Three essays on the economics of innovation and regional economics

by

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CHPATER 1: GENERAL INTRODUCTION

1.1 Introduction

In modern economies, knowledge and innovation are the main driving forces behind technological progress and the resulting increase in social welfare. At the same time, it is well understood that economic agents who produce new ideas and goods rarely capture the whole social product of their activities. For example a new invention might serve as a springboard to countless new products but their full social value most likely is not reflected in the original innovator's payoff, even if her invention is protected by intellectual property rights. Similarly, a firm that decides to locate its production facilities in a given geographical area will not necessarily be properly rewarded for the benefits which might accrue to other firms in the area (because of potential economies of scale and knowledge spillovers which may increase labor productivity). The presence of such external effects implies that there exists a potential scope for government intervention which might be welfare improving. Consequently, it is important to understand which policies, if any, will be most efficient in achieving the best possible outcome in a given situation.

One such area of active current research is the design of the optimal incentive structure for the innovation processes which are cumulative and sequential, i.e., when each new innovation is derived directly from the previous one. Cast in the simplest possible terms the problem here is how to ensure that the division of profits between the initial and subsequent inventors is such that both have an incentive to invest in research and development (Green and Scotchmer (1995)). This problem might be further complicated if one is willing to relax the somewhat limiting assumption that ideas are scarce and allow both inventors to participate in the each stage of the innovation process. Even though the resulting model of the R&D race is well known, most of the results pertaining to the optimal structure of intellectual property rights in such a context are limited in that they usually consider races with exogenous finish lines and prizes collected at the end of the R&D contest.

Another important limitation of the literature on the economics of the intellectual property rights is its exclusive focus on the instruments of patent length and breadth. In particular, it is often implicitly assumed that the act of doing research using a protected innovation, which is essential in the cumulative innovation context, is itself non-infringing. This assumption is however at odds with the current intellectual property systems in many developed countries where there exists no statutory "research exemption" provision in patent law (Eisenberg (2003)).

The first two essays of my dissertation attempt to fill gaps in the theoretical analysis of the optimal incentive structure when innovation is sequential and cumulative. In particular, the models studied in these chapters feature infinite horizon races with prizes collected continuously and study the effects of the research exemption provision on the incentives for sequential innovation. The first essay (chapter 2) sets up a dynamic model of an infinite horizon R&D race between two firms and characterizes the Markov Perfect Equilibria of this race. Then it analyzes the welfare properties of the research exemption provision in this context and relates these welfare properties to the cost structure which characterizes the research and development process. It is shown that firms ex ante prefer a stronger intellectual property regime, one which does not envision the research exemption provision. At the same time, the model implies that social welfare might be higher or lower in presence of the research exemption provision depending on the cost structure. In particular, when the cost of the initial innovation is much higher than the cost of subsequent improvements (e.g., plant breeding), the stronger intellectual property regime which does not envision a research exemption will be socially optimal.

The second essay (chapter 3) revisits the question of the welfare properties of the research exemption in the context of a biological innovation, the value of which is affected by the problem of pest adaptation and resistance. This particular setup is relevant for studying incentives to invest in R&D which is directed towards improving the characteristics of commercially produced crop varieties. It is shown that in this case both firms might prefer a weaker intellectual property regime if the R&D cost is below a certain threshold. At the same time, it is shown that there exist conditions under which a stronger intellectual property regime is beneficial from the social point of view. The main methodological contribution of this chapter is to depart from the traditional nonrenewable resource approach to the pest resistance problem and to demonstrate that consideration related to the nature of the innovation process and intellectual property rights should play a role in guiding public policy in this area.

The third essay (chapter 4) attempts to cover new ground by undertaking an empirical study of the phenomenon of the urban wage premium. It has been argued that wage advantage of the workers residing in densely populated urban areas over the identical workers in rural areas reflects primarily the productivity advantage of the urban labor force (Glaeser and Mare (2001)). In particular, it is often argued that both economies of scale and knowledge spillovers are the driving forces in this process. If true, such claims provide empirical support to policies which seek to create such effect, by subsidizing various forms of agglomerations such as technology parks and innovation clusters.

In my essay however I draw attention to important caveats in the empirical analysis commonly employed in the urban wage premium studies. I argue that potential endogeneity of the geographical location of a given individual might lead to inconsistent estimates of the urban wage premium. In particular, if cities attract workers of higher unobserved ability, then one would expect to observe a wage premium even in the absence of the local spillover effects. To test this hypothesis I use data from the National Survey of Families and Households to evaluate two econometric models which explicitly account for non-random selection based on unobservable characteristics. I find that the wage premium can be fully explained by unobserved heterogeneity in the workers characteristics.

1.2 Thesis Organization

The three essays described in the introduction are all self-contained with their own Introduction, Conclusion and Reference sections. They are followed by the General Conclusion section.

1.3 References

Eisenberg, R.S., "Patent swords and shields," *Science*, 2003, 299(February 14), 1018-1019.

E.L. Glaeser and D.C. Mare. Cities and skills. *Journal of Labor Economics*, 19:316–342, 2001.

Green, J., and Scotchmer, S., "On the division of profit in sequential innovation," *RAND Journal of Economics*, 1995, 26(1), 20-33.

CHAPTER 2. PATENTS, RESEARCH EXEMPTION, AND THE INCENTIVE FOR SEQUENTIAL INNOVATION

2.1 Introduction

The economic analysis of intellectual property rights (IPRs) has long emphasized their ability to provide a solution to the appropriability and free-rider problems that beset the competitive provision of innovations (see Scotchmer, 2004, for an overview). But whereas there is agreement that legally provided rights and institutions are necessary to offer suitable incentives for inventive and creative activities, it is less clear what the extent of such rights should be. The predicament here is very much related to the second-best nature of the proposed solution to the market failures that arise in this context (Arrow, 1962). Because they work by creating a degree of monopoly power, IPRs introduce a novel source of distortions. Whereas the prospect of monopoly profits can be a powerful *ex ante* incentive for the would-be innovator, and can bring about innovations that would not otherwise take place, the monopoly position granted by the exclusivity of IPRs is inefficient from an *ex post* point of view (the innovation is underutilized). This is the essential economic trade-off of most IPR systems: there are dynamic gains due to more powerful innovation incentives, but there are static losses because of a restricted use of innovations (Nordhaus, 1969).

The trade-off of IPR systems is more acute when one considers that new products and processes are themselves the natural springboard for more innovations and discoveries (Scotchmer, 1991). When innovation is cumulative, the first inventor is not necessarily compensated for her contribution to the social value created by subsequent inventions. This problem is particularly evident when the first invention constitutes basic research (perhaps leading to so-called research tools) that is not directly of interest to final users. To address this intertemporal externality requires the transfer of profits from successful applications of a given patented innovation to the original inventor(s). What the features of an IPR system should be to achieve that has been addressed in a number of studies. Green and Scotchmer (1995) consider how patent breadth and patent length should be set in order to allow the first inventor to cover his cost, subject to the constraint that the second-generation innovation is profitable, and highlight the critical role of licensing. This and related studies, including Scotchmer (1996), and Matutes, Regibeau, and Rockett (1996), can be viewed as supporting strong patent protection for the initial innovations. Somewhat different conclusions can emerge, however, when the two innovation stages are modeled as R&D races (Denicolò, 2000).

A critical issue, in this setting, relates to how one models the features of an IPR system, and the foregoing studies emphasize the usefulness of the concepts of "patentability" and "infringement." For instance, in the two-period model of Green and Scotchmer (1995), both innovations are presumed patentable, and the question is whether or not the second innovation should be considered as infringing on the original discovery. The notion of patentability refers broadly to the "novelty" and "nonobviousness" requirements of the patents statute (so that, as in O'Donoghue (1998) and Hunt (2004), one can define the minimum innovation size required to get a patent). On the other hand, the context for infringement is defined by the "breadth" of patent rights. This property can be made especially clear in quality ladder models of sequential innovation through the notion of "leading breadth"—the minimum size of quality improvement that makes a follow-on innovation non-infringing (O'Donoghue, Scotchmer, and Thisse, 1998; Denicolò and Zanchettin, 2002).

By contrast, in this paper we study how the IPR system affects incentives in a sequential innovation setting by focusing on the so-called "research exemption" or "experimental use" doctrine. When a research exemption exists, proprietary knowledge and technology can be used freely in others' research programs aimed at developing a new product or process (which, if achieved, would in principle still be subject to patentability and infringement standards). On the other hand, if a research exemption is not envisioned, the mere act of trying to improve on an existing product may be infringing (regardless of success and/or commercialization of the second-generation product). In the U.S. patent system there is no general statutory "research exemption" and, as clarified by the 2002 *Madey v. Duke University* decision by the Court of Appeals for the Federal Circuit (CAFC), the experimental use defense against infringement based on case law precedents can only be construed as extremely narrow (Eisenberg, 2003). On the other hand, a special research exemption is contemplated for pharmaceutical drugs as part of the provisions of the Hatch-Waxman Act of 1984, whereby firms intending to market generic pharmaceuticals are exempted from patent infringement for the purpose of developing information necessary to gain federal regulatory approval.[1] Furthermore, a few specialized intellectual property statutes—including the 1970 Plant Variety Protection Act and the 1984 Semiconductor Chip Protection Act—contemplate a well-defined research exemption. Indeed, the innovation environment and the intellectual property context for plants offer perhaps the sharpest characterization of the possible implications of a research exemption in a sequential setting, and we will consider them in more detail in what follows.

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[1] The recent decision of the U.S. Supreme Court, in *Merck v. Integra*, appears not only to uphold but also to extend the scope of the Hatch-Waxman experimental use defense (Feit 2005).

The intense debate that followed the CAFC ruling in *Madey* has renewed interest in the desirability of a research exemption in patent law (Thomas, 2004). Quite clearly, a broad research exemption may have serious consequences for the profitability of innovations from basic research, thereby adversely affecting the incentives for research and development (R&D) in some industries that rely extensively on research tools (e.g., biotechnology). On the other hand, there is the concern that limiting the experimental use of proprietary knowledge in research may have a negative effect on the resulting flow of innovations. Explicit economic modeling of the research exemption, however, appears to be lacking. In this paper we propose to contribute to the economic analysis of the research exemption in IPR systems by focusing on the case of strictly sequential and cumulative innovations.

