# R&D CONCENTRATION UNDER ENDOGENOUS FIXED COSTS: EVIDENCE FROM GENETICALLY MODIFIED CORN SEED

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We examine the role of fixed costs in research and development (R&D) in the market for genetically modified (GM) corn seed. In a mixed model of horizontal differentiation by genetic traits and vertical differentiation by productivity, we derive the empirically testable lower bounds to R&D concentration when R&D investments and market entry are jointly determined. When R&D investments translate into higher product quality, industries are said to be characterized by endogenous fixed costs such that the lower bound to R&D concentration increases with market size, but is less than the lower bound to market concentration based on sales. Using data on field trial applications of GM corn seed, we estimate the lower bound to R&D concentration, and find evidence of endogenous fixed costs with R&D concentration that is significantly greater than perfectly competitive levels. These endogenous fixed costs imply that concentration in the agricultural biotechnology industry is occurring due to the nature of R&D investment in product quality and not through anticompetitive practices. Adjusting for past merger and acquisition activity significantly raises the lower bound for infinitely-sized markets, but has no impact upon current market sizes, implying the industry may still undergo additional consolidation.

*Key words*: Endogenous fixed costs, genetically modified corn seed, market structure, R&D.

*JEL codes*: L22, Q16.

In 2009, in response to an open call for comments by the U.S. Department of Justice and the USDA (2009) on competition in agriculture, a group of fourteen state attorneys general raised concerns regarding concentration in the seed industry, citing that "increased vertical integration and acquisitions may have raised the bar for entry so high that entry into the *trait market* is difficult, or nearly impossible,"[1] (Munson, London, and Lindeback 2010). In addition to concerns regarding market concentration as measured by firm sales, there is also concern about concentration in traits and germplasm in the seed industry (Hubbard 2009). If property rights over seed traits and germplasm are sufficiently strong, then concentration in ownership of intellectual property (IP) can act as a barrier to entry. The increase in concentration, and any subsequent increase in markups over marginal costs, could be due either to anti-competitive behavior, quality-improving research and development (R&D), or some combination of both. Regulatory intervention may be warranted under anti-competitive behavior, but could also adversely affect firms that compete via quality-enhancing R&D by constraining their ability to increase markups.

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[1] The emphasis contained in the quote was added by the authors.

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In order to examine concerns about concentration in R&D in agricultural biotechnology, we derive the theoretical lower bounds to R&D concentration based upon Sutton's (1991; 1998) theory of market structure under endogenous fixed costs, and empirically test the model's predictions using field trial data on releases of genetically modified (GM) corn seed varieties. We exploit variation in market size along two dimensions: (*a*) geographically, as adoption rates for GM corn seed varieties vary by state and agricultural region; and (*b*) inter-temporally, as adoption rates for GM corn seed have been steadily increasing over time. We test the robustness of our estimation results by considering alternate definitions of geographic sub-markets and the scope of field trials. Finally, we examine the concern that mergers and acquisitions (M&A) have increased the concentration of innovative activity and IP in the agricultural biotechnology sector, an issue discussed in Moss (2009), Dillon and Hubbard (2010), and Moschini (2010).

Sutton (1998) develops a theory of market structure and innovation in which the number and size of firms are determined endogenously in equilibrium via firm investments in quality-enhancing R&D. Without making additional assumptions on the underlying structure of competition or strategic interactions between firms, Sutton (1998) derives empirically testable hypotheses regarding the nature of fixed costs in an industry. When quality improvements are more costly or there is little substitution between firms in the product market, an increase in market size will be accompanied by the entry of additional firms undertaking minimum R&D investments (*exogenous fixed costs*), the market share of any single firm is decreasing, and markets become increasingly fragmented. However, when it is less costly to improve product quality or product substitution is greater, then a firm that increases its investments in quality-enhancing R&D can gain a greater market share at the expense of rival firms (*endogenous fixed costs*). Such costs are "fixed" in the sense that they are unchanging in the quantity produced in the product market. In these industries, existing firms will escalate the quality offered in response to an increase in market size rather than permit additional entry, and the market share of any single firm is non-decreasing. From a policy perspective, detrimental impacts on consumers from increased concentration are offset by increased investments in product quality.

Sutton's (1998) theory provides empirically testable hypotheses for the minimum concentration ratios and R&D intensity that can be expected under either exogenous or endogenous fixed costs. We extend these results by deriving the minimum R&D concentration ratios, defined as the share of R&D by the market-leading firm to total industry R&D, under both exogenous and exogenous fixed costs. In a Spence-Dixit model, fixed investments in R&D can act as a barrier to entry such that concentration in R&D would be associated with lower consumer welfare (Spence 1977; Spence 1979; Dixit 1979; Dixit 1980). Conversely, when R&D investments are quality-enhancing, the returns to additional R&D are increasing in the level of R&D concentration yielding both greater R&D investment by the market-leading firm and higher consumer welfare. The empirical predictions imply that: (*a*) the lower bound to R&D concentration under endogenous fixed costs as market size becomes large is less than the lower bound to market concentration; and (*b*) the lower bound to R&D concentration is increasing in market size such that larger markets are characterized by greater concentration in R&D activity. The theoretical results imply that lower levels of concentration in R&D investments can be consistent with high levels of market concentration, but neither is necessarily indicative of anti-competitive practices when R&D is quality-improving. Aggregate investment in R&D, a standard measure of welfare, can therefore be consistent with many firms making minimum investments in quality under exogenous fixed costs in order to enter the product market, or fewer firms endogenously investing larger amounts in quality-improving R&D. From the perspective of societal welfare, the former case may reflect higher industry R&D, but a proliferation of low-quality goods. Similar to the optimum product diversity results of Dixit and Stiglitz (1977), welfare is greater when fewer firms realize scale economies, in this case pertaining to quality and not quantity, and realize higher quality via additional R&D.

The theory has already been utilized to empirically examine lower bounds to concentration depending upon the intensity of advertising or R&D across industries (Sutton 1991; Robinson and Chiang 1996; Sutton 1998; Marin and Siotis 2007). Evidence of endogenous fixed costs has been found for online book retailers (Latcovich and Smith

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2001), supermarkets (Ellickson 2007), banking (Dick 2007), and newspapers (Berry and Waldfogel 2010), whereas barbers and salons (Ellickson 2007) and restaurants (Berry and Waldfogel 2010) are characterized by exogenous fixed costs. These analyses have focused on examining the relationship between market concentration, captured by the ratio of firm to industry sales, and investments in either capacity (Marin and Siotis 2007), product quality (Ellickson 2007; Berry and Waldfogel 2010), or advertising (Robinson and Chiang 1996; Latcovich and Smith 2001). To our knowledge, ours is the first empirical examination of a specific industry in the context of firm-level investments in R&D, although the empirical analysis of Marin and Siotis (2007) of chemical manufacturers does differentiate between product markets characterized by either high or low R&D intensities.

The estimated levels of R&D intensity, measured as the ratio of R&D-to-sales, 11.0% in 1994, 15.0% in 2000, and 10.5% in 2009, and four-firm market concentration ratios, 21.1% in 1994, 32.5% in 2000, and 53.9% in 2009, would suggest that agricultural biotechnology firms are characterized by R&D that increases product quality as well as market share (Fuglie et al. 2011). By estimating the lower bounds to R&D concentration, we are able to empirically examine the relationship between R&D investments and market structure without placing additional assumptions on the nature of product market competition. The empirical objective is to determine whether the size distribution of firms is consistent with firm competition in product quality via R&D investments, or if these fixed costs in product quality are insufficient to explain the observably high levels of concentration.

Sutton's (1998) model, which focuses on long-run equilibrium, has very little to say regarding M&A as these act as one of several mechanisms by which markets can become concentrated under endogenous fixed costs. In our empirical estimations, we explore the impact of M&A activity in agricultural biotechnology by estimating whether firm consolidation has significantly raised the lower bounds to R&D concentration at current market sizes. A significant increase would provide support for the hypothesis of anti-competitive motives behind acquisitions rather than consolidation consistent with industry dynamics under endogenous fixed costs.

The results of the empirical estimations support the hypothesis that GM corn seed markets are characterized by endogenous fixed costs associated with product quality. The theoretical lower bound to R&D concentration, measured as the market-leading firm's share of R&D activity, ranges from 45.0% to 57.2%, with the results being robust to alternate definitions of market size and R&D concentration. We find that accounting for M&A in the agricultural biotechnology industry increases the lower bound to R&D concentration as market size becomes large, but has little effect upon the predicted levels of concentration for current market sizes. The results reveal the importance of R&D investments in jointly determining the levels of concentration and innovation activity and will be of interest to both regulators concerned with the observed high levels of concentration, and in particular the high levels of concentration in IP in GM corn seed.

The remainder of the analysis is organized as follows: first, a brief overview of the relevant features of the agricultural biotechnology industry and GM corn seed markets is presented. Second, the literature addressing innovation and concentration in GM crops is discussed. Third, a theoretical model of R&D concentration is developed from which empirically testable hypotheses are derived. Fourth, field trial applications (FTAs) as well as the other data utilized in the estimation are discussed. Fifth, the results are presented and discussed. Finally, the paper is summarized and conclusions drawn.

## The Agricultural Biotechnology Industry

The expansion of cellular and molecular biology in the 1960s and 1970s improved the ability of crop scientists to identify and isolate desired crop traits (James 2010). Combined with the Cohen-Boyer gene-splicing technology for recombinant DNA, discovered in 1973 and patented in 1980, plant scientists were able to incorporate specific genetic material, within the same species or across species, into the DNA of another organism (Moschini 2010). Despite the technological advances, the commercial introduction of GM crop varieties proceeded gradually. The first U.S. field trials of any GM variety occurred in 1987, and for GM corn seed in 1990, when we first start observing our proxy

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for R&D. The first deregulation of a GM product (the FlavrSavr tomato) occurred in 1994 with the first commercially available variety of GM corn seed (Bt corn) in 1996, followed by the first "stacked" variety, containing multiple traits, in 1997 (Shoemaker et al. 2001).

