industry Structure." AgBioForum 4(2): 137-151.

Gaisford, J., J. Hobbs, W. Kerr, N. Perdikis, and M. Plunkett. 2001. The Economics of Biotechnology. Edward Elgar, Northampton, MA, USA.

Goodhue, R., G. Rausser, S. Scotchmer, and L. Simon. 2002. "Biotechnology, Intellectual Property and Value Differentiation in Agriculture." CUDARE Working Paper 901R, Dept. of Agriculture and Natural Resources, UCB.

Graff, G., G. Rausser, and A. Small. 2003. "Agricultural Biotechnology's Complementary Intellectual Assets." Review of Economics and Statistics 85(2): 349-363.

Johnson, S.R. and T.A. Melkonyan. 2003. "Strategic Behavior and Consolidation in the Agricultural Biotechnology Industry." American Journal of Agricultural Economics 85(1): 216-233.

Harhoff, D., P. Régibeau, and K. Rockett. 2001. "Some Simple Economics of GM Food." Economic Policy 33(16): 263-299.

Kalaitzanodakes, N. and B. Bjornson. 1997. "Vertical and Horizontal Coordination in the Agro-biotechnology Industry: Evidence and Implications." Journal of Agricultural and Applied Economics 29(1): 129-139.

Kalaitzanodakes, N. and M. Hayenga. 2000. "Structural Changes in the Biotechnology and Seed Industrial Complex: Theory and Evidence." In W.H. Lesser (ed.) Transitions in Agbiotech: Economics of Strategy and Policy, Proceedings of NE-165 Conference, Food Marketing Policy Center, University of Connecticut, pp. 217-227.

Kalaitzanodakes, N. and M. Hayenga. 2000. "Innovation Dynamics and Optimal Licensing Strategies in the Agro-biotechnology Industry." In W.H. Lesser (ed.) Transitions in Agbiotech: Economics of Strategy and Policy, Proceedings of NE-165 Conference, Food Marketing Policy Center, University of Connecticut, pp. 207-216.

Lavoie, B.F. 2004. "Real Options and the Management of R&D Investment: An Analysis of Comparative Advantage, Market Structure, and Industry Dynamics in Biotechnology." Unpublished PhD Dissertation, The Ohio State University.

Marco, A. and G. Rausser. 2008. "The Role of Patent Rights in Mergers: Consolidation in Plant Biotechnology." American Journal of Agricultural Economics 90(1): 133-151.

Oehmke, J., C. Wolf, and K. Raper. 2005. "On Cyclical Industry Evolution in Agricultural Biotechnology R&D." Journal of Agricultural & Food Industrial Organization 3(2): 1107-1131.

Schimmelpfennig, D., C. Pray, and M. Brennan. 2004. "The Impact of Seed Industry Concentration on Innovation: A Study of U.S. Biotech Market Leaders." Agricultural Economics 30(2): 157-167.

Sheldon, I. 2008. "The Biotechnology Sector: "Bounds" to Market Structure". Selected Paper for presentation at the American Agricultural Economics Association Annual Meeting, Orlando, FL: July 27-29, 2008.

Shi, G. 2009. "Bundling and Licensing of Genes in Agricultural Biotechnology." American Journal of Agricultural Economics 91(1): 264-274.

Sutton, J. 1997. "One Smart Agent". RAND Journal of Economics 28(4): 605-628.

Sutton, J. 1998. Technology and Market Structure, Cambridge, MA: MIT Press.

Sutton, J. 2008. "Market Structure: Theory and Evidence". Handbook of Industrial Organization Vol. 3, Ch. 9, (eds.) M. Armstrong and R. Porter. Amsterdam: North-Holland.