The quality ladder model developed in this paper draws upon the modeling approach of Bessen and Maskin (2002), while conceptually it belongs to the line of research on the optimal patent breadth discussed earlier. Bessen and Maskin find that it might be optimal, both from the social and individual firm's point of view, to have weak patent protection when innovation is cumulative. This result is driven by a critical complementarity assumption, in particular that the improvement possibilities on the quality ladder are exhausted if all firms fail to innovate in any given period (implying that having rivals engaged in R&D might, in principle, be beneficial). We depart from the Bessen and Maskin setup by formulating a fully dynamic model of an infinite-horizon stochastic innovation race suitable for an explicit characterization of equilibrium. To do so, we find it desirable to formulate the "complementarities" between firms somewhat differently. Specifically, in our formulation the quest for the next innovation step does not end when both firms are unsuccessful (both can try again).

Related literature includes formal models of dynamic R&D competition between firms engaged in "patent races."[2] As with most contributions in this setting we postulate a memoryless stochastic arrival of innovation; to keep a closer connection with the setup of Bessen and Maskin (2002), we model that process by means of a geometric distribution, rather than with exponential distribution typically used when modeling R&D races (e.g., Reinganum 1989). More importantly, in our model we delineate precisely the differences between the two IPR modes of interest (i.e., patents with and without the research exemption). In most R&D dynamic competition models, on the other hand, the nature of the underlying intellectual property regime is not addressed explicitly and IPR effects are often captured by a generic winner-takes-all condition. In addition, in our model both the incumbent and challenger can perform R&D, production takes place alongside R&D, and the stage payoffs are

[2] We cannot begin to do justice to this copious literature—see Tirole (1988, chapter 10) for an introduction.

state-dependent (an attractive feature, in a quality ladder setting, under typical market structures). Conversely, to keep the analysis tractable, here we consider a fixed number of firms (two) and thus we neglect the issue of entry in the R&D contest that has been prominent in many previous studies. We also assume away the inefficiency of the static patent-monopoly case, as in other studies in this area, but still allow for dynamic welfare spillovers to consumers via a Bertrand competition assumption.

In what follows we first discuss in some detail the intellectual property environment for plants, a context that provides perhaps the sharpest example of the possible implications of a research exemption. We then develop a new game-theoretic model of sequential innovation that captures the stylized features of the problem at hand. The model is solved by relying on the notion of Markov perfect equilibrium under the two distinct intellectual property regimes of interest. The results permit a first investigation of the dynamic incentive issues entailed by the existence of a research exemption provision in intellectual property law. First, we find that the firms themselves always prefer (*ex ante*) the full patent protection regime (unlike what happens in Bessen and Maskin, 2002). The social ranking of the two intellectual property regimes, on the other hand, depends on the relative magnitudes of the costs of initial innovation and improvements. It must be said that we impose a rather stark assumption about the nature of IP regime in the absence of research exemption provision (the winner of the first race becomes a monopolist forever and faces no competition), which in principle should bias our results in favor of the research exemption.[3] Interestingly, even with this stylized model, we still find that research exemption need not result in higher level of social welfare. In particular, the research exemption is most likely to provide inadequate incentives when there is a large cost to establishing a research program (as is arguably the case for the plant breeding industry where developing a new variety typically takes several years). On the other hand, when both initial and improvement costs are small relative to the expected profits (perhaps the case of the software industry noted by Bessen and Maskin, 2002), the weaker incentive to innovate is immaterial (firms engage in R&D anyway) and the research exemption regime dominates.

[3] Even though this assumption is restrictive, it is fairly standard in the economics of innovation literature to consider only very stylized environments, such as monopoly versus duopoly, or monopoly versus free entry, in order to obtain a tractable model which would allow for sharper conclusions (see Mitchell and Skrzypacz (2005) for a recent example).

2.2 A Model of Sequential and Cumulative Innovation

We develop an infinite-horizon production and R&D contest between two firms under two possible IPR regimes—that is, with and without the research exemption. The model that we construct is sequential and cumulative and reflects closely the stylized features of plant breeding. This industry is also of interest because, as mentioned, it has access to a *sui generis* IPR system that contemplates a well-defined research exemption.

2.2.1 A Motivating Example: PVP, Patents, and the "Research Exemption"

The Plant Variety Protection (PVP) Act of 1970 introduced a form of IPR protection for sexually reproducible plants that complemented that for asexually reproduced plants of the 1930 Plant Patent Act and represented the culmination of a quest to provide IPRs for innovations thought to lie outside the statutory subject matter of utility patents (Bugos and Kevles, 1992). PVP certificates, issued by the U.S. Department of Agriculture, afford exclusive rights to the varieties' owners that are broadly similar to those provided by patents, including the standard 20-year term, with two major qualifications: there is a "farmer's privilege," that is, seed of protected varieties can be saved by farmers for their own replanting; and, more interestingly for our purposes, there is a "research exemption," meaning that protected varieties may be used by other breeders for research purposes (Roberts, 2002). In addition to PVP certificates, to assert their intellectual property, plant innovators can rely on trade secrets, the use of hybrids, and specific contractual arrangements (such as bag-label contracts). More importantly, in the United States plant breeders can now also rely on utility patents. The landmark 1980 U.S. Supreme Court decision in *Diamond v. Chakrabarty* opened the door for patent rights for virtually any biologically based invention and, in its 2001 *J.E.M. v. Pioneer* decision, the U.S. Supreme Court held that plant seeds and plants themselves (both traditionally bred or produced by genetic engineering) are patentable under U.S. law (Janis and Kesan, 2002).

As noted earlier, the U.S. patent law does not have a statutory research exemption (apart from the provisions of the Hatch-Waxman Act discussed earlier). Hence, a plant breeder who elects to rely on patents can prevent others from using the protected germplasm in rivals' breeding programs. That is not possible when the protection is afforded by PVP certificates. The question then arises as to which IPR system is best for plant innovation, and whether the recently granted access to utility patents significantly changed the innovation incentives for U.S. plant breeders. Alternatively, one can consider the differences in the degrees of protection conferred by patents and PVPs in an international context. Rights similar to those granted by PVP certificates, known generically as "plant breeder's rights" (PBRs), are available for plant innovations in most other countries, but patents are not (Le

Buanec, 2004). Indeed, under the TRIPS (trade-related aspects of intellectual property rights) agreement of the World Trade Organization, it is not mandatory for a signatory country to offer patent protection for plant and animal innovations, as long as a *sui generis* system (such as that of PBRs) is available (Moschini, 2004). Thus, in many countries (including most developing countries), PBRs are the only available intellectual property protection for plant varieties.[4]

Given the structural differences between patents and PBRs, the notion of a research exemption is clearly central to this intellectual property context. Furthermore, it is interesting to note that the prototypical sequential and cumulative nature of R&D in plant breeding can be closely represented by a quality ladder model. Plant breeding is a lengthy and risky endeavor that has been defined as consisting of developing new genetic diversity (e.g., new varieties) by the reassembling of existing diversity. Thus, the process is both sequential and cumulative, because new varieties would seek to maintain the desirable features of the ones they are based on while adding new attributes. As such, a critical input in this process is the starting germplasm (whole genome), and that in turn is critically affected by whether or not one has access to existing successful varieties, which in turns is directly affected by a research exemption. In a dynamic context, of course, the quality of the existing germplasm is itself the result of (previous) breeding decisions, and so it is directly affected by the features of the IPR regime in place. Industry views on the matter highlight the possibility that freer access to others' germplasm will erode the incentive for critical pre-breeding activities aimed at widening the germplasm diversity base (Donnenwirth, Grace, and Smith, 2004).

2.2.2 Model Outline

We consider two firms that are competing to develop a new product variety along a particular development trajectory. At time zero both firms have access to the same germplasm and, upon investing an amount c_0, achieve success with probability p (each firm's outcome is independent of the other's). We refer to the pursuit of the first innovation as the "**Initial Game**." Note that in this model the R&D process is costly and risky, and that the two firms are identical *ex ante* (i.e., the game is symmetric). If at least one firm is successful, the initial game terminates and a patent is awarded. When only one firm is successful, that firm gets the patent. When both firms are successful, the

[4] Even in European countries, where plant innovations are included in the patentable subject matter, somewhat anachronistically, plant varieties *per se* are explicitly not patentable by the statute of the European Patent Office (Fleck and Baldock, 2003).

patent is randomly awarded (with equal probability) to one of them. If neither firm is successful, they have the option of trying again, which would require a new investment of c_0.

Given at least one success, the contest moves to the production and improvement stage, which we call the "**Improvement Game**." At the start of this game, firms are asymmetric: one of them, referred to as the "Leader," has been successful (and holds the patent) whereas the other firm, referred to as the "Follower," has not (does not). There are two relevant activities that characterize the improvement game: rent extraction through production, and further R&D efforts. Rent extraction is the prerogative of the Leader: specifically, the leading firm captures a return of Δ in the first period of the improvement game. What happens to the distribution of rent after the first period may depend on possible R&D undertaken in the improvement game, and that, in turn, depends on the property rights conveyed by the patent awarded at the end of the initial game. For the latter, we distinguish between two prototypical IPR regimes that differ according to the treatment reserved for the research exemption. The R&D structure of the improvement game is similar to that of the initial game: upon an initial investment, a firm achieves the next improvement with probability p. But to recognize that the initial innovation is "more important" in some well-defined sense, we assume that the per-period cost of R&D in the improvement game is $c \leq c_0$.

Whether or not both firms can participate in the improvement game depends on the nature of IPRs, specifically on whether or not a "research exemption" is contemplated. The first regime that we consider, which we refer to as "**Full Patent**" (FP), presumes that the patent awards an exclusive right to the patent holder, such that further innovations can be pursued only by the patent holder (or upon a license by the patent holder). Thus, the FP regime characterizes the environment of U.S. utility patents which, as discussed earlier, envisions an extremely limited role for a research exemption. The second regime, which we refer to as the "**Research Exemption**" (RE), allows any firm (i.e., including the Follower) to pursue the next innovation, although the patent gives the right of rent extraction (i.e., collecting Δ in the current period) to the holder of the patent. Hence, the RE regime reflects the attributes of a PBR system, such as the one implemented in the United States under the PVP Act. We should note that both patents and PBRs confer rights that are limited in time (20 years). But because we are characterizing the differences between the two regimes, without much loss of generality we ignore this feature and model both rights as having, in principle, infinite duration.