Motivated by these innovations in plant science, and substantial changes in the agricultural input industry over the past three decades, there have been several empirical studies of market structure and innovation in the agricultural biotechnology industry. Consistent with the lack of an empirical consensus in the broader literature on the relationship between concentration and R&D intensity, there is mixed evidence on the relationship between innovation and concentration in the seed industry as well (Kalaitzandonakes and Bjornson 1997; Brennan, Pray, and Courtmanche 1999; Schimmelpfennig, Pray, and Brennan 2004; Oehmke, Wolf, and Raper 2005). Consistent with endogenous fixed costs, Brennan et al. (2005) find increasing concentration in patents and field trials, but that larger firms with larger investments are able to limit their exposure to competition from new entrants. Although our empirical methodology is unable to determine the exact relationship, if any, between industry concentration and the level of R&D investment, we find evidence that the industry is characterized by endogenous fixed costs, which is consistent with both higher levels of R&D investment and greater market share for the largest firms.

The industry attributes consistently identified in the literature include: (*a*) substantial expenditures on R&D; (*b*) seed and agricultural chemical technologies that potentially act as complements within firms and substitutes across firms; (*c*) property rights governing plant and seed varieties that have become more clearly defined since the 1970s; (*d*) high levels of consolidation activity in the form of M&A of seed manufacturers; and (*e*) an increasing number of cross-license agreements between patent holders of complementary genetic traits. Since the passing of the Plant Variety Protection Act in 1970, IP rights over seed varieties in the United States have strengthened following the Supreme Court decisions in *Diamond v. Chakrabarty*, 447 U.S. 303 (1980) and *J.E.M. Ag Supply, Inc. v. Pioneer Hi-Bred International, Inc*. 534 U.S. 124 (2001). The consolidation activity alluded to refers to the widespread acquisition of seed manufacturers, and their germoplasm IP, by chemical conglomerates such as Monsanto, DuPont, Syngenta, Dow, Bayer, and BASF, which has resulted in considerable concentration in the global seed industry (King 2001; Howard 2009; Fuglie et al. 2011).

In figure 1, the expansion of private R&D and increased concentration in the seed industry is illustrated by plotting the total number of and four-firm concentration ratios in FTAs for GM corn seed. The FTAs, as both intermediate outputs and inputs in the research process, provide a proxy for R&D activity similar to patent applications. In addition to the increasing rates of adoption across time, the concentration ratios have exceeded 80% since the early 2000s. Also plotted in figure 1 are estimates from Fuglie et al. (2011) of the four-firm concentration ratio, R&D intensity, and total private R&D expenditure for the seed industry as a whole. These estimates illustrate that the GM seed industry has become increasingly concentrated, even though the escalation in R&D appears to have had an ambiguous effect on R&D intensity. These aggregate numbers obscure significant heterogeneity across firms as the eight largest seed companies have an average R&D intensity of 15.8% while accounting for 75.6% of the global R&D share (Fuglie et al. 2011).

We rely on two key aspects of the industry to model and estimate the lower bounds to R&D concentration in GM corn seed: (*a*) domestic R&D expenditures are recouped in the domestic seed market; and (*b*) horizontal (spatial) differentiation occurs in traits offered, while vertical (quality) differentiation occurs through trait and germplasm productivity. The R&D investments in GM corn seed made by firms in the United States are recouped via commercialization in the U.S. market. The disparate regulatory processes across countries provide an additional regulatory hurdle to firms seeking to innovate domestically and commercialize abroad. Recent surveys of global agricultural biotechnology firms indicate that many of the GM crop varieties adopted outside of the United States have also been developed abroad (James 2010). The United States constituted 66.7% of the total global area harvested with GM corn varieties in 2010, which was down from much higher levels that persisted from the first GM adoptions in 1997 through the mid-2000s (Barrows, Sexton, and Zilberman 2014).

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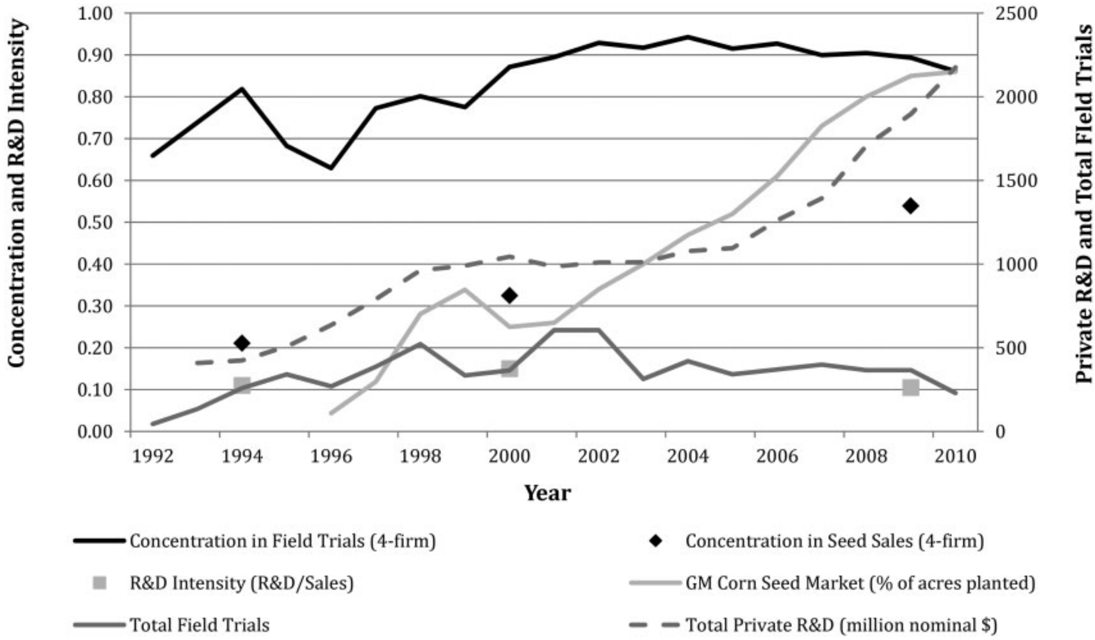


**Figure 1. Concentration and R&D in the corn seed industry**

Source: Biotechnology Regulatory Services (2010), Fernandez-Cornejo (2013), and Fuglie et al. (2011).

There is observable variation across geographic regions in the United States for corn seed varieties. Regional differences in agro-climatic conditions, and the suitability and productivity of certain seed traits such as herbicide tolerance or insect resistance, create geographically-distinct sub-markets. Shi, Chavas, and Stiegert (2010) and Stiegert, Shi, and Chavas (2011) find evidence of both spatial pricing differences across geographic regions in the United States and product differentiation via the bundling of seed traits according to climate and other external factors related to production. Ma and Shi (2013) find significant geographic variation in survival rates for both GM and non-GM hybrid corn seeds such that "the introduction of GM technology did not change the region-specific nature of seed development" (Ma and Shi 2013). These empirical results, consistent with horizontal differentiation in the traits offered in particular geographies, motivates our theoretical model that separates the corn seed market into distinct sub-markets.

Differences in traits offered, and the associated yield improvements or reduction in other agricultural inputs, has led to the widespread adoption of GM corn seed varieties (Barrows, Sexton, and Zilberman 2014; Fernandez-Cornejo et al. 2014). However, the market for GM corn seed varieties is also characterized by quality differences across those varieties in the form of yield improvements and/or productivity enhancements. For instance, Shi et al. (2013) find that some of the improved productivity of GM varieties arose from the acquisition of IP for higher-yielding germplasm. When farmers in a particular geographic region can differentiate between seed varieties based upon expected productivity, even if they contain the same traits, then the market is characterized by vertical product differentiation. Therefore, R&D investments in GM corn seed serve the dual purpose of developing new traits suitable to particular agro-climatic conditions, and also improving upon the existing traits to further offer yield or productivity improvements.

## Endogenous Market Structure and Innovation: The "Bounds" Approach

We adapt Sutton (1998) in order to derive the empirically testable hypotheses for the lower bound to R&D concentration when the level of R&D investment and market entry are jointly, and endogenously, determined in

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equilibrium. In order to clarify the differences between exogenous and endogenous fixed costs and the relevance of these differences, consider a simple model where firms produce identical products and engage in Cournot competition. Suppose that the inverse industry demand is given by $P = a - bQ$, marginal costs of production $c$ are constant, and there is an exogenous fixed cost $F$ associated with R&D required for market entry. In an $n$-firm Cournot-Nash equilibrium, the quantity produced by each firm $i$ is $q_i = \left(\frac{1}{n+1}\right)\left(\frac{a-c}{b}\right)$, and firm profit is $\pi_i = \left(\frac{1}{n+1}\right)^2 \frac{(a-c)^2}{b}$. In the long run, entry occurs until profits net of the fixed entry cost $F$ are equal to zero. That is, entry occurs until $\pi_i - F = 0$ such that the long-run equilibrium number of firms is given by the condition $n = \frac{a-c}{\sqrt{bF}} - 1$.