# Appendix A: Additional Graphical Illustrations

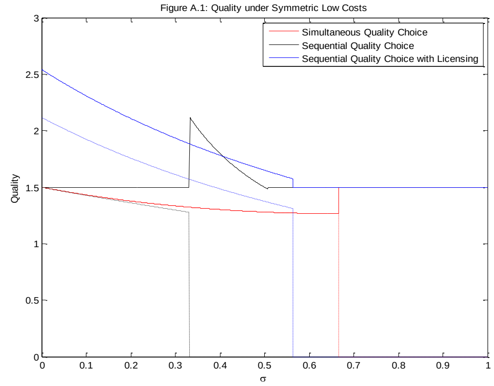


Figure A.1: Quality under Symmetric Low Costs

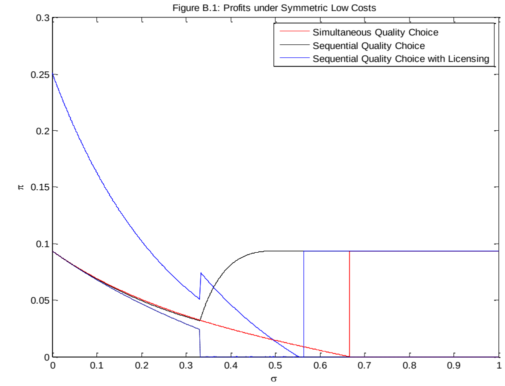


Figure B.1: Profits under Symmetric Low Costs

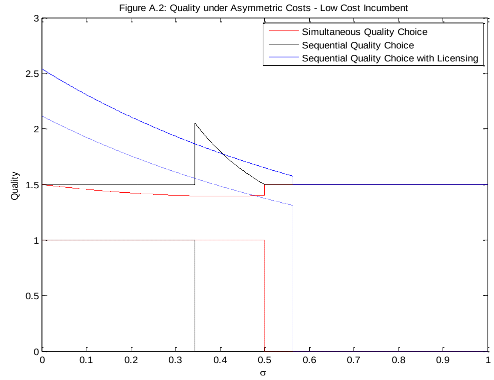


Figure A.2: Quality under Asymmetric Costs - Low Cost Incumbent

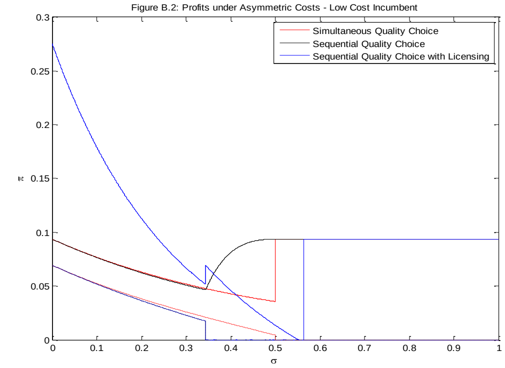


Figure B.2: Profits under Asymmetric Costs - Low Cost Incumbent

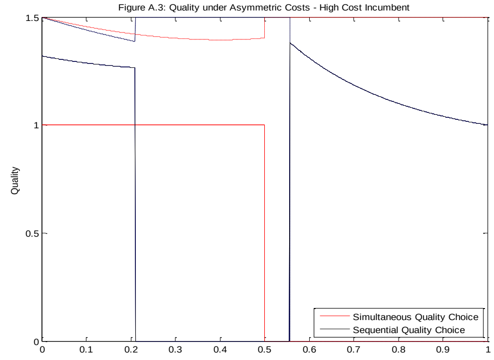


Figure A.3: Quality under Asymmetric Costs - High Cost Incumbent

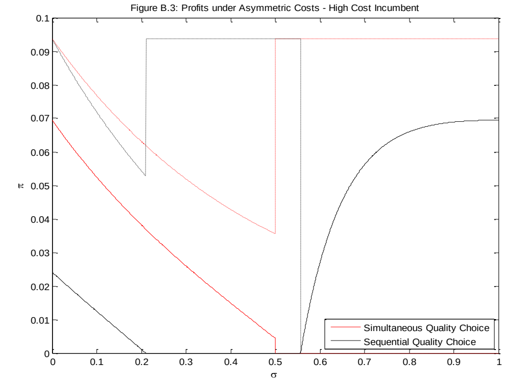


Figure B.3: Profits under Asymmetric Costs - High Cost Incumbent

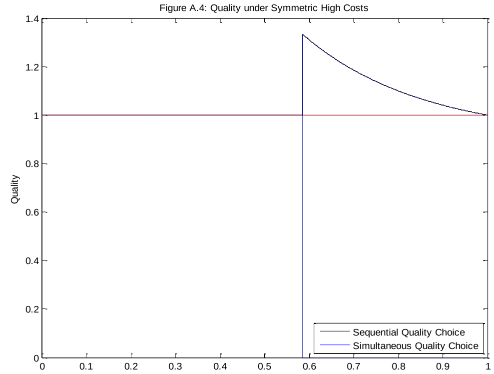


Figure A.4: Quality under Symmetric High Costs

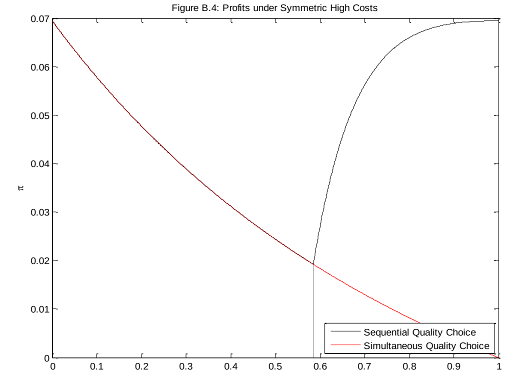


Figure B.4: Profits under Symmetric High Costs