Under the FP regime, therefore, only the patent holder can pursue further innovations. Ignoring the possibility of licensing (we will return to this issue later), we model the improvement game under the FP regime as a monopoly undertaking by the firm that won the initial game. Under the RE regime, on the other hand, both firms are allowed to participate in the follow-up R&D. Because under the RE both firms can use the same starting point, upon a success in the first improvement game we either have the Leader owning two consecutive innovations or the Follower being the successful firm and thereby becoming the Leader. We emphasize again that the foregoing structure reflects the strict sequential and cumulative nature of the innovation process that we wish to model: the current quality level is, in effect, an essential input into the production of the next quality level.

Each additional innovation is worth an additional Δ, per period, to society.[5] What a success is worth to the innovator, however, depends on the IPR regime and on the possible constraining effects of competition among innovators. We make the simplifying assumption that only the best product is sold in this market, but what the owner can charge is the marginal value over what the competitor can offer (i.e., we assume Bertrand competition). For example, if two firms have achieved n and m innovation steps, respectively, with $m > n$, the firm with m steps will be the one selling any product and will make an *ex post* per-period profit of $(m-n)\Delta$.

To summarize, we consider an infinite-horizon R&D contest between two firms under two possible IPR regimes. Under the FP regime both firms can participate in the initial game, but only the successful firm may be engaged in the improvement games. Under the RE regime both firms can participate in both the initial game and the improvement games.

2.2.3 The Stochastic Game

To formalize the model outlined in the foregoing as an infinite-horizon R&D stochastic game, the set of players (the two firms) is $G \equiv \{1,2\}$. At each stage $t = \{0,1,2,....\}$ of the initial game, labeled Γ_0, the two firms simultaneously choose an action a_t^i from the history-invariant action set $A \equiv \{I, N\}$, where I = invest and N = no investment. Action I entails a cost to the firm of $c_0 > 0$ and brings success with probability $p \in (0,1)$ if the other firm does not invest, whereas it brings success with probability $q \in (0, p)$ if the other firm also invests. Specifically, when both firms invest, and firms' outcomes are independent, the probability of at least one success is $1-(1-p)^2$, and thus $q \equiv p(2-p)/2$. At the beginning of the initial game, firms are identical and the game is symmetric. After a single "success" the firms will be asymmetric for the rest of the game. Under the FP regime

[5] Because in our model we capture the asymmetry between initial innovation and follow-up improvements by postulating different R&D costs (c_0 and c), we assume that the value of each successive quality improvement is the same.

the loser of the initial game drops out and the winner becomes a monopolist in both the exploitation of the innovation and in further R&D activities. Under the RE regime, on the other hand, both firms can participate in the improvement game. If a firm chooses to invest in any period of the improvement game, the required cost is $c \in [0, c_0]$, and the success probabilities are just as in the initial game (i.e., a single firm innovates with probability p, and when both firms invest each wins the contest with probability q).

The improvement game under the FP regimes is technically not a game because there are no strategic interactions (the winner of the initial game is a monopolist). Under the RE regime, on the other hand, we actually have a family of improvement games, which we label as Γ_k, with each distinguished by the number $k = 1, 2, 3, ...$ of successive innovation steps held by the Leader. Thus, after the first innovation we have $k = 1$. If the Leader is the firm that innovates again then we have $k = 2$ and the status of each firm does not change. Whenever the Follower wins the stage game, however, then firms swap their roles (e.g., the Follower becomes the Leader) and the number of steps ahead that determines the payoff drops back to $k = 1$. Hence, $k = 1, 2, 3, ...$ represents one of the "state" variables of the game. Figure 1 provides an illustration. Note that, in this setup, the RE regime ensures that "leapfrogging" is possible, although the Leader's advantage can also accumulate and persist, whereas with the FP regime there is "persistence" of the monopoly position provided by the initial innovation.[6]

Stage payoffs are determined under a Bertrand competition assumption. Specifically, under either regime, in each period the last firm to be successful (the Leader) collects an amount $k\Delta$, where $\Delta > c$ measures the per-period value of a stage innovation, and $k \in \{1, 2, 3, ...\}$ denotes the total number of innovation steps that the leading firm has over the competitor. The value of the entire game to the firms, from the perspective of the initial period and under the two IPR regimes of interest, is derived in what follows. Throughout, $\delta \in (0,1)$ denotes the discount factor.

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[6] These are two recurrent concepts in patent race models (Tirole, 1988, chapter 10). The persistence of monopoly was studied by, among others, Gilbert and Newbery (1982) and Reinganum (1983). The notion of leapfrogging was introduced by Fudenberg et al. (1983). Whereas our model does not focus on these two issues, it does emphasize that they may be directly affected by the specific features of the relevant IPR system.

2.3 Equilibria in the Improvement Games

We characterize the equilibrium solution of the improvement games first and, by standard backward induction principles, analyze the initial games next, under both IPR regimes that we have described. As explained in more detail in what follows, we will focus on "Markov strategies," whereby the history of the game is allowed to affect strategies only through state variables that summarize the payoff-relevant attributes of the strategic environment (Fudenberg and Tirole, 1991, chapter 13). Thus, our equilibrium concept will be that of *Markov Perfect Equilibrium* (MPE), that is, a profile of Markov strategies that yields a subgame perfect Nash equilibrium (Maskin and Tirole, 2001).

2.3.1 Improvement Game under the Full Patent Regime

As noted, here we do not really have a game, just an optimization problem where, at each stage, the firm that is allowed to invest has to choose an action from $\{I, N\}$. Such a firm is effectively a monopolist in the improvement game. If it chooses action I at any one stage success will occur with probability p and hence the expected payoff to choosing action I in that stage is $-c + p\delta\Delta/(1-\delta)$ (because success yields a stage payoff Δ forever starting with the next period). Hence action I is optimal in any one stage i.f.f. $c/\Delta \leq \delta p/(1-\delta) \equiv x_0$. Naturally, if it is optimal for such a monopolist to choose action I at any one stage, then it is optimal to do so in every stage and hence the investment rule does not depend on k. If the condition $c/\Delta \leq x_0$ for the optimality of action I holds, the expected payoff of the patent holder at the start of the improvement game when the state is k, labeled $V_M(k)$, therefore is:

$$V_M(k) = \frac{k\Delta - c}{1-\delta} + \frac{\delta p\Delta}{(1-\delta)^2} \quad . \tag{1}$$

If, on the other hand, $c/\Delta > x_0$, then the patent holder's optimal action would be N and the payoff $V_M(k) = k\Delta/(1-\delta)$.

2.3.2 Improvement Game(s) under the Research Exemption Regime

In the improvement game under the RE regime firms are asymmetric. The firm with the last success is the Leader who can earn returns from the market (in proportion to the number of extra innovation steps that it has relative to the competitor, which we have denoted as k). The other firm, labeled as the Follower, does not earn current return but has the same opportunities to engage in R&D

as the other firm. As discussed earlier, $k = 1,2,3,...$ represents one of the "state" variables of the game. The other state variable of the game is the identity of the Leader, $\ell \in G \equiv \{1,2\}$. Together, (k,ℓ) summarize all the payoff-relevant information of the history of the game leading up to any particular subgame.

We consider only *Markov strategies*, so that the strategy of a firm only depends on the state of the game. The state space of the game is $S \equiv G \times \mathbb{N}$, where G is the set of players defined earlier, and $\mathbb{N} \equiv \{1,2,...\}$ is the set of natural numbers. A Markov strategy here is defined as a function $\sigma_i : S \to [0,1]$, $i \in G$. Specifically, the strategy $\sigma_i(\ell,k)$ tells us the probability that player i will attach to action I when the state is (ℓ,k). Thus, at any stage of the game with the same state, the Markov strategy σ_i specifies the same probability distribution over available actions. Although the use of Markov strategies is somewhat restrictive, it is standard in the dynamic oligopoly models in general and in the models of innovation races in particular (e.g., Bar, 2005; Hörner, 2004).

Alternatively, we can characterize the strategy of the two "types" of firms. Conditional on being a Leader, the only payoff-relevant state is the number of innovation steps k that the Leader has over the Follower. Similarly, conditional on being the Follower, the only relevant state is again the number of innovations steps k that the Leader is enjoying. [Note: the stage and continuation payoffs to the Follower actually do not depend on k. But because k affects the Leader's payoffs, a Markov strategy for the Follower must also condition on k.] Thus, with some abuse of notation, we can write the strategy of the Leader as $\sigma_L(k)$ and the strategy of the Follower as $\sigma_F(k)$.[7]

At any stage of the game, the expected payoff of a firm for the subgame starting at that point, for given strategies of the two firms, depends on the firm being a Leader or a Follower. For given strategies of the two firms, the payoff to the Follower does not depend on how many steps behind the Follower is lagging the Leader. The payoff to the Leader, on the other hand, does depend on the number of leads it has. Thus, for a given strategy profile $\sigma \equiv (\sigma_L, \sigma_F)$, for the game Γ_k we can write the payoff to the Follower as $V_F(\sigma_L, \sigma_F)$ and the payoff to the Leader as $V_L(\sigma_L, \sigma_F, k)$. Recalling that δ denotes the discount factor, these value functions must satisfy the following recursive equations:

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[7] Hörner (2004) similarly uses Markov strategies where the state space is the set of integers. But note that the stage payoff in Hörner only depends on whether the firm is a Leader or a Follower, whereas in our model stage payoffs ($k\Delta$) are state-dependent.

$$V_L(\sigma,k) = \Delta k + \sigma_L\sigma_F\left[-c + q\delta V_L(\sigma,k+1) + q\delta V_F(\sigma) + (1-2q)\delta V_L(\sigma,k)\right]$$
$$+\sigma_L(1-\sigma_F)\left[-c + p\delta V_L(\sigma,k+1) + (1-p)\delta V_L(\sigma,k)\right] \quad (2)$$
$$+(1-\sigma_L)\left[\sigma_F\left(p\delta V_F(\sigma) + (1-p)\delta V_L(\sigma,k)\right) + (1-\sigma_F)\delta V_L(\sigma,k)\right]$$

$$V_F(\sigma) = \sigma_F\sigma_L\left[-c + q\delta V_L(\sigma,1) + (1-q)\delta V_F(\sigma)\right]$$
$$+\sigma_F(1-\sigma_L)\left[-c + p\delta V_L(\sigma,1) + (1-p)\delta V_F(\sigma)\right] + (1-\sigma_F)\delta V_F(\sigma) \quad (3)$$

As discussed earlier, we have a family of improvement games Γ_k, each of which differs only in the number of improvement steps that the Leader has over the Follower—the number k that identifies the state variable of the game. Under our Bertrand pricing assumption, only the highest quality of the product is sold in the market and the per-period (gross) return to the firm selling it is $k\Delta$. To find the MPE we start with the simplest case in which $\sigma_L(k) = \sigma_F(k) = 1$ for all $k = 1,2,\ldots$.