In this simple example, the costs of entry are fixed, equivalent across all firms, and independent of the quantity produced such that they can be considered *exogenous*. Market concentration, measured by the sales concentration ratio $C_1$ and defined as the ratio of individual firm sales to industry sales, is simply the inverse of the number of entrants, that is, $C_1 = \frac{1}{n}$. The corresponding R&D concentration ratio, defined as the ratio of individual firm R&D to industry-wide R&D, is also equal to the inverse of the number of entrants. The empirically testable hypotheses focus on the lower bounds to this pair of concentration ratios measured as the limiting values for different market sizes. As the demand parameter for market size increases $a \to \infty$, the equilibrium number of entrants increases $n \to \infty$ and the concentration ratios converge to zero. In other words, the lower bounds to the sales or R&D concentration ratios that one would expect to observe in equilibrium are equal to zero. The size of the R&D cost parameter $F$ affects the path of concentration, but has no impact upon long-run concentration in large markets.

A critical assumption in this simple model is that firms produce identical products and are unable to vertically differentiate by increasing product quality. In a supplementary online appendix, we explore the role of vertical quality differentiation in a model of Cournot competition with linear demand.[2] As in the previous case, firms are required to invest some minimum amount in R&D, and realize some minimal quality, in order to enter the market. When this constraint is binding, that is, firms would choose to invest less if there were no minimum quality requirement, the industry is said to be characterized by *exogenous fixed costs*. However, since firms are not restricted to offering identical products, when the minimum quality constraint is not binding firms are able to offer higher-quality products by increasing their investments in R&D (*endogenous fixed costs*). By improving product quality in this case, a firm raises its margin per unit of sales and blocks entry by additional rivals, and therefore is able to successfully recoup the higher initial costs.

Under endogenous fixed costs, the concentration ratios for both sales and R&D do not converge to zero as the market becomes indefinitely large. For certain parameter combinations, it is possible that the equilibrium number of firms initially increases with market size, but eventually decreases as market size grows large. This pattern is consistent with a U-shaped—rather than a monotonically decreasing—relationship between concentration and market size. Therefore, Sutton (1998) highlighted that market concentration in expanding industries need not be decreasing and, in fact, may be increasing in market size.

As the online supplementary appendix highlights, there is typically a “switching point” in industries from being characterized by exogenous to endogenous fixed costs. In particular, exogenous fixed costs are more likely when the size of the industry is small, the minimum level of R&D is high, and the products are more highly substitutable across segments. Rather than categorize industries as exhibiting either exogenous or endogenous fixed costs, Sutton’s (1998) model permits an industry to encompass both, depending upon the size of the market, the degree of product substitutability, and the cost of R&D. Without placing any restrictions on the functional forms or nature of product market competition, Sutton (1998) derives the lower bounds to the sales concentration ratio and R&D intensity, defined as the firm R&D-to-sales ratio. The first part of the theory developed below extends Sutton’s (1998) results by deriving the lower bound to the R&D concentration ratio. The lower bound to the R&D concentration ratio is then compared

[2] Online supplementary appendix A: An Illustrative Model, explores the quality-indexed linear demand model first proposed in Sutton (1998).

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to the lower bound for the sales concentration ratio in order to establish some general properties of R&D concentration and derive empirically testable hypotheses for the lower bound to R&D concentration.

### *Theoretical Lower Bound to R&D Concentration*

In deriving the theoretical lower bound, it is useful to introduce notation for sales revenue, R&D expenditure, and total fixed costs. Firm-level sales revenue, $S_m y_{im}$, is defined for firm $i$ in sub-market $m$ with market size $S_m$. Total industry sales revenue, $S_m y_m$, is obtained by summing across all firms in sub-market $m$, such that $S_m y_m = S_m \sum_{i \in m} y_{im}$. The total fixed costs $F_{im}$ incurred by firm $i$ in sub-market $m$ are defined as $F_{im} = F_0 u_{im}^{\beta}$, where $F_0$ is a minimum setup cost associated with entry into sub-market $m$, $u_{im}$ is the product quality of firm $i$ in sub-market $m$, and $\beta$ is the elasticity of R&D expenditures. These costs are "fixed" in the sense that they are unchanging in the quantity produced in the product market although they are changing in the level of product quality, $u_{im}$. Further, R&D expenditure $R_{im}$ by firm $i$ in sub-market $m$ is defined as the fixed expenditure in excess of the minimum entry costs, that is, $R_{im} = F_{im} - F_0$, and total industry R&D, $R_m$, is obtained by summing across all firms in sub-market $m$ such that $R_m = \sum_{i \in m} R_{im}$. We define the degree of sub-market segmentation, or product homogeneity, $h_m \in [0, 1]$, as the share of industry sales revenue in sub-market $m$ accounted for by the largest product category $l$ such that $h_m = \max_l \frac{y_{lm}}{y_m}$, where $h_m = 1$ corresponds to a homogenous sub-market with a single product.

Sutton (1998) specifies "viability" and "stability" conditions to derive non-convergence results on the lower bound to the single-firm concentration ratio, $C_{1m}$, and the R&D-to-sales ratio, $\frac{R_{im}}{S_m y_{im}}$. In our notation, the viability condition can be specified as

$$(1) \qquad S_m y_{im} - F(u_{im}) \geq 0$$

such that a firm that enters in sub-market $m$ in equilibrium earns non-negative profits in that sub-market in aggregate, but does not preclude the possibility that the firm earns non-positive profits within a single product category in the sub-market. The stability condition restricts the ability of an entrant firm to escalate product quality and earn non-negative profits in sub-market $m$ such that

$$(2) \qquad S_m y_{(N+1)m} - F\left(u_{(N+1)m}\right) \leq 0.$$

The lower bound to the single-firm concentration ratio $C_{1m}$, defined in terms of the quality-leading firm with sales revenue $\hat{y}_m$ offering quality $u_m$ in sub-market $m$, can be stated as

$$(3) \qquad C_{1m} = \frac{S_m \hat{y}_m}{S_m y_m} \geq \alpha(\sigma, \beta) \cdot h_m$$

where $\alpha$ is some constant for a given set of parameter values $(\sigma, \beta)$, $\sigma$ is a parameter capturing consumer preferences and product market substitutability, and $\beta$ is as defined earlier. The value of alpha $\alpha$ depends upon industry technology, product market competition, and consumer preferences, and signifies the extent that a firm can escalate product quality via R&D investment and capture market share from rivals. Equation (3) implies that the lower bound to market concentration is independent of the size of the market in industries with endogenous fixed costs, which contrasts with exogenous fixed cost industries in which the lower bound to market concentration is decreasing and approaches zero as the size of the market increases. The lower bound result implies that when products are more homogenous within a sub-market, that is, higher $h_m$, firms are able to escalate their R&D investments in product quality as market size increases and preclude additional firm entry. As there is horizontal differentiation across sub-markets, the individual sub-market homogeneity is greater than overall industry homogeneity.

Sutton (1998) derives an expression for the lower bound to R&D intensity, the R&D-to-sales ratio, for the quality-leading firm such that

$$(4) \qquad \frac{\hat{R}_m}{S_m \hat{y}_m} \geq \alpha(\sigma, \beta) \cdot h_m - \frac{F_0}{S_m y_m}.$$

Equation (4) implies that the R&D-to-sales ratio shares the same lower bound as the single-firm concentration ratio as the size of the market becomes large (i.e., $S_m \to \infty$). For finitely-sized markets, the lower bound to R&D intensity is increasing in the size of the market as the largest firms respond to these increases with an escalation of R&D.

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THEOREM 1. Given the lower bound to market concentration, $C_{1m}$, and R&D-to-sales ratio under endogenous fixed costs derived in Sutton (1998), there is a lower bound to R&D concentration, $C_{1m}^{R\&D} \geq \left[\alpha^2(\sigma,\beta)h_m^2 - \alpha(\sigma,\beta)h_m \frac{F_0}{S_m y_m}\right]$, under endogenous fixed costs that is less than the bound to market concentration.

*Proof*. See appendix.

The lower bound to R&D concentration, $C_{1m}^{R\&D}$, under endogenous fixed costs is

$$(5) \qquad C_{1m}^{R\&D} \geq \left[\alpha^2(\sigma,\beta)h_m^2 - \alpha(\sigma,\beta)h_m \frac{F_0}{S_m y_m}\right].$$

Equation (5) provides the basis for the empirically testable hypothesis of endogenous R&D expenditures. If sunk R&D costs are endogenous, there is a nonlinear relationship between the degree of market segmentation (product homogeneity), $h_m$, and the single-firm R&D concentration ratio for a given sub-market, $m$. Equation (5) also implies a lower bound to the ratio of R&D concentration that converges to some constant, $\alpha^2(\sigma,\beta)h_m^2$, as the size of the market becomes large, which is less than the lower bound to market concentration, $\alpha(\sigma,\beta)h_m$, since both the product homogeneity parameter, $h$, and the escalation parameter, $\alpha$, lie between 0 and 1. Additionally, for finitely-sized markets, the lower bound to R&D concentration retains the feature of the lower bound to R&D intensity of increasing with market size such that R&D expenditures are less concentrated in smaller-sized markets.

COROLLARY TO THEOREM 1. When fixed costs are exogenous, there is an upper bound to R&D concentration $C_{1m}^{R\&D} \leq \frac{1}{N_m}$ that is decreasing as market size increases.

*Proof*. See appendix.

Under exogenous fixed costs, firms have no incentive to invest in R&D in order to realize higher product quality in excess of the minimum R&D required for entry. Firms that invest in excess of the minimum are unable to realize a greater market share since firms offering lower-quality goods at lower prices are able to profitably enter and undercut the higher-quality, higher-price firms. This implies that the single-firm R&D concentration ratio in a sub-market, $m$, is bounded from above and is no greater than the single-firm market concentration ratio. Particularly, the number of entrants varies positively with market size under exogenous fixed costs such that market and R&D concentration are greatest in smaller-sized markets and decreasing as the size of the market increases.

In figure 2 a comparison is made of the lower bounds to R&D concentration for industries with sub-markets characterized by low- and high-levels of product homogeneity, $h$, for a range, $\alpha$, of parameters as market size, $S$, increases. If an industry has sub-markets with homogenous products, that is, high $h$, and $\alpha$ is sufficiently large, there is an incentive for firms to escalate R&D investment to increase product quality such that R&D concentration remains bounded away from zero as market size increases. However, if there is a proliferation of products in a sub-market such that each product variety has a small market share, that is, low $h$, there is no range of $\alpha$ such that firms invest in R&D in excess of the minimum setup cost.

## Empirical Specification

Theorem 1 and its corollary lead directly to the empirically-testable hypotheses for the lower bound to R&D concentration. Specifically, an industry characterized by endogenous fixed costs in R&D should exhibit a lower bound to R&D concentration that is non-decreasing in market size (Theorem 1), whereas R&D concentration in exogenous fixed cost industries is decreasing in market size (Corollary to Theorem 1). Sutton (1991) derives a formal test for estimating the lower bound to concentration in an industry, based upon Smith (1985; 1994), in which the concentration ratio is characterized by a Weibull distribution, which has since been adapted and extended by Giorgetti (2003), Dick (2007), and Ellickson (2007). It is necessary to transform the R&D concentration ratio $C_1^{R\&D}$ such that the predicted concentration measures will lie between 0 and 1. Specifically, the concentration measure is transformed according to

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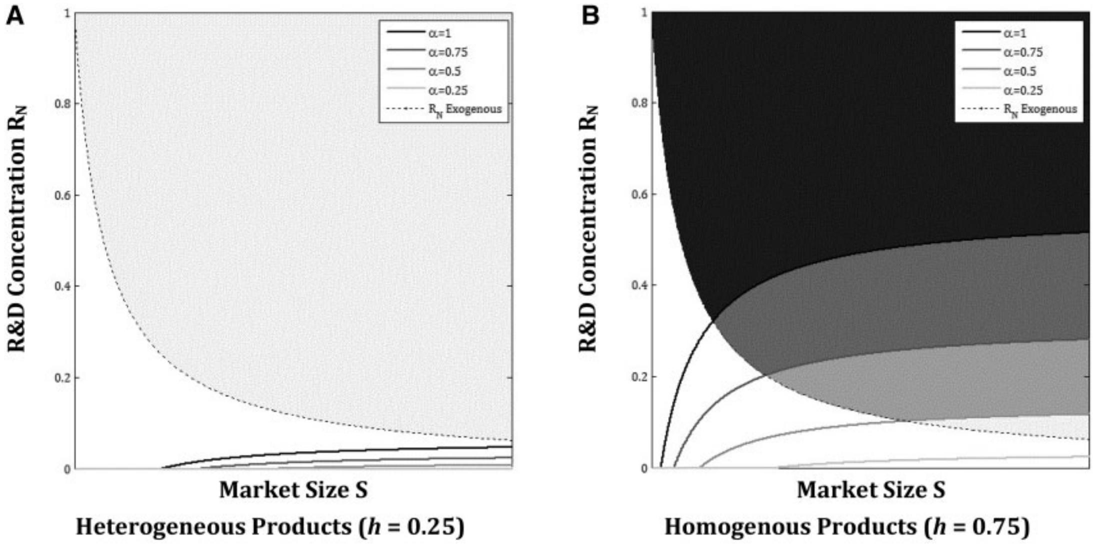


**Figure 2. Equilibrium R&D concentration levels and market size**

$$(6) \quad \tilde{C}_1^{R\&D} = \ln\left(\frac{C_1^{R\&D}}{1 - C_1^{R\&D}}\right).^{3}$$

We follow the functional form suggested by Sutton (1991) for the lower bound estimation such that for some sub-market, $m$, the $\sim C_{1m}^{R\&D}$ concentration ratio is characterized by

$$(7) \quad \frac{\tilde{C}_{1m}^{R\&D}}{h_m^2} = \theta_0 - \theta_1 \frac{1}{h_m \ln(S_m y_m / F_0)} + \epsilon_m$$

where $(\theta_0, \theta_1)$ are the parameters of the empirical model. The intercept parameter $\theta_0$ reflects the theoretical lower bound as the market size becomes large, whereas the slope parameter $\theta_1$ reflects how the lower bound changes with changes in market size. The residuals $\epsilon$ between the observed values of R&D concentration and the lower bound are distributed according to the Weibull distribution such that

$$(8) \quad F(\epsilon) = 1 - \exp\left[-\left(\frac{\epsilon - \mu}{\delta}\right)^{\gamma}\right], \ \gamma > 0, \ \delta > 0$$

on the domain $\epsilon \geq \mu$. The case of $\mu = 0$ corresponds to the two-parameter Weibull distribution such that nonzero values of the shift parameter $\mu$ represent horizontal shifts of the distribution. The shape parameter, $\gamma$, corresponds to the degree of clustering of observations along the lower bound, whereas the scale parameter $\delta$ captures the dispersion of the distribution. Testing for a lower bound to R&D concentration is equivalent to testing whether the residuals fit a two- or three-parameter Weibull distribution, that is, testing whether $\mu = 0$. However, as Smith (1985) identifies, fitting equation (7) directly via maximum likelihood estimation is problematic for shape parameter values $\gamma \leq 2$.[4] Smith (1985; 1994) provides a two-step procedure for fitting the lower bound that is feasible over the entire range of shape parameter values.

Following the methodology of Giorgetti (2003), we first solve a linear programming problem using the simplex algorithm to obtain consistent estimators of $\{\theta_0, \theta_1\}$ in which the fitted residuals are non-negative. Therefore, $\{\hat{\theta}_0, \hat{\theta}_1\}$ solves

[3] As transformed R&D concentration is undefined for values of $R_{nm} = 1$, we monotonically shift the R&D concentration data by $-0.0001$ prior to the transformation.

[4] Specifically, for $1 < \gamma \leq 2$, a maximum for the likelihood function exists, but it does not have the same asymptotic properties and may not be unique. Moreover, for $0 \leq \gamma \leq 1$, no local maximum of the likelihood function exists.

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$$(9)\quad \min_{\{\theta_0,\theta_1\}} \sum_{m=1}^{N}\left[\frac{\tilde{C}_{1m}^{R\&D}}{h_m^2} - \left(\theta_0 - \theta_1 \frac{1}{h_m \ln(S_m y_m / F_0)}\right)\right]$$

$$\text{s.t.}\ \frac{\tilde{C}_{1m}^{R\&D}}{h_m^2} \geq \left(\theta_0 - \theta_1 \frac{1}{h_m \ln(S_m y_m / F_0)}\right),\ \forall m.$$

From the first step, we obtain parameter estimates for $\{\hat{\theta}_0, \hat{\theta}_1\}$, and fitted residual values $\hat{\epsilon}$ that can be used to estimate the parameters of the Weibull distribution via maximum likelihood. Specifically, as there are $k$ parameters to be estimated in the first stage, there will be $N-k$ fitted residuals with positive values. By keeping only the fitted residuals with values that are strictly greater than zero, we maximize the log pseudo-likelihood function

$$(10)\ \max_{\{\gamma,\delta,\mu\}} \sum_{m=1}^{N-k} \ln\left[\left(\frac{\gamma}{\delta}\right)\left(\frac{\epsilon_m - \mu}{\delta}\right)^{\gamma-1} \exp\left[-\left(\frac{\epsilon_m - \mu}{\delta}\right)^{\gamma}\right]\right]$$

with respect to $\{\gamma, \delta, \mu\}$ in order to test whether $\mu = 0$, which is equivalent to testing the two-parameter versus three-parameter Weibull distribution via a likelihood ratio test with one degree of freedom. If the three-parameter Weibull distribution cannot be rejected, then this implies the presence of a horizontal shift in the distribution corresponding to an industry in which R&D is exogenous. Finally, we compute standard errors for the first-stage estimations via bootstrapping and standard errors for the second-stage estimations according to the asymptotic distributions defined in Smith (1994).

## Data and Descriptive Statistics

In order to estimate the endogenous fixed-cost model, it is necessary to have both firm-level sales data and total market size for each associated sub-market. Although such data are of limited availability across all markets for GM corn seed, estimating the endogenous lower bound to R&D concentration is feasible using publicly available data. The model specifically requires: (*a*) firm-level data on R&D investment within a sub-market; (*b*) industry-level data on sub-market size; (*c*) industry-level data on product homogeneity; and (*d*) industry-level data on minimum setup costs. We exploit two dimensions of variation in R&D investment and market size by estimating the lower bound across geographic sub-markets as well as over time. In doing so, we are able to capitalize upon changes in farmer and consumer attitudes towards GM crops over time as well as advances in technology and/or regulation changes that decrease R&D fixed costs.

The ideal data for analyzing an endogenous lower bound to R&D concentration would be R&D expenditures broken down at the product, sub-market, and firm level for the entire industry. Since this level of detail of R&D expenditure is unavailable for GM corn seed, we consider a proxy for R&D investment. Common proxies for R&D activity are either patent applications or patent approvals under the assumption of a positive correlation between patents and R&D expenditure. Since we are interested in variations in innovative activity at a sub-national level, patent applications are not useful in this context as they are not tied to a particular geographic region. Fortunately, the regulatory approval process for GM crops provides a suitable alternative—FTAs of GM crops.