Lemma 1. Suppose that, in the improvement game with a research exemption, $\sigma_L(k) = 1$ and $\sigma_F(k) = \phi \in [0,1]$, for all $k = 1,2,\ldots$. Then,

(i) $$V_F(\sigma) = \frac{\text{v}\Delta q\delta\left[1-\delta(1-2\text{v}q-(1-\text{v})p)\right]}{(1-\delta)\left(1-\delta(1-2\text{v}q)\right)\left(1-\delta(1-\text{v}q)\right)} - \frac{\text{v}c\left(1-\delta(1-(1+\text{v})q)\right)}{(1-\delta)\left(1-\delta(1-2\text{v}q)\right)} \equiv V_F \quad (4)$$

(ii) $$V_L(\sigma,k) = \frac{-c+\text{v}q\delta V_F}{1-\delta(1-\text{v}q)} + \frac{\Delta k}{1-\delta(1-\text{v}q)} + \frac{\Delta\delta\left(\text{v}q+(1-\text{v})p\right)}{\left(1-\delta(1-\text{v}q)\right)^2} . \quad (5)$$

The proof of this result is confined to the Appendix. Thus, when the Leader invests in every period with probability one while the Follower invests with the same probability $\phi \in [0,1]$ in every period, Lemma 1 provides close-form expression for the value of being the Leader or the Follower (conditional on the constant, but arbitrary, mixing probability ϕ). These expressions will prove useful in establishing the MPE for the improvement game claimed in Proposition 1. Note that the value to being the Follower does not depend on the number of leads possessed by the Leader. This is because, if successful in the stage R&D race, the new Leader obtains a one-step lead over the other firm (under our Bertrand pricing assumption). The value to being a Leader, on the other hand, increases with k, the number of improvement steps of the Leader not matched by the Follower, as well as being increasing in the stage payoff Δ and decreasing in R&D cost c.

Next we establish a complete characterization of the conditions under which the Follower and/or the Leader actually invest in the equilibrium of the improvement games. For that purpose, we define the threshold levels:

$$x_0 \equiv \frac{\delta p}{1-\delta} \tag{6}$$

$$x_1 \equiv \frac{q\delta\left(1-\delta(1-p)\right)}{(1-\delta)\left(1-\delta(1-q)\right)} \tag{7}$$

$$x_2 \equiv \frac{q\delta}{\left(1-\delta(1-q)\right)} \ . \tag{8}$$

Note that, under the assumed structure of the model, $x_0 > x_1 > x_2$. Given that, the firms' equilibrium investment decisions in the improvement game are as follows.

Proposition 1. Then MPE of the improvement game satisfies:

(i) If $c/\Delta \le x_2$ then $\sigma_L(k) = 1$ and $\sigma_F(k) = 1$ for all $k = 1, 2, \ldots$.

(ii) If $x_2 \le c/\Delta \le x_1$ then $\sigma_L(k) = 1$ and $\sigma_F(k) = \phi \in [0,1]$ for all $k = 1, 2, \ldots$.

(iii) If $x_1 \le c/\Delta \le x_0$, then $\sigma_L(k) = 1$ and $\sigma_F(k) = 0$ for all $k = 1, 2, \ldots$.

(iv) if $x_0 \le c/\Delta$, then $\sigma_L(k) = \sigma_F(k) = 0$ for all $k = 1, 2, \ldots$.

The proof, confined to the Appendix, relies on establishing that neither Leader nor Follower have a one-stage deviation from the proposed strategy that would increase his payoff. Because this game is continuous at infinity—that is, the difference between payoffs from any two strategy profiles will be arbitrary close to zero provided that these strategy profiles coincide for sufficiently large number of periods starting from the beginning of the game—Theorem 4.2 in Fudenberg and Tirole (1991) implies that the proposed strategy profile is the MPE.

Thus, when the R&D cost c is low enough, relative to the stage reward Δ, both firms invest with probability one in every stage. In this case the value functions of the Leader and of the Follower reduce to:

$$V_L(\sigma,k) = \frac{\Delta - c}{(1-\delta)} + \frac{(k-1)\Delta}{\left(1-\delta(1-q)\right)} \ . \tag{9}$$

$$V_F = \frac{q\delta\Delta - \left(1-\delta(1-q)\right)c}{(1-\delta)\left[1-\delta(1-q)\right]} \tag{10}$$

Note that the value of being a Leader when $k > 1$ is decreasing in the R&D success probability. Intuitively, when both firms engage in R&D in every period, the Leader with more than one step lead has more to lose than to gain from the R&D context. As for the Follower, $V_F \to 0$ as $c/\Delta \to x_2$.

But were the Follower to choose action N for all $c/\Delta \geq x_2$, the value to being a Leader would jump from $V_L(\sigma,k)$ as in equation (9) to V_M as given in equation (1). But then, if the firm that is a Follower in any one stage believes that future Followers always choose action N, then by deviating to I in that stage the firm would obtain a positive probability of becoming an uncontested Leader, with an associated strictly positive payoff. Thus, $\sigma_F(k)=0$ for all k cannot be part of an equilibrium when $x_2 < c/\Delta$ but c/Δ is close to x_2. The MPE in the domain $x_2 \leq c/\Delta \leq x_1$, therefore, entails the Follower's use of a mixed strategy, whereby the Follower invests with probability $\phi \in [0,1]$ in all stages. Specifically, as derived in the Appendix, the mixing probability ϕ in this domain is the positive root that solves the quadratic equation

$$-c\left[1-\delta\left(1-q(1+\mathrm{v})\right)\right]\left(1-\delta(1-\mathrm{v}q)\right)+\Delta q\delta\left(1-\delta(1-2\mathrm{v}q)+\delta(1-\mathrm{v})p\right)=0 \qquad (11)$$

At $c/\Delta = x_1$ equation (11) yields $\mathrm{v}=0$. At this point the Follower drops out of the improvement game and only the Leader finds it profitable to invest. In fact, it can be verified that, when evaluated at $c/\Delta = x_1$ and $\mathrm{v}=0$, the Leader's payoff is equal to the monopolist's payoff. For $x_1 \leq c/\Delta \leq x_0$ only the Leader invests (with probability one) in the improvement stage, whereas for $x_0 < c/\Delta$ no firm invests. Thus, for $x_1 \leq c/\Delta$ the FP regime and the RE regimes are equivalent as far as the improvement game is concerned.

The conclusions of Proposition 1 are illustrated in Figure 2, which represents the type of equilibrium strategies that apply for various ranges of the parameter ratio c/Δ. When R&D is too costly, relative to the expected payoff, no innovation takes place; the range of parameters that supports this outcome is the same under either regimes (i.e., $c/\Delta > x_0$). With a more favorable cost/benefit ratio the incumbent in the FP regime will find it worthwhile to engage in improvements. In this parameter space the RE regime supports only one firm if $x_1 < c/\Delta \leq x_0$, and two firms if $0 \leq c/\Delta \leq x_1$.

The payoff to the two firms in this type of equilibrium are of some importance. By using the expression in equation (4) of Lemma 1, and evaluating it at the ϕ which solves the equilibrium condition in (11), we find that $V_F = 0$ in the domain $x_2 \leq c/\Delta \leq x_1$.

The payoff to the Leader, on the other hand, at the ϕ which solves (11) is:

$$V_L(\sigma,k)=\frac{c}{q\delta}+\frac{(k-1)\Delta}{1-\delta(1-\mathrm{v}q)} \qquad (12)$$

Thus, in the domain $x_2 \le c/\Delta \le x_1$ the payoff to the Leader is increasing in the R&D cost c. That is, the gain from the weakening R&D competition (the Follower invests with a decreasing probability as c increases) more than outweigh the direct negative impact of R&D cost. That the Leader's payoff must be increasing on some part of the domain when $x_2 \le c/\Delta$ is clear when one notes that the monopolist's payoff at $c/\Delta = x_0$ and the Leader's payoff at $c/\Delta = x_2$ satisfy:

$$V_M(k)\big|_{c/\Delta=x_0} = \frac{k\Delta}{(1-\delta)} \quad > \quad \frac{k\Delta}{\left(1-\delta(1-q)\right)} = V_L(\sigma,k)\big|_{c/\Delta=x_2} \qquad (13)$$

The equilibrium payoff to the Leader and the Follower are illustrated in Figure 3.

The threshold levels x_0, x_1 and x_2 that we have identified satisfy intuitive comparative statics properties, such as $\partial x_0/\partial p > \partial x_1/\partial p > \partial x_2/\partial p > 0$ and $\partial x_0/\partial \delta > \partial x_1/\partial \delta > \partial x_2/\partial \delta > 0$. More interestingly, the foregoing analysis shows that, in a well defined sense, under the RE regime the Leader has a stronger incentive to invest in improvements than does the Follower. This property of the MPE reflects the carrot and stick nature of the incentives at work here, what Beath, Katsoulacos and Ulph (1989) call the "profit incentive" and the "competitive threat." The carrot is the same for both contenders—a successful innovation brings an additional per-period reward of Δ. But the stick differs. For the Follower, failure to innovate when the opponent is successful does not change her situation (recall that the value function of the Follower is invariant to the state of the game). But for the Leader, failure to innovate when the opponent is successful implies the loss of the current gross returns $k\Delta$.

2.4 Equilibrium in the Initial Game

The initial investment game has a structure similar to that of the improvement game. The major differences are the following: (i) the cost of investment in R&D is equal to $c_0 \ge c$; (ii) both firms are in exactly the same position and the per-period profit flow in the investment game is equal to zero; and (iii) the game ends as soon as one of the firms obtains the first successful innovation. We will consider the FP regime first.

2.4.1. Full Patent Regime

We find that the equilibrium depends critically on the postulated asymmetry between initial innovation and follow-on improvements. To facilitate exposition, it is useful to refer to Figure 4, which illustrates the parametric regions of the types of equilibria that arise. The regions of interest are defined by the following functions:

$$H_1(x) \equiv \frac{p\delta}{1-\delta}\left(\frac{1-\delta+p\delta}{1-\delta}-x\right) \tag{14}$$

$$H_2(x) \equiv \frac{q\delta}{1-\delta}\left(\frac{1-\delta+p\delta}{1-\delta}-x\right) \tag{15}$$

For notational simplicity, let σ_0 denote the strategy $\sigma(k)$ when $k=0$, that is, the probability of investment of a given firm in the initial investment game. We can then state the following results (details of the proof are in the Appendix).

Proposition 2. The symmetric equilibrium of the investment game under the FP regime is given by the strategy profile (σ_0, σ_0), where σ_0 satisfies the following conditions:

(i) if $c/\Delta > x_0$, then $\sigma_0 = 0$.

(ii) if $c/\Delta \le x_0$ and $c_0/\Delta > H_1(c/\Delta)$, then $\sigma_0 = 0$.

(iii) if $c/\Delta \le x_0$ and $c_0/\Delta < H_2(c/\Delta)$, then $\sigma_0 = 1$.

(iv) if $c/\Delta \le x_0$, and $H_2(c/\Delta) \le c_0/\Delta \le H_1(c/\Delta)$, then $\sigma_0 = \dfrac{p\delta V_M - c_0}{(p-q)\delta V_M}$,

where V_M is the value function, at the start of the first improvement game, for the patent holder who will be investing in every period (as derived in equation (1), with $k=1$).

As one would expect, for a given value of c, relatively low values of initial R&D cost c_0 will induce both firms to invest with probability one, as in part (iii) of Proposition 2. If the R&D cost parameters c and/or c_0 are large enough (as in parts (i) and (ii) of Proposition 2), on the other hand, neither firm invests. For intermediate values of the R&D cost parameters, as exactly identified in part (iv) of Proposition 2, each firm would want to invest if the other does not. Thus, in addition to such pure-strategy equilibria, here we have a (symmetric) mixed-strategy equilibrium. Note that the mixed-strategy equilibrium converges to a pure-strategy equilibrium in the appropriate limit: $\sigma_0 \to 0$ as $c_0/\Delta \to H_1(c/\Delta)$ and $\sigma_0 \to 1$ as $c_0/\Delta \to H_2(c/\Delta)$. Thus, with respect to Figure 4, in equilibrium both firms randomize between investing and not when the parameter vector $(c/\Delta, c_0/\Delta)$ lies in the area labeled "mixed strategies," and both firms invest with probability one when the parameter vector lies in the area labeled "pure strategies."

2.4.2 Research Exemption Regime

The equilibrium of the investment game under the RE regime similarly depends on the relative magnitude of the R&D costs that characterize the initial innovation as opposed to the follow-on improvements. As derived earlier, under RE regime one can distinguish three intervals of values of c/Δ in which the strategy of the follower and the resulting equilibrium in the improvement stage is qualitatively different: $[0, x_2]$, $[x_2, x_1]$ and $[x_1, x_0]$. In what follows we will analyze the equilibrium of the initial stage in these cases. The various possibilities that arise are illustrated in Figure 5, where the parametric regions of interest are defined by the functions $H_1(x)$ and $H_2(x)$ defined earlier, and by the following functions:

$$H_3(x) = \frac{p\delta}{1-\delta}(1-x) \tag{16}$$

$$H_4(x) = \frac{q\delta(1-\delta+2\delta q)}{(1-\delta+p\delta)(1-\delta+\delta q)} - \frac{\delta(2q-p)}{(1-\delta+p\delta)}x \tag{17}$$

$$H_5(x) = \frac{p}{q}x \tag{18}$$

Functions $H_3(x)$ and $H_4(x)$ determine the threshold levels of c_0 and the resulting strategy profiles for a given value of $(c/\Delta) \in [0, x_2]$, and the function $H_5(x)$ does the same for the parametric region $(c/\Delta) \in [x_2, x_1]$. The following proposition characterize the equilibrium of the investment game under the RE regime for all values of $c/\Delta \geq x_1$.

Proposition 3. Suppose that $c/\Delta \geq x_1$. Then the strategy profile (σ_0, σ_0) constitutes the symmetric equilibrium of the investment game under the research exemption regime i.f.f.

(i) if $c/\Delta > x_0$, then $\sigma_0 = 0$;

(ii) if $x_1 \leq c/\Delta \leq x_0$ and $c_0/\Delta > H_1(c/\Delta)$, then $\sigma_0 = 0$;

(iii) if $x_1 \leq c/\Delta \leq x_0$ and $c_0/\Delta \leq H_1(c/\Delta)$, then $\sigma_0 = \dfrac{p\delta V_M - c_0}{(p-q)\delta V_M}$.

The results of this proposition follow directly from observing that, as was shown in Proposition 1, when $c/\Delta \geq x_1$ the Follower does not invest at the improvement stage. This implies that payoffs of the Leader and the Follower are identical to the payoffs of the patent holder and of the firm that did not innovate under the FP regime, respectively. Therefore the resulting equilibrium must also be identical to the one obtained under the FP regime (see Proposition 2). It is also readily verified that

$H_2(x_1) = x_1$. This implies that there is no pure strategy equilibrium in the investment game in this case.

Next we consider the interval $[x_2, x_1]$. Recall that in this case both the Leader and the Follower take part in the improvement game, but the payoff of the Follower is equal to zero. The resulting equilibrium as the investment stage is characterized as follows.

Proposition 4. Suppose that $x_2 \le c/\Delta \le x_1$ and let $V_1 \equiv V_L(\sigma,1)$ denote the payoff of the winner of the investment game (i.e., the first Leader), as given by equation (5). Then the strategy profile (σ_0, σ_0) constitutes the symmetric equilibrium of the investment game under the research exemption regime i.f.f. it satisfies the following conditions

(i) if $c_0 = c$, then $\sigma_0 = 1$;

(ii) if $c/\Delta \le c_0/\Delta \le H_5(c/\Delta)$, then $\sigma_0 = \dfrac{p\delta V_1 - c_0}{(p-q)\delta V_1}$;

(iii) if $c_0/\Delta > H_5(c/\Delta)$, then $\sigma_0 = 0$.

The proof of this result is given in the Appendix. Thus, in the initial investment game we can have an equilibrium in which both firms invest with probability one even if $x_2 \le c/\Delta$ (that is, even though, at the improvement stage, under these conditions the Follower will only play a mixed strategy).

Finally, consider the case $(c/\Delta) \in [0, x_2]$, that is when both the Leader and the Follower invest with probability one in the improvement stage.

Proposition 5. Suppose that $c/\Delta \le x_2$. Then the strategy profile (σ_0, σ_0) constitutes the symmetric equilibrium of the investment game under the research exemption regime i.f.f.

(i) if $c_0/\Delta \le H_4(c/\Delta)$, then $\sigma_0 = 1$

(ii) if $c_0/\Delta > H_3(c/\Delta)$, then $\sigma_0 = 0$

(iii) if $c/\Delta < x_1$ and $H_4(c/\Delta) \le c_0/\Delta \le H_3(c/\Delta)$, then $0 \le \sigma_0 \le 1$.

The proof of the proposition is given in the Appendix, where the quadratic equation defining σ_0 for part (iii) is also explicitly derived. With respect to Figure 5, therefore, pure strategies are used in the parameter regions labeled C_1, and symmetric mixed strategies are used in regions A, B_1 and C_2. As one might expect, the equilibrium strategies in the initial game reflect the nature of equilibrium at the improvement stage. Recall that, in the improvement game, the Follower will not take part whenever $c/\Delta > x_1$. If this condition is satisfied, once one of the firms succeeds in completing the first innovation step, its rival will immediately drop out of the race. This type of equilibrium is similar to the one obtained by Fudenberg, Gilbert, Stiglitz and Tirole (1983) in the context of race with a known finish line, and by Hörner (2004) in an infinite-horizon setting. Specifically, the incentives to invest in R&D is highest when the firms compete for the *entire market*, i.e., when the winner of the initial game faces no competition afterwards. In particular, note that whenever $c/\Delta < x_1$, no investment takes place if $c_0/\Delta \geq H_3(0) = x_0$. But, when $x_1 < c/\Delta < x_0$ we can find a range of c_0/Δ such that $c_0/\Delta \geq x_0$ and still both firms invest with positive probability in equilibrium, as can be seen with the aid of Figure 5. The same conclusion applies to the case $x_2 < c/\Delta < x_1$, when the Leader faces a Follower which randomizes and does not invest with probability one in each period.

Comparing the equilibrium outcomes under the FT and RE regimes, we note that in the parameter regions C_4 and B_4 of Figure 5 we have no initial R&D investment under the RE regime, whereas the FP regime leads to some initial investment (given by the mixed-strategy equilibrium). Similarly, in regions C_3 and B_3 of Figure 5 we again have no initial R&D investment under the RE regime, whereas under the FP regime both firms invest with probability one in the initial game. Thus, it is apparent that the presence of a RE clause unambiguously weakens the initial incentive of firms to invest in R&D. The welfare consequences of this weakened investment incentives are analyzed next.

2.5 Welfare Analysis

Having characterized the MPE of the model, we can now turn the normative implications of the analysis. We consider first the returns, from an *ex ante* perspective, to the two firms, and next derive the aggregate welfare of the economy.

2.5.1. Firms' Expected Profit

The expected profit of the two firms at time zero, before the initial research investment c_0 is made, depends on the particular equilibrium solution that applies to the region of the parameter space. The regions of interest (labeled A, B_1 to B_4, and C_1 to C_4) are illustrated in Figure 4. Our findings are as follows.

Proposition 6. The firms' expected profits under the FP regime are never lower, and can be strictly higher, than those under the RE regime. Specifically:

(i) Firms' expected profit under RE and FP regimes are the same if $c_0 / \Delta \geq H_2(c/\Delta)$.

(ii) Firms' expected profit under the FP regime is higher than under the RE regime

(a) if $x_2 < c/\Delta < x_1$ and $c_0 / \Delta \leq H_2(c/\Delta)$,

(b) if $c/\Delta < x_2$ and $c_0 / \Delta \leq H_2(c/\Delta)$.