Animal Plant and Health Inspections Services (APHIS) regulate the release of any genetically engineered (GE) organism that potentially threatens the health of plant life. Prior to the release of any GE organism, the releasing agency must submit a permit application to Biotechnology Regulatory Services (BRS; 2010). This organization publishes applications for the importation, interstate movement, or release of GE organisms, covering 1985 through present day, in an online database. The database includes information on the applicant, relevant dates, the status of the application, the plant type, the state-level release locations, and the crop phenotypes and genotypes. As of October 2010, the database included 33,440 total applications for crop release across all crop types and, after dropping applications by non-profit institutions and research laboratories and those unrelated to GM corn varieties, there were 6,696 observations remaining in the database.

The FTAs reflect both intermediate outcomes of the R&D process, as well as

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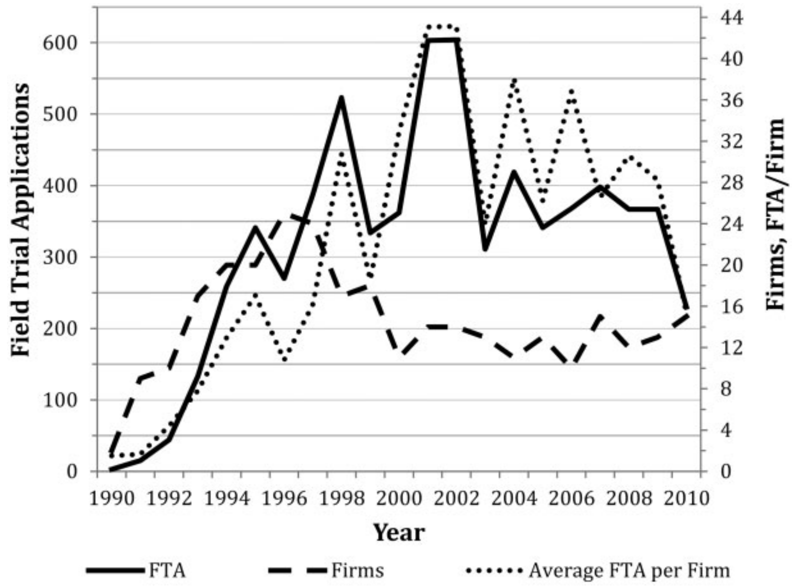


**Figure 3. Field trial applications and number of applicant firms**

Source: Biotechnology Regulatory Services (2010).

research inputs. Previous analyses that have utilized FTA data have examined the relationship between R&D investment, output, and M&A activity (Brennan, Pray, and Courtmanche 2000), R&D activity across public and private organizations (Oehmke 2001), the positive correlation between FTAs and subsequent commercialization for corn and soybean varieties (Stein and Rodríguez-Cerezo 2009), and the impact that labeling regime differences between the United States and the European Union have upon firm incentives to innovate (O'Connor 2010). The validity of using FTAs as a proxy for R&D investment relies on the assumption that FTA are increasing at a constant or decreasing rate with the level of R&D investment.[5] In the case of measurement error arising from calculating R&D concentration using FTA rather than R&D expenditure, the estimated lower bounds would remain unbiased, but the standard errors and confidence intervals would be estimated with less precision.

In figure 3 the annual number of FTAs by private enterprises for GM corn seed varieties between 1988 and 2010 are plotted, as well as the yearly number of firms that submitted an application. The data reveal that the number of distinct firms applying for at least one field trial in a given year peaked in the mid-1990s, with twenty-five firms submitting applications in 1995, before falling and roughly leveling off by the early 2000s. This is consistent with an industry characterized by a new technology in which significant initial entry occurred, followed by a "shakeout" of firms when the commercialization possibilities of the technology are realized. The FTA data indicate that GM corn applications increased throughout the 1990s and peaked in the early 2000s before falling and leveling off by the mid 2000s. The number of yearly applications, together with the firm data, illustrates that average per firm R&D activity was increasing through the early 2000s for GM corn seed varieties before leveling off, a story that is consistent with maturity in the first generation, and the slow introduction of subsequent generations of GM crops.

[5] We thank an anonymous referee for highlighting the potential nonlinear relationship between FTAs and R&D expenditure. A positive, linear relationship will lead to unbiased parameter estimates. If larger firms are more efficient at screening innovations prior to field trials, then FTAs are increasing at a decreasing rate with R&D expenditure, and the parameter estimates will be biased towards the null hypothesis of exogenous fixed costs. Given the observable pattern of increasing R&D expenditures and decreasing field trials since the early to mid 2000s, we rule out the possibility that FTAs are increasing at an increasing rate with R&D expenditure.

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A critical assumption of our estimations is that R&D expenditures are recouped within geographic sub-markets. As a robustness check, we estimate the lower bound to R&D concentration when field trials are conducted solely within a particular sub-market, both when permitting and excluding field trials that were also conducted in Hawaii and Puerto Rico, where many agricultural biotechnology firms have research facilities. These robustness checks are valid under the weaker assumption that field trials that are conducted exclusively in a particular region are related to that region's product market and are independent of the product markets in other regions.

In estimating this type of model for a single industry, an initial crucial step is the proper identification of the relevant product markets. For the case of retail industries, such as those examined by Ellickson (2007) and Berry and Waldfogel (2010), markets are clearly delineated spatially. The identification of distinct markets in agricultural biotechnology is more problematic as investments in R&D may be spread over multiple geographic retail markets, both domestic and foreign. We rely on the assumption that investments in a sub-market are recouped via sales within that particular sub-market.

We noted earlier in the paper that there is empirical evidence for regional variation in the market for GM corn seed (Shi, Chavas, and Stiegert 2010; Stiegert, Shi, and Chavas 2011; Ma and Shi 2013). Although the data utilized in these analyses covers a substantial proportion of U.S. corn production and is defined at a lower geographic level, it does not account for variation that occurs in regions outside of the Corn Belt. Since our R&D concentration data is only observable at the state level, we define sub-markets as groups of entire states within a geographic region.

We consider three alternate classifications of regional sub-markets for corn seed varieties, summarized in table 1, that account for both the categorization of corn-producing states into "core" and "fringe" regions according to Stiegert, Shi, and Chavas (2011), as well as state-level observable differences in climate, agricultural characteristics, and corn-specific production. In the broadest classification, we consider only three sub-markets: the "core" Corn Belt region; the "fringe" Corn Belt region; and the remaining states comprise a single non-Corn Belt region. We then relax the assumption of a unitary "fringe" region by using climate and agricultural production data from the period prior to the widespread adoption of GM varieties (1990–1995) to classify the "fringe" states according to observable differences in climate and production practices.[6] Finally, we relax the assumption of a unitary non-Corn Belt sub-market and allow for geographic variation in the sub-markets for corn seed within regions in which corn production is not the primary agricultural commodity.

In order to estimate the lower bound to R&D concentration, we require data on the size of the market, the amount of product homogeneity, and the minimum R&D setup costs, in addition to the measures of R&D concentration. We estimate market size using acreage reports from the June Agricultural Surveys and yearly seed costs in dollars per acre based upon the Agricultural Resource Management Surveys (ARMS; USDA National Agricultural Statistics Service (NASS) 1990–2010) After adjusting for inflation, we multiply seed costs by total corn acres planted in order to arrive at total market size as a proxy for industry sales in equation (9).

Since 2000, the June Agricultural Survey has also questioned farmers regarding the adoption of GM seed varieties in a sample of corn-producing states.[7] In using these survey data, the USDA Economic Research Service computes and reports estimates for the extent of GM adoption separated by crop type and GM characteristics. The GM adoption rates, supplemented with the adoption data from Fernandez-Cornejo and McBride (2002) for the years 1996–1999, are used to construct a product homogeneity index for corn seed that

[6] Additional discussion of the analysis of the geographically distinct sub-markets is presented in online supplementary appendix B: Sub-Market Analysis.

[7] The USDA NASS estimates that the states reported in the GM adoption tables account for 81–86% of all corn acres planted. For states without an adoption estimate, overall U.S. adoption estimates are used to compute the homogeneity index.

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**Table 1 GM Corn Seed Sub-Markets**

| Sub-Market | 2010 Market Shares (%) | Field Trial Applications | States |
|---|---|---|---|
| **Classification #1** | | | |
| "Core" States | 29.47 | 2,650 | IL, IA |
| "Fringe" States | 56.47 | 2,315 | CO, IN, KS, KY, MI, MN, MO, NE, ND, OH, SD, WI |
| "Non-Corn Belt" States | 14.06 | 1,574 | All others (33) |
| **Classification #2** | | | |
| "Core" States | 29.47 | 2,650 | IL, IA |
| Eastern "Fringe" States | 12.43 | 949 | IN, KY, OH |
| Northern "Fringe" States | 15.76 | 824 | MI, MN, WI |
| Southern "Fringe" States | 10.64 | 736 | CO, KS, MO |
| Western "Fringe" States | 17.64 | 911 | NE, ND, SD |
| "Non-Corn Belt" States | 14.06 | 1,574 | All others (33) |
| **Classification #3** | | | |
| "Core" States | 29.47 | 2,650 | IL, IA |
| Eastern "Fringe" States | 12.43 | 949 | IN, KY, OH |
| Northern "Fringe" States | 15.76 | 824 | MI, MN, WI |
| Southern "Fringe" States | 10.64 | 736 | CO, KS, MO |
| Western "Fringe" States | 17.64 | 911 | NE, ND, SD |
| Mid-Atlantic/Appalachia | 3.15 | 592 | DE, MD, NC, TN, VA, WV |
| Northeast | 3.03 | 480 | CT, ME, MA, NH, NJ, NY, PA, RI, VT |
| Southeastern | 1.16 | 386 | AL, FL, GA, SC |
| S. Plains/MS Delta | 4.87 | 401 | AR, LA, MS, OK, TX |
| Western | 1.84 | 364 | AZ, CA, ID, MT, NM, OR, UT, WA, WY |