The domain of part (i) of this proposition encompasses the parameter space labeled as A, B_2, B_4, and C_4 in Figure 5. In area A the firms have exactly the same equilibrium strategies under either regime (see Propositions 1, 2 and 3): in the improvement games only the Leader invests whenever $c/\Delta > x_1$. Consequently the firms have the same behavior in the initial game as well. The firms' equilibrium strategy is to invest with probability one in the parameter space of area A (earning a positive expected payoff). In the area C_4 there is no investment in the initial game under the RE regime, whereas firms invest with a mixed strategy under the FP regime (but earn a zero expected payoff). In area B_2 firms randomize in the investment game under both regimes. Finally, in area B_4 there is a mixed strategy equilibrium under FP regime and none of the firms invests under the RE regime. For the domain of part (ii)(a), *ex ante* expected profits are positive under FP regime and zero under RE regime (because none of the firms invests in the investment game in area B_3, and because firms firm randomize in area B_1). The domain of part (ii)(b) encompasses areas C_1, C_2, and C_3 in Figure 5. Consider are C_1 first. Under either regime both firms invest with probability one in both the investment game and the improvement games. Because firms have the same probability of success, it follows that both firms prefer the FP regime, *ex ante*, i.f.f. $V_M \geq V_L + V_F$. By using the expressions derived in Lemma 1 (for the case $\phi = 1$), this inequality is equivalent to:

$$\frac{p\delta\Delta}{1-\delta} \geq \frac{q\delta\Delta}{1-\delta+q\delta} - c \tag{19}$$

which is clearly satisfied. Turning to the parameter space comprising area C_2, we note that here firms invest with probability one in the FP regime, whereas they randomize in the mixed strategy equilibria under the RE regime. The expression for the expected profit of each firm under the FP regime solves the recursive equation $V_0^{FP} = -c_0 + q\delta V_M + (1-2q)\delta V_0^{FP}$, and thus:

$$V_0^{FP} = \frac{q\delta V_M - c_0}{1-(1-2q)\delta}. \tag{20}$$

whereas under the RE regime expected profit is given by

$$V_0^{RE} = \frac{\sigma_0 p\delta V_F}{1-\delta(1-\sigma_0 p)} \tag{21}$$

where σ_0 is the investment probability in the equilibrium mixed strategy. As shown in the Appendix, a sufficient condition for $V_0^{FP} > V_0^{RE}$ holds. Finally, for the parameter space of area C_3, firms invest with probability one in the initial game and enjoy a positive profit, whereas there is no investment (and zero profit) under the RE regime.

Thus, Proposition 6 establishes that firms, *ex ante*, would never prefer the RE regime over the FP regime. This result differs from that of Bessen and Maskin (2002), where a (suitably defined) weaker patent system, in a similar sequential innovation setting, can produce higher *ex ante* returns to the innovating firms than a full patent system. The root of that result is a complementarity assumption that is appealing in a sequential setting: the presence of a competitor increases the probability that future profitable innovations (improvements) may be undertaken (although it erodes the firm's expected profit in a given stage innovation race). The former effects counters the latter (standard) effect, and can lead to a firm benefiting from its innovation being used by others for future innovations. A flavor of Bessen and Maskin's complementarity assumption is certainly present in our model as well: prior to knowing the identity of the winner of the initial innovation stage, a RE may be appealing because it guarantees the possibility of taking part in future (profitable) innovation stages. But the specific structure of the IPR regimes that we have modeled, and the explicit requirement of a MPE solution, in our setting ensure that the FP protection is preferred *ex ante* by the firms.

2.5.2 Welfare

Because under the Bertrand pricing condition that we have used the sum of firms' profits does not coincide with social welfare, we have to take into account consumer surplus when evaluating efficiency of patents and research exemptions. First we compute the expected social welfare starting at stage one of the improvement game. Let W_i denote this welfare measure when there are i firms ($i = 1, 2$) investing (in equilibrium) in every period of the game, and let W_ϕ denote the corresponding welfare measure when the Leader invests with probability one and the Follower invests with probability ϕ, evaluated at the beginning of the improvement game. Clearly W_1 coincides with monopoly profits V_M because the monopolist captures the entire surplus when it is the only one to invest in every period. Hence,

$$W_1 \equiv V_M = \frac{\Delta - c}{1-\delta} + \frac{p\delta\Delta}{(1-\delta)^2}\,. \tag{22}$$

On the other hand, the situation in which two firms invest in every period from the social point of view is the same as the situation in which there is a monopolist with cost $2c$ and success probability $2q > p$ that invests in every period. Hence the sum of firms' profits and consumer surplus is equal to the profits of such a monopolist. Therefore,

$$W_2 = \frac{\Delta - 2c}{1-\delta} + \frac{2q\delta\Delta}{(1-\delta)^2}. \tag{23}$$

The measure of social welfare when the Follower randomizes between investing and not can be shown to be given by the following expression (see Appendix for an explicit derivation):

$$W_\phi = \frac{\Delta - c(1+\phi)}{1-\delta} + \frac{\Delta(\phi 2q\delta + (1-\phi)p\delta)}{(1-\delta)^2} \tag{24}$$

Note that, as one would expect, when $\phi = 0$ we have $W_\phi = W_1$, and when $\phi = 1$ we have $W_\phi = W_2$. Similarly to the analysis of the equilibrium of the investment game, we will compare welfare under the two IPR regimes in the three possible cases: $(c/\Delta) \in [0, x_2]$, $(c/\Delta) \in [x_2, x_1]$ and $(c/\Delta) \in [x_1, x_0]$. Note that for the case $(c/\Delta) \in [x_1, x_0]$, we have shown that the equilibrium strategies of firms are exactly the same in both regimes. This implies that the social payoffs are equal. It turns out that in the two remaining cases it is possible to characterize social welfare ranking only for a subset of the domain of possible values of $(c/\Delta, c_0/\Delta)$. We present these analytic results in the following two propositions and then perform numerical analysis of the remaining cases.

Proposition 7. Suppose that $c/\Delta \in [0, x_2]$. The social payoffs under the RE and FP regimes are related as follows:

(i) If $H_3(c/\Delta) < c_0/\Delta < H_2(c/\Delta)$, then the FP regime yields higher welfare.

(ii) If $c_0/\Delta \le H_4(c/\Delta)$, then

(a) if $(1-p)(2-p) \ge (1-\delta)/\delta$, the RE regime yields a higher welfare.

(b) if $(1-p)(2-p) < (1-\delta)/\delta$, the FP regime gives higher social welfare if $(1-p)x_0 < c/\Delta \le x_1$ but the RE regime yields higher welfare if $0 \le c/\Delta \le (1-p)x_0$.

For the case of part (i), with FP protection both firms invest with probability one; hence, the social payoff is positive and greater than the social payoff with the RE (which is zero because none of the firms invests in equilibrium). For part (ii), here both firms invest with probability one in both investment and improvement games. The question of whether the RE is better than the FP regime is essentially the same as the question of whether it is better to have two firms (as under the RE regime) or one firm (as under the FP regime) in the improvement game. Thus, the RE regime yields higher welfare i.f.f. $W_2 \geq W_1$, that is whenever

$$\frac{c}{\Delta(1-p)} \leq \frac{\delta p}{1-\delta} \equiv x_0 \tag{25}$$

We know that in this region $c/\Delta < x_1$. We conclude that in this region the RE regime will yield a higher welfare as long as parameter values satisfy the following inequality:

$$(1-p)x_0 \equiv \frac{\delta p(1-p)}{1-\delta} \geq \frac{q\delta}{1-\delta+q\delta} \equiv x_1 \quad \Leftrightarrow \quad (1-p)(2-p) \geq (1-\delta)/\delta . \tag{26}$$

Proposition 8. Suppose that $c/\Delta \in [x_2, x_1]$. The social payoffs under the RE and FP regimes are related as follows:

(i) For all values of $(c/\Delta, c_0/\Delta)$ that satisfy the condition $H_5(c/\Delta) < c_0/\Delta < H_2(c/\Delta)$ (region B_3) the FP regime yields higher welfare.

(ii) For all values of $(c/\Delta, c_0/\Delta)$ that satisfy the condition $H_2(c/\Delta) < c_0/\Delta < H_5(c/\Delta)$ (region B_2) the RE regime yields higher welfare.

(iii) For all values of $(c/\Delta, c_0/\Delta)$ that satisfy $\max\{H_2(c/\Delta), H_5(c/\Delta)\} < c_0/\Delta < H_1(c/\Delta)$, that is region B_4, there is no difference in welfare between the two IP regimes.

For the parameter region of part (i), with FP protection both firms invest with probability one; hence, the social payoff is positive and greater than the social payoff with the RE, which is equal to zero because none of the firms invests in equilibrium. For part (ii) firms randomize in the investment game under both IP regimes. Even though expected profits are zero under both IP regimes, RE regime yields a higher welfare because firms do not appropriate the whole consumer surplus (under our Bertrand pricing assumption). Finally, for part (iii) firms randomize under FP regime (earning zero expected profit), and there is no investment under RE regime. We conclude that welfare is equal to zero in both cases.

2.5.3 An Illustration

Propositions 8 and 9 do not say anything conclusive about the welfare ranking of the two IPR regimes when the parameters of interest fall in areas C_2 and B_1 of Figure 5. It turns out that either welfare ranking is possible in these areas, depending on parameter values. That much can easily be established by deriving explicit expressions for the welfare functions of interest that are then numerically evaluated for alternative parameter values. Suppose that both firms invest with probability σ_0 in the investment game and, as before, the social welfare in the improvement game is W_i ($i = 1,2$) or W_ϕ. Then the expected social payoff of the whole game is defined by the following recursive equation:

$$\begin{aligned} V_0(\sigma_0) &= \sigma_0{}^2\left[-2c_0 + 2q\delta W_i + (1-2q)\delta V_0\left(\sigma_0\right)\right] \\ &\quad + 2\sigma_0\left(1-\sigma_0\right)\left[-c_0 + p\delta W_i + (1-p)\delta V_0\left(\sigma_0\right)\right] + \left(1-\sigma_0\right)^2 \delta V_0\left(\sigma_0\right) \end{aligned} \tag{27}$$

yielding (upon some simplification):

$$V_0\left(\sigma_0\right) = \frac{\sigma_0 p\left(2-\sigma_0 p\right)\delta W_i - 2\sigma_0 c_0}{1-\delta\left[1-2\sigma_0\left(\left(1-\sigma_0\right)p+\sigma_0 q\right)\right]} \tag{28}$$

Therefore, the social welfare measures under the FP and RE regimes are given by, respectively,

$$W^{FP} = V_0(1) = \frac{p(2-p)\delta W_1 - 2c_0}{1-\delta+2q\delta} \tag{29}$$

$$W^{RE} = V_0\left(\sigma_0\right) = \frac{\sigma_0 p\left(2-\sigma_0 p\right)\delta W_i - 2\sigma_0 c_0}{1-\delta\left[1-2\sigma_0\left(\left(1-\sigma_0\right)p+\sigma_0 q\right)\right]} \tag{30}$$

where W_i is equal to W_2 or W_ϕ, depending on the equilibrium of the improvement game, and σ_0 is the corresponding equilibrium probability of investment in the initial stage.

These welfare functions can now be compared for any given set of parameter values (upon calculation of the equilibrium mixed strategy parameter σ_0). Consider for example $\Delta = 1$ (without loss of generality), and suppose that $p = 0.5$ and $\delta = 0.8$.[8] The welfare comparison of the two IPR regimes that we obtain in this case is summarized in Figure 6 where, for concreteness, the various regions are drawn to scale (i.e., given $p = 0.5$ and $\delta = 0.8$). The un-shaded regions in Figure 6

[8] These parameter values broadly reflect the nature of plant breeding, where the probability of success of a research program may be good, but where it usually takes several years to bring a new variety to the market. For example, $\delta = 0.8$ corresponds to a research period of five years if the annual discount rate is approximately equal to 4.5 percent.

(labeled E) represent the parameter space where the FP and RE regimes are equivalent in terms of social welfare. In the rightmost portion of this parameter space (region A in Figure 5) there is no difference in welfare because the equilibrium is the same under the two intellectual property regimes. In the other portion of this parameter space welfare equivalence results because no investment takes place under the RE regime, whereas under the FP regime all the surplus is competed away by the two firms (who engage in a mixed strategy equilibrium in the initial investment game). In the red colored regions of Figure 6, labeled FP , the full patent regime is better from the social point of view; these regions correspond to parts (i) and (ii) of Proposition 7, part (i) of Proposition 8 and the conclusions of the analysis of regions C_2 and B_1 discussed in the foregoing. Finally, in the blue colored regions of Figure 6, labeled RE , the RE regime dominates patents from the social point of view. These regions were described in part (ii) of Proposition 7 and part (ii) of Proposition 8 and in the context of the analysis of regions C_2 and B_1 .

The fact that the parameter space in which the RE regimes dominates is disjoint exhibits one the simplifying features of our model. Specifically, the assumption that the entire surplus created by the innovation can be extracted by a monopolist patent holder means that there is no residual consumer surplus in region B_2 ; and, in this region there is no expected profit either under the FP regime, although some investment takes place, because the mixed-strategy equilibria competes away all the expected profit. Under the RE regimes firms earn zero initial expected profits (they also play a mixed strategy in both the initial and the improvement games). But given the Bertrand pricing assumption, consumers can capture some of the benefits of innovation here, and thus the RE regimes dominates the FP regime in this region. In other words, the limited avenue for R&D benefit spillover to consumers that we allow in our model somewhat slants the comparison in favor of the RE regime. Whereas this result underlies a limiting feature of the model (which could, of course, be relaxed, at the cost of making the characterization of the results even more cumbersome), it does reinforce the significance of the parameter space where we have shown that the FP regimes dominates.

2.5.4 On Licensing

In this paper we have assumed that, under both intellectual property regimes, no licensing takes place between competing firms. The type of licensing that we might consider here is for the right to carry out R&D (there is clearly no incentive for the Leader and patent holder to license the right to produce). Because licensing was a central theme of some earlier cumulative innovation models (e.g., Green and Scotchmer, 1995), it might be useful to articulate how licensing would affect our results. First note that, unlike some other quality ladder models in this area, here we have assumed that ideas are not scarce in that both the initial innovator and the other firm can pursue the follow-on innovation. But we have also implicitly assumed that firms can operate only one project at a time (i.e., each firm has a given stock of R&D capabilities), so that in principle licensing the ability to perform product-improving R&D might be useful.

Under the RE regime, it is clear that there is no scope for licensing because the lagging firm has free access to the latest innovation for R&D purposes (or, to put it differently, follow-on innovations are patentable and non-infringing). Under the FP regime, on the other hand, the winner of the initial game would find it profitable to license the right to innovate if the monopoly profit from investing in the two separate projects is higher than the profit from a single project. In fact, because in our setting the monopolist captures the entire surplus from innovation, this condition is equivalent to whether it is better, from the social point of view, to have one or two firms engaged in R&D.[9] In part (ii) of Proposition 7 we have shown that two firms are better than one i.f.f. $(1-p)x_0 \geq c/\Delta$. Therefore, in this domain, licensing could occur. Because in our setting the monopolist fully internalizes the social benefit of innovation, allowing for licensing arrangements would improve the welfare properties of the FP regime, without affecting the nature of the equilibrium under the RE regime. We should conclude, therefore, that if licensing were allowed in this model the FP regime would weakly dominate the RE in every case. But we caution against this overly strong conclusion. In our model it is not particularly meaningful to consider licensing because we do not explicitly model an asymmetric information structure, a feature that has been shown to be critical in the licensing of technology, especially in a cumulative innovation setting (Gallini and Wright, 1990; Bessen, 2004).

2.6 Conclusion

Recent court decisions have renewed interest, both in the United States and abroad, in the question of whether patent law reform should include a statutory research exemption (Merrill, Levin and Myers, 2004; Thomas, 2004; Rimmer, 2005). Conversely, for the case of plant breeder's rights (an intellectual property right system that already possesses a well-defined research exemption), there has been considerable debate on whether the access provided by the research exemption should be curtailed (Le Buanec, 2004). Little economic research on this feature of intellectual property rights exists, however. In this paper we attempt to fill this gap in the policy analysis of intellectual property rights by studying the welfare properties of the research exemption and its ability to provide

[9] The presumption that firms can carry out only one project at a time rules out the "invariance" effect of Sah and Stiglitz (1987).

incentives for R&D investment when the innovation process is sequential and cumulative. We develop a dynamic model of production and R&D competition in which the cost of the initial innovation effort differs from the cost of subsequent improvements. In this framework we derive explicit solutions for the Markov perfect equilibria of the investment and improvement games and analyze the social welfare properties of full patent and research exemption regimes.

Among the findings of the paper, it turns out that the firms themselves always prefer (*ex ante*) the full patent protection regime. The social ranking of the two intellectual property regimes, on the other hand, depends on the relative magnitudes of costs of initial innovation and improvements. In particular, there exists a range of improvement cost parameters in which the social ordering of the two regimes depends on the magnitude of the initial innovation cost: for low values of this initial cost the research exemption regime yields a higher welfare, whereas when the initial cost is large the full patent regime is optimal from the social point of view. This implies that the research exemption is most likely to provide inadequate incentives when there is a large cost to establishing a research program, as is arguably the case for the plant breeding industry (where developing a new variety typically takes several years). On the other hand, when both initial and improvement costs are small relative to the expected profits (perhaps the case of the software industry noted by Bessen and Maskin, 2002), the weaker incentive to innovate is immaterial (firms engage in R&D anyway) and the research exemption regime results in a higher social payoff.

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2.8 Figures

Figure 1. Stages, states, and implied games under the "research exemption"