*Source:* Authors' estimates from NASS (2010) Acreage Report and Field Trial Applications.

varies across time. The product homogeneity index is calculated as the percentage of industry sales in a sub-market captured by the largest product group. We treat GM corn seed varieties as homogenous within product groups, broadly defined as conventional, insect resistant (IR), herbicide tolerant (HT), and "stacked" varieties consisting of IR and HT traits, and equate the product homogeneity index to the percentage of acres accounted for by the largest group.[8]

In order to derive the minimum setup cost associated with product market entry, we use data reported in Frey (1996) to obtain a measure of the R&D setup cost for innovations in GM corn seed.[9] Frey reports information on the number of "scientist years" (SY) as well as estimated costs per SY for state agricultural experiment stations, the Agricultural Research Service, and private firms for various crops including field (dent) corn.[10] Frey reports the number of projects undertaken by the public sector agencies and the total number of private firms, but not the total number of private projects. In order to calculate the minimum setup cost, we divide the total number of SY for public agencies (35.30) by the total number of projects (32) in order to determine the average

[8] The construction of the homogeneity index introduces measurement error if product categories are more appropriately defined at the trait level. This potential measurement error, in which actual homogeneity is less than measured homogeneity, would bias our results towards finding endogenous fixed costs by overestimating the market share gained from an escalation in product quality. In order to examine the impact of the homogeneity index upon the estimated lower bound, we consider a sensitivity analysis, column 4 in table C.1 in online supplementary appendix C, in which we artificially set the homogeneity index at 6.7% for all sub-markets. The assumption of a 6.7% market share is based upon the (most conservative) assumption that each of the GM product traits (European corn borer resistance, root worm resistance, and two types of herbicide tolerance) identified in Shi, Chavas, and Stiegert (2010), as well as conventional varieties and the stacked versions of these traits, have an equal market share.

[9] Traxler et al. (2005) update the results of Frey (1996) with additional data from 2001 to examine changes in public funding of plant breeding in the previous seven years. However, they do not include information on private R&D spending on plant breeding or information on the number of projects conducted by each research agency.

[10] A "scientist year" is defined as "work done by a person who has responsibility for designing, planning, administering (managing), and conducting (a) plant breeding research, (b) germplasm enhancement, and (c) cultivar development in one year (i.e., 2080 hours)" (Frey 1996, p. 21).

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SY per project. We use the data from the public agencies since we are unable to determine the number of SY per project in the private sector and only observe the average number of SY per firm doing research in corn seed. The minimum setup cost per project is obtained by multiplying the average public SY per project by the private industry cost per SY ($290,000) for the largest firms and adjusting for inflation.[11]

## Empirical Results and Discussion

Prior to estimating the lower bound to R&D concentration, we examine graphically whether the GM corn seed market appears to be characterized by an endogenous lower bound to R&D concentration. In figure 4, the one- and four-firm R&D concentration ratios are plotted against the market size of each sub-market for every sample. The plots show that R&D concentration ratios are non-decreasing in market size, regardless of the definition of sub-markets, implying the possibility of a lower bound. However, these descriptive plots do not account for differing levels of product homogeneity across time and it is not possible to reconcile them directly with the lower bound to R&D concentration implied by the theory.

After adjusting for R&D concentration in each submarket according to equation (6), we estimate the relationship between the single-firm R&D share and the ratio of total market size to private setup costs. We subsequently check the robustness of the results to alternate sub-market definitions and measures of R&D concentration derived from field trials conducted only within each sub-market. Finally, we adjust for M&A activity in the agricultural biotechnology sector and examine the impact of this consolidation activity upon concentration in R&D.

[11] If the private SY per project are greater than the public SY per project, then we could be underestimating the minimum setup costs. To test the sensitivity of our estimates to these setup costs, we consider the possibility that private SY per project are three or six times greater than the public SY per project, in columns 2 and 3, respectively, in table C.1 in online supplementary appendix C.

### Estimating the Lower Bounds to R&D Concentration

The two-stage estimation results of the lower bounds to R&D concentration in GM corn seed are reported in table 2. Our baseline specification, column 1, considers ten sub-markets and all field trials conducted within those sub-markets. In robustness checks, we consider both alternate sub-market definitions, columns 2 and 3, and alternate definitions of R&D concentration as measured from field trials occurring only within a particular sub-market, columns 4 and 5. The alternate sub-market definitions, for six sub-markets in column 2 and three sub-markets in column 3, ensure that our results are not driven by the smallest-sized markets where concentration in R&D may be more influenced by outliers. By focusing on field trials that occur only within a single regional sub-market, both including (column 4) and excluding (column 5) those that occurred simultaneously in Hawaii or Puerto Rico, we address the concern of properly attributing R&D that occurs across multiple sub-markets under the assumption that any spillovers between sub-markets would have to undergo additional field trials prior to commercialization.

The logit transformation of R&D concentration complicates the direct interpretation of the estimated coefficients, but the coefficient on the intercept term $\hat{\theta}_0$ can be interpreted as the theoretical lower bound as market size becomes large, that is, $S_m \to \infty$, and the coefficient on market size $\hat{\theta}_1$, adjusted for product homogeneity and fixed setup costs, indicates whether the lower bound is increasing, decreasing, or unchanging to market size. The null hypothesis of exogenous fixed costs implies that the theoretical lower bound to R&D concentration converges to approximately zero as market size becomes large and that the predicted lower bound is non-increasing in market size, that is, $\hat{\theta}_1 \leq 0$. Our hypothesis test for endogenous fixed costs examines whether the single-firm R&D concentration ratio converges to less than 10% under large market sizes.

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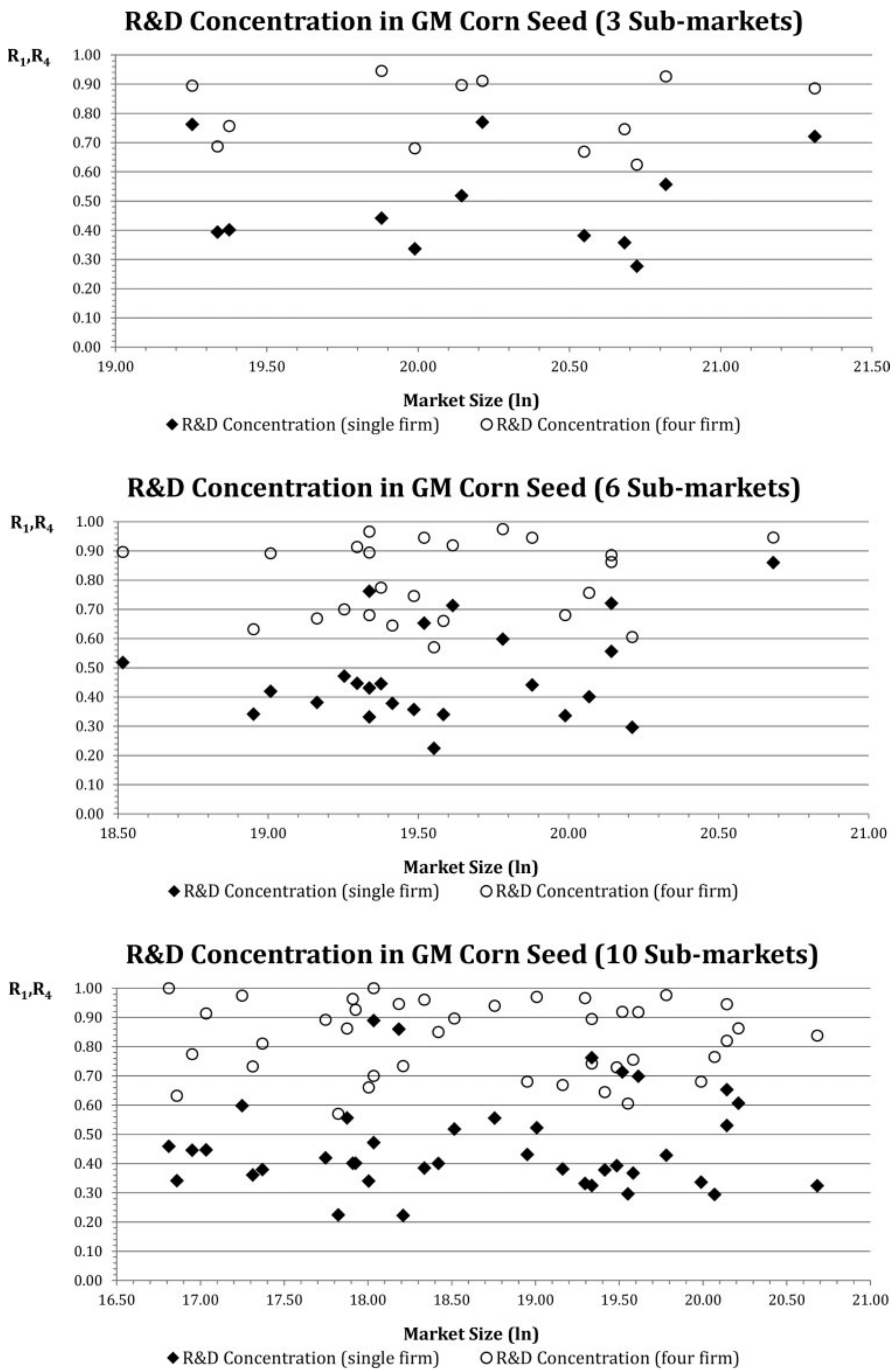


**Figure 4. R&D concentration and market size in GM corn seed**

The results from the first-stage estimation reveal that the predicted lower bound to R&D concentration is significantly increasing in market size, that is, $\hat{\theta}_1 > 0$, for the baseline case of ten regional sub-markets including all field trials, for the robustness check of six

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**Table 2 Lower Bound Estimations for GM Corn Seed**

| | Baseline | Alternate Sub-market Definitions | | Field Trials in Sub-market Only | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| **Theoretical Lower Bound ($R_1^\infty$)** | **0.572** | **0.572** | **0.469** | **0.466** | **0.450** |
| Lower Bound (95% confidence) | 0.559 | 0.542 | 0.405 | 0.405 | 0.386 |
| Fitted Lower Bound (Largest Submarket) | 0.318 | 0.318 | 0.412 | 0.394 | 0.411 |
| **First-Stage** | | | | | |
| Intercept ($\theta_0$)^ | 1.195** | 1.195** | −0.507** | −0.558** | −0.832** |
| | (0.131) | (0.291) | (0.599) | (0.612) | (0.642) |
| Adjusted Market Size ($\theta_1$) | 16.474** | 16.474** | 3.640 | 4.615* | 2.467 |
| | (0.790) | (1.635) | (3.385) | (2.482) | (2.427) |
| First-stage Observations | 40 | 24 | 12 | 40 | 40 |
| **Second-Stage** | | | | | |
| Shape Parameter ($\gamma$) | 1.348** | 1.144** | 1.005** | 0.863** | 0.836** |
| | (0.027) | (0.039) | (0.082) | (0.018) | (0.018) |
| Scale Parameter ($\delta$) | 3.876** | 3.317** | 1.962** | 5.402** | 5.192** |
| | (0.080) | (0.140) | (0.206) | (0.174) | (0.172) |
| Likelihood Ratio ($\chi^2$=1)^ | −0.164 | −0.754 | −0.033 | −0.263 | −0.260 |
| Second-stage Observations | 38 | 22 | 10 | 38 | 38 |
| Number of Regional Sub-markets | 10 | 6 | 3 | 10 | 10 |
| Include Hawaii & Puerto Rico Field Trials | Y | Y | Y | Y | N |
| *h* value for bounds calculations | 0.491 | 0.491 | 0.491 | 0.491 | 0.491 |

*Note:* Standard errors in parentheses.^ Null hypothesis ($H_0$): As market size becomes large, does the lower bound to R&D concentration converge to less than 10% for the given product homogeneity index? ^^: Null hypothesis ($H_0$): Non-zero first-stage residuals fit a two-parameter Weibull distribution. **, *: Significance at the 99% and 95% levels, respectively.

sub-markets and all field trials, as well as for the robustness check of ten sub-markets, and including only regional field trials that also occurred in Hawaii and Puerto Rico. Across all sub-market and R&D concentration definitions, the theoretical lower bound to R&D concentration is significantly greater than 10%. The theoretical lower bound for infinitely-sized markets, reported in table 2, is derived by performing an inverse logit transformation of the intercept parameter, $\hat{\theta}_0$, multiplied by the square of the product homogeneity index for the largest sub-market. The estimated bounds imply that the largest firm in an infinitely-sized sub-market would account for 45.0–57.2% of R&D activity in GM corn seed varieties. Although the fitted lower bound, with single-firm R&D concentration of at least 31.8–41.2%, implies that the GM corn seed market is relatively concentrated in terms of R&D, the gap between the theoretical and fitted lower bounds implies that the possibility remains for additional concentration in R&D activity.

In figure 5, the fitted and theoretical lower bounds to R&D concentration with 95% confidence intervals and the observed levels of R&D concentration under ten regional sub-markets and including all field trials are illustrated. These results are consistent with an endogenous lower bound to R&D concentration as illustrated in figure 2 in which concentration is very low in small-sized markets and increasing in market size. The clustering of observations between the theoretical and fitted lower bounds in GM corn seed illustrates convergence to the theoretical lower bound as market size increases as predicted under EFC.

The second-stage estimations explore whether the non-zero first-stage residuals fit a two- or three-parameter Weibull distribution. The results on the shape parameter $\gamma$, which is less than two in all estimations, imply a high degree of clustering on the lower bound GM corn seed sub-markets, and that the two-step procedure of Smith (1985; 1994) is appropriate. The estimates of the scale parameter $\delta$ indicate a relatively wide dispersion of R&D concentration in GM corn sub-markets. The likelihood ratio tests, with one degree of freedom, fail to reject the null hypothesis that

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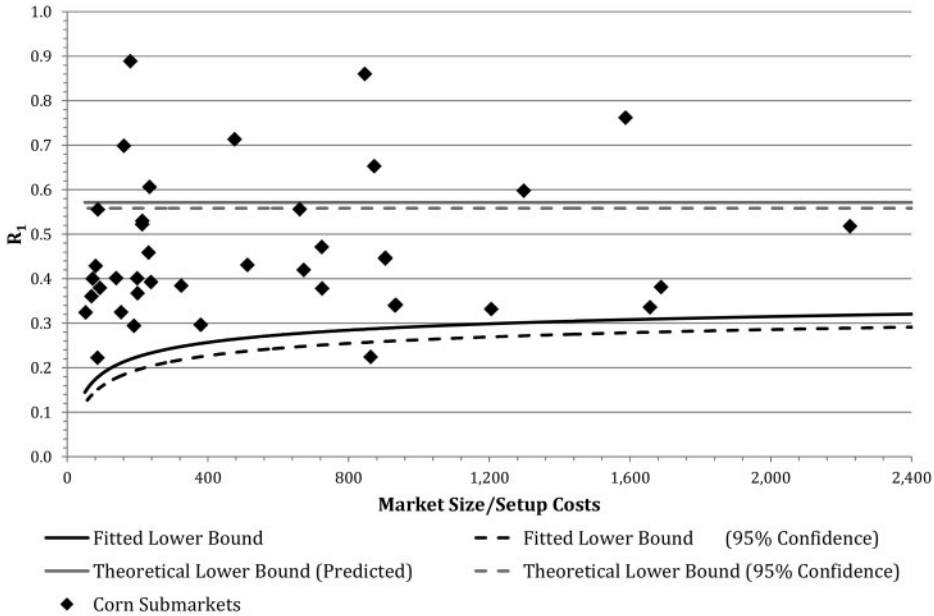


**Figure 5. Lower bound to R&D concentration in GM corn seed**

the first-stage residuals fit a two-parameter Weibull distribution. This implies that the location parameter $\mu$ is not significantly different from zero, and we fail to reject the hypothesis that the sub-markets for GM corn are characterized by endogenous fixed costs.

## Estimating the Lower Bounds to R&D Concentration under Firm Consolidation

In the final set of estimations, we consider the impact of M&A activity in the agricultural biotechnology sector upon R&D concentration in the GM corn seed market. Rather than consider R&D concentration based upon the firm applying for field trials as we have in the previous estimations, we now assign these field trials to firms according to the M&A activity that occurred between 1990 and 2010. We utilize company histories and Lexis-Nexis news releases to identify M&A activity and the effective merger date in order to construct a measure of R&D concentration accounting for ownership changes.[12] This exercise allows us to explore whether M&A activity by agricultural biotechnology firms has served to increase concentration in R&D activity above and beyond the levels of R&D concentration that would occur under endogenous fixed costs alone.

The results in the "Unadjusted" column in table 3 correspond to our baseline estimations for ten regional sub-markets, whereas the results in the "M&A Adjusted" column account for the M&A activity. After controlling for firm consolidation, we continue to fail to reject the null hypothesis of endogenous fixed costs and a lower bound to R&D concentration that is increasing in market size. In figure 6, we plot the theoretical and fitted lower bounds, along with the 95% confidence intervals, for both the baseline and M&A-adjusted estimations. This figure illustrates that adjusting R&D activity for M&A significantly raises the theoretical lower bound to R&D concentration from 57.2% to 66.1% for the market-leading firm. However, we fail to reject equivalence of the fitted lower bounds at currently-sized markets as the unadjusted fitted lower bound falls within the 95% confidence interval for the M&A-adjusted fitted lower bound. Jointly, these results imply that M&A activity has significantly increased the concentration of R&D activity in GM corn seed,

[12] Although completed independently, our list of changes in corporate ownership, reported in online supplementary appendix D: Industry Mergers and Acquisitions, corresponds to the activity reported in Fuglie et al. (2011).

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**Table 3 Lower Bound Estimates Adjusting for Mergers and Acquisitions in GM Corn Seed**

| | Unadjusted | M&A Adjusted |
|---|---|---|
| **Theoretical Lower Bound ($R_1^\infty$)** | **0.572** | **0.661** |
| Lower Bound (95% confidence) | 0.559 | 0.649 |
| Fitted Lower Bound (Largest Submarket) | 0.318 | 0.344 |
| **First-Stage** | | |
| Intercept ($\theta_0$)^ | 1.195** | 2.773** |
| | (0.131) | (0.139) |
| Adjusted Market Size ($\theta_1$) | 16.474** | 20.658** |
| | (0.790) | (0.886) |
| First-stage Observations | 40 | 40 |
| **Second-Stage** | | |
| Shape Parameter ($\gamma$) | 1.348** | 1.295** |
| | (0.027) | (0.027) |
| Scale Parameter ($\delta$) | 3.876** | 3.931** |
| | (0.080) | (0.084) |
| Likelihood Ratio ($\chi^2$=1)^ | −0.164 | −0.104 |
| Second-stage Observations | 38 | 38 |
| Number of Regional Sub-markets | 10 | 10 |
| Include Hawaii & Puerto Rico Field Trials | Y | Y |
| *h* value for bounds calculations | 0.491 | 0.491 |

*Note:* Standard errors in parentheses.^ Null hypothesis ($H_0$): As market size becomes large, does the lower bound to R&D concentration converge to less than 10% for the given product homogeneity index?^Null hypothesis ($H_0$): Non-zero first-stage residuals fit a two-parameter Weibull distribution. **,*: Significance at the 99% and 95% levels, respectively.

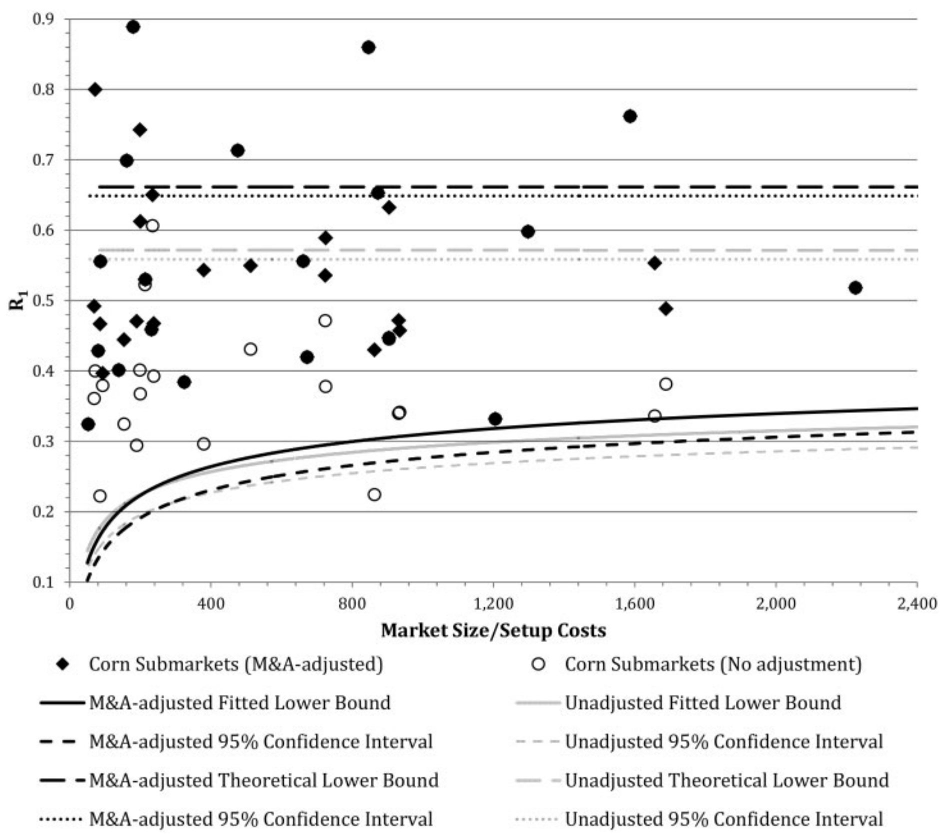


**Figure 6. Lower bound to R&D concentration adjusting for mergers and acquisitions**

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but that this increase has had little economic significance at current market sizes and relative to the concentration in R&D due to the endogenous fixed cost nature of innovation in agricultural biotechnology.

## Summary and Conclusions

In this paper, we examine whether the market for GM corn seed is characterized by endogenous fixed costs associated with R&D investment. We derive the theoretical lower bound to R&D concentration from Sutton's (1998) model of market concentration and innovation under horizontal and vertical product differentiation. The empirically testable hypothesis implies that the lower bound to R&D concentration under endogenous fixed costs will be less than the lower bound to market concentration, but is increasing in the size of the market. Using data on FTAs, we subsequently estimate the lower bound to R&D concentration in GM corn seed varieties using exogenous variation in market size across time as adoption rates of GM crops increase, as well as across agricultural regions.

We find evidence supporting the hypothesis that GM corn seed markets are characterized by endogenous fixed investments in R&D, which is robust to alternate definitions and measurements of regional markets, R&D concentration, and minimum setup costs. As market sizes become large, the empirical results imply that the R&D share of the market-leading firm converges from 45.0% to 57.2%, and that under current market sizes, the estimated share of R&D activity is 31.8% to 41.2%. Adjusting for firm consolidation via M&A activity significantly increases the lower bound to R&D concentration as markets become large (57.2% to 66.1%) but has no significant impact for current market sizes (31.8% to 34.4%).

The empirical results are consistent with an industry characterized by endogenous fixed costs such that the observed concentration in R&D activity, as well as in sales, arises due to the nature of fixed investments in product quality. Whereas increased levels of concentration are often associated with anticompetitive behavior, the presence of endogenous fixed costs and the nature of technology competition in agricultural biotechnology imply that a certain level of concentration is to be expected. Although the levels of concentration in the GM corn seed industry are potentially of concern, regulators should understand that higher levels of concentration are to be expected under quality-enhancing R&D investments. Accounting for the additional product market concentration from M&A yields higher estimates of R&D concentration, but the magnitude of these impacts is small relative to the concentration that arises due to the nature of R&D investment in the GM corn seed market. The empirical model leaves open the possibility that the introduction of second and third generation GM varieties, the opening of foreign markets to GM crops, future exogenous shocks to technology, or reductions in regulatory costs could lead to additional entry, exit, or consolidation in the industry.

## Supplementary Material

Supplementary material are available at *American Journal of Agricultural Economics* online.

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## Appendix

*Proof of Theorem 1*

In order to derive the lower bound to R&D concentration, consider the lower bound to R&D intensity for the quality-leading firm specified in equation (4):

$$\text{(A.1)} \qquad \frac{\hat{R}_m}{S_m\hat{y}_m} \geq \alpha(\sigma,\beta)\cdot h_m - \frac{F_0}{S_m y_m}.$$

Multiplying both sides by the sales revenue of the market-leading firm and dividing by the total industry R&D in sub-market $m$ yields

$$\text{(A.2)} \qquad \frac{\hat{R}_m}{\mathrm{R}_m} \geq \left[\alpha(\sigma,\beta)\cdot h_m - \frac{F_0}{S_m y_m}\right]\cdot\frac{S_m\hat{y}_m}{\mathrm{R}_m}.$$

The viability condition (1), implies

$$\text{(A.3)} \qquad R_{im} \leq S_m y_{im} - F_0.$$

Since this condition must hold for all firms that enter in equilibrium, we can sum across all entrants and write the viability condition as

$$\text{(A.4)} \qquad R_m \leq S_m y_m - N_m F_0$$

where $N_m$ is the number of entrants. Since $R_m \leq S_m y_m - N_m F_0$, the expression for R&D concentration can be written as

$$\text{(A.5)} \qquad \frac{\hat{R}_m}{\mathrm{R}_m} \geq \left[\alpha(\sigma,\beta)\cdot h_m - \frac{F_0}{S_m y_m}\right]\cdot\frac{S_m\hat{y}_m}{\mathrm{R}_m} \geq \left[\alpha(\sigma,\beta)\cdot h_m - \frac{F_0}{S_m y_m}\right] \times \frac{S_m\hat{y}_m}{S_m y_m - N_m F_0}.$$

Since the number of entrants and the minimum setup costs are non-negative, an equivalent condition for R&D concentration is

$$\text{(A.6)} \qquad \frac{\hat{R}_m}{\mathrm{R}_m} \geq \left[\alpha(\sigma,\beta)\cdot h_m - \frac{F_0}{S_m y_m}\right] \times \frac{S_m\hat{y}_m}{S_m y_m - N_m F_0} \geq \left[\alpha(\sigma,\beta)\cdot h_m - \frac{F_0}{S_m y_m}\right]\cdot\frac{S_m\hat{y}_m}{S_m y_m}.$$

Finally, the lower bound to market concentration in equation (3) implies $\frac{S_m\hat{y}_m}{S_m y_m} \geq \alpha(\sigma,\beta)\cdot h_m$. The lower bound to R&D concentration thus satisfies

$$\text{(A.7)} \quad C_{1m}^{R\&D} = \frac{\hat{R}_m}{\mathrm{R}_m} \geq \left[\alpha^2(\sigma,\beta)h_m^2 - \alpha(\sigma,\beta)h_m\frac{F_0}{S_m y_m}\right]. \blacksquare$$

*Proof of Corollary to Theorem 1*

In an industry characterized by exogenous fixed costs, the single-firm concentration ratio $C_{1m}$ is simply equal to

$$\text{(A.8)} \qquad C_{1m} = \frac{S_m\hat{y}_m}{S_m y_m} = \frac{1}{N_m}$$

where the number of firms that enter in equilibrium depends primarily upon the size of the sub-market, $S_m$, and the minimum fixed setup cost, $F_0$, such that concentration converges to zero as the size of the sub-market $m$ becomes large. Combining this expression for the single-firm concentration ratio under exogenous fixed costs with the viability condition (2), which must hold in equilibrium, yields

$$\text{(A.9)} \qquad S_m\hat{y}_m - \hat{F}_m = \frac{S_m y_m}{N_m} - \hat{F}_m \geq 0.$$

Recall that the viability condition must hold at the industry level as well (i.e., $R_m \leq S_m y_m - N_m F_0$) such that

$$\text{(A.10)} \qquad \frac{S_m y_m}{N_m} - \hat{F}_m \geq \frac{R_m + N_m F_0}{N_m} - \hat{F}_m \geq 0.$$

Substituting for the expression for R&D for the quality-leading firm $\hat{R}_m$ implies

$$\text{(A.11)} \qquad \frac{R_m + N_m F_0}{N_m} - \left(\hat{R}_m + F_0\right) \geq 0.$$

Simplifying yields an upper bound to R&D concentration under exogenous fixed costs

$$\text{(A.12)} \qquad C_{1m}^{R\&D} = \frac{\hat{R}_m}{\mathrm{R}_m} \leq \frac{1}{N_m}. \qquad \blacksquare$$

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