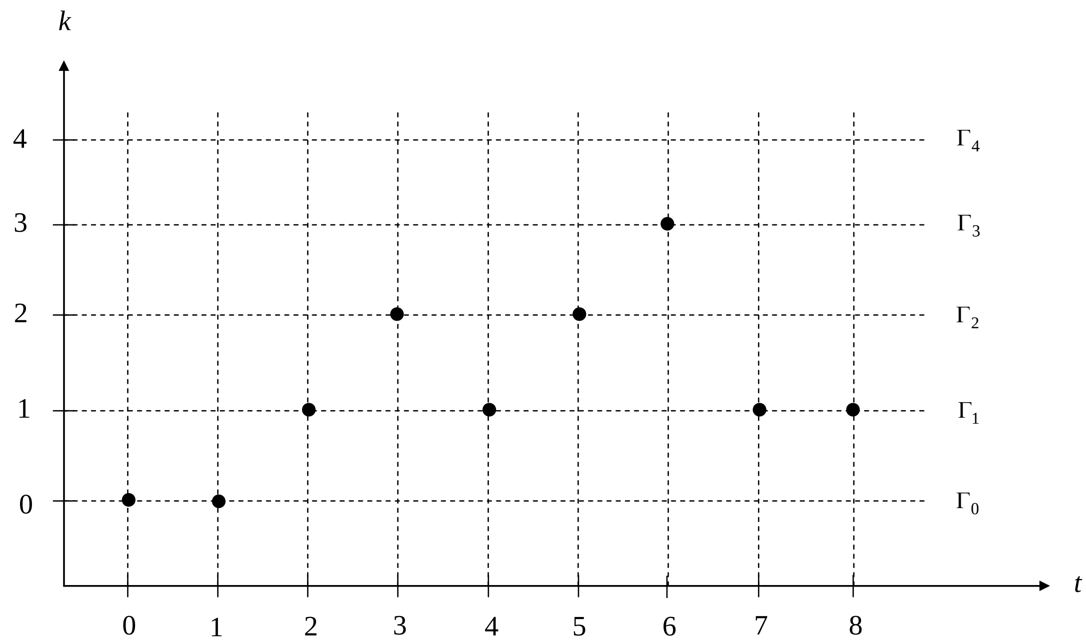


Figure 2. Types of Markov perfect equilibria in the improvement games

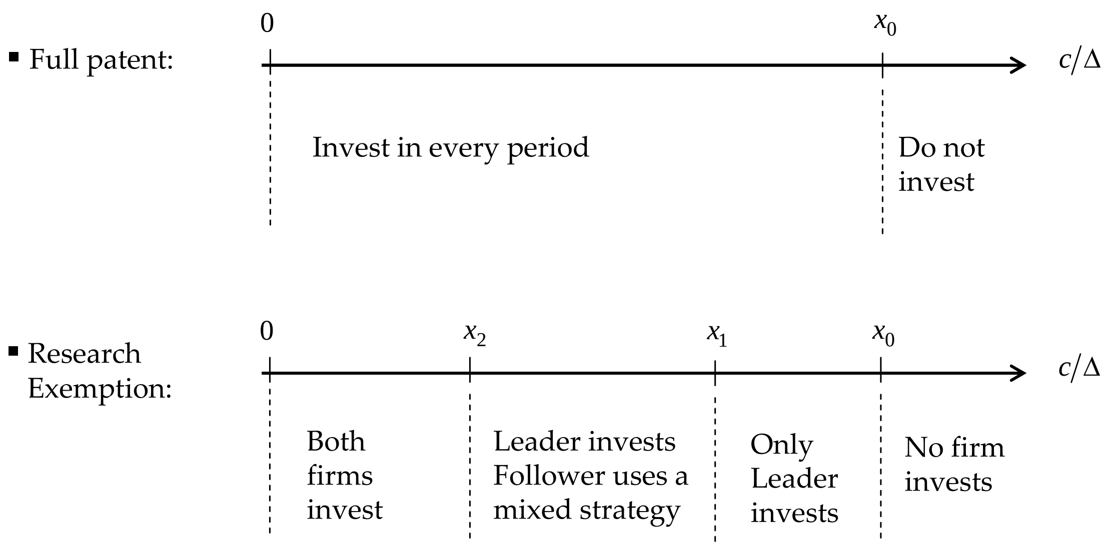


Figure 3. Equilibrium payoffs in the improvement games

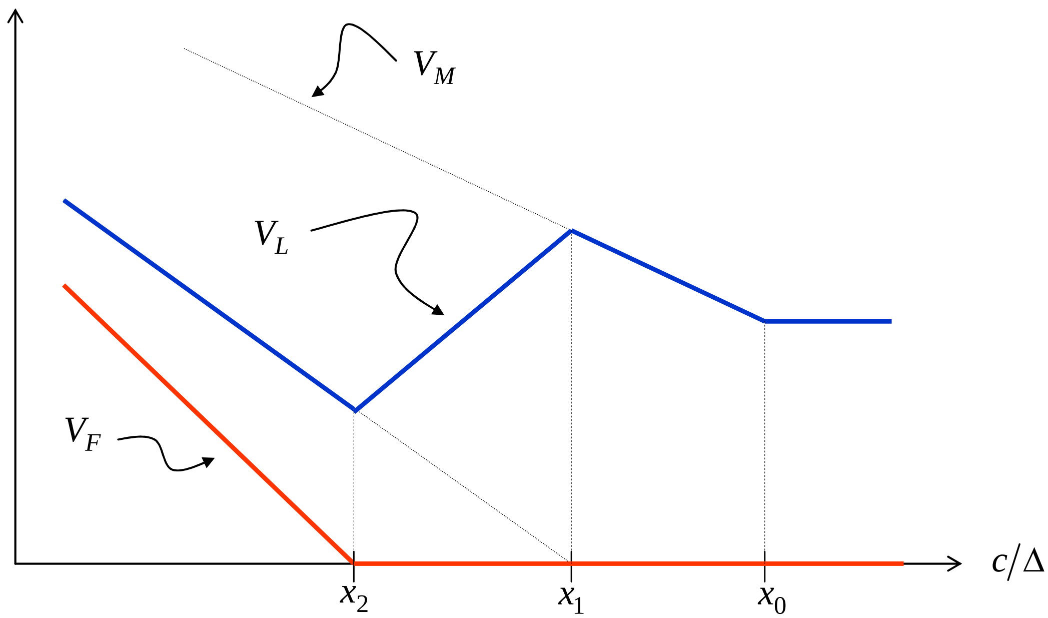


Figure 4. Equilibrium with "full patent" protection

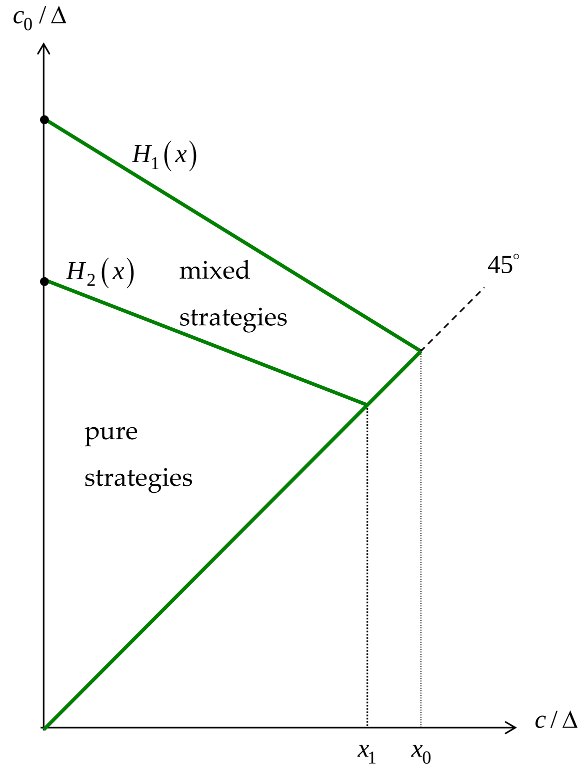


Figure 5. Equilibrium with the “research exemption”

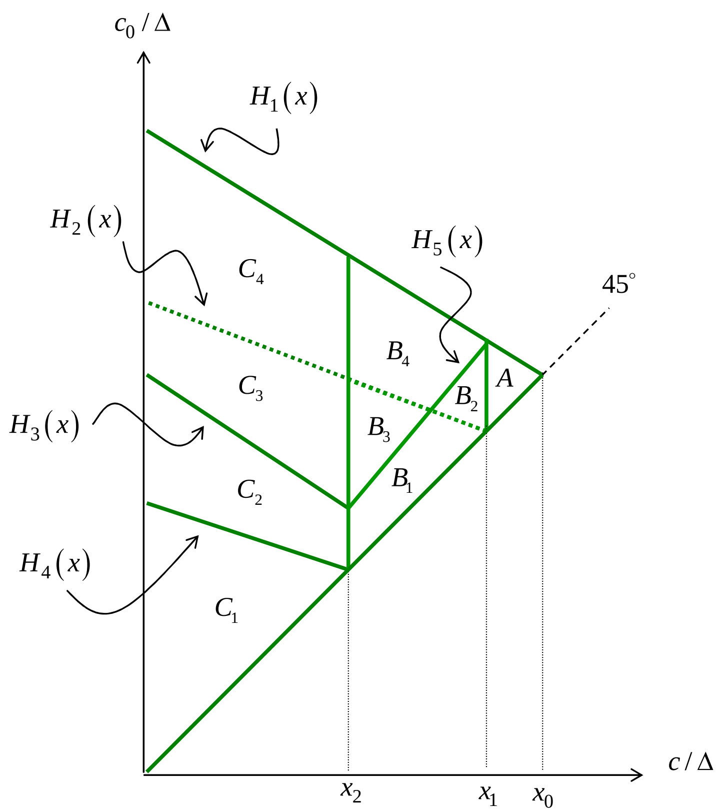
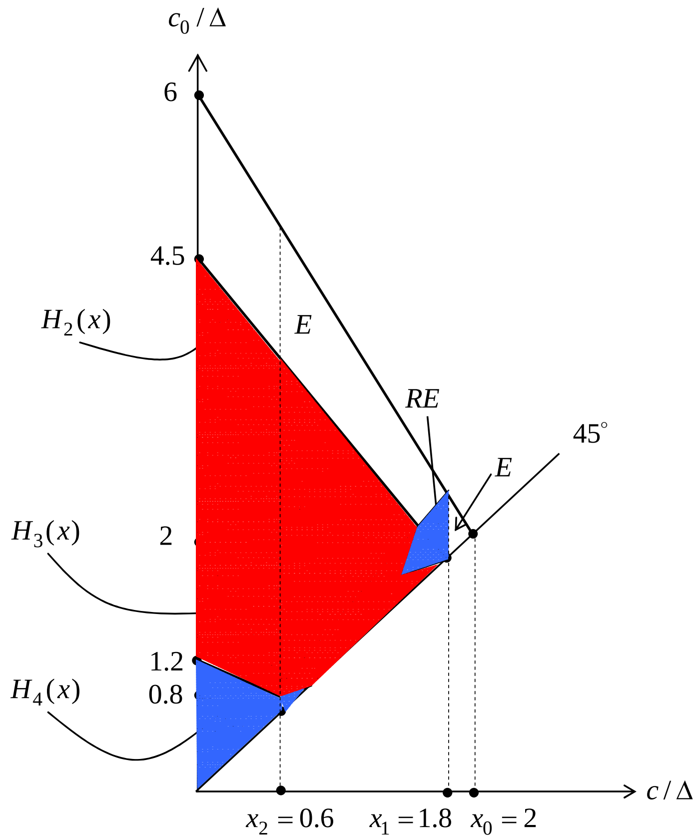


Figure 6. Welfare comparisons (case of $\delta = 0.8$ and $p = 0.5$)



2.9 Appendix

2.9.1 Proof of Lemma 1

Consider the situation where the Leader invest with probability one in every period, whereas the follower invest with the same probability $\phi \in [0,1]$ in every period (i.e., $\sigma_L(k) = 1$ and $\sigma_F(k) = \mathrm{v}$, $\forall k$). As in the text, the value to the Follower is written as V_F (this value is independent of the state), whereas for the Leader we simplify the notation and write $V_k \equiv V_L\left(\sigma_L(k), \sigma_F(k), k\right)$. From the recursive equations in (2) and (3) we have:

$$V_k = \Delta k - c + \phi\left[q\delta V_{k+1} + q\delta V_F + (1-2q)\delta V_k\right] + (1-\phi)\left[p\delta V_{k+1} + (1-p)\delta V_k\right] \qquad (31)$$

$$V_F = \mathrm{v}\left[-c + q\delta V_1^L + (1-q)\delta V_F\right] + (1-\mathrm{v})\delta V_F \qquad (32)$$

Hence, for the Leader we have

$$V_k = \alpha + \beta k + \gamma V_{k+1} \qquad k = 1, 2, \ldots$$

where the parameters α, β and γ are defined as follows:

$$\alpha \equiv \frac{-c + \mathrm{v}q\delta V_F}{\left(1 - \mathrm{v}\delta(1-2q) - (1-\mathrm{v})(1-p)\delta\right)}$$

$$\beta \equiv \frac{\Delta}{\left(1 - \mathrm{v}\delta(1-2q) - (1-\mathrm{v})(1-p)\delta\right)}$$

$$\gamma \equiv \frac{\mathrm{v}q\delta + (1-\mathrm{v})p\delta}{\left(1 - \mathrm{v}\delta(1-2q) - (1-\mathrm{v})(1-p)\delta\right)} < 1 .$$

Assuming that the following convergence condition holds,

$$\lim_{n\to\infty} \quad \gamma^n V_{k+n} \to 0 \qquad (33)$$

the general solution to the value of the leader can be written as

$$V_k = \frac{\alpha}{1-\gamma} + \frac{\beta k}{1-\gamma} + \frac{\beta\gamma}{(1-\gamma)^2} . \qquad (34)$$

Note that, by using (34), the term in the convergence condition (33) reduces to:

$$\gamma^n V_{k+n} = \gamma^n \left(\frac{\alpha}{1-\gamma} + \frac{\beta\gamma}{(1-\gamma)^2} + \frac{\beta k}{1-\gamma}\right) + \frac{\beta}{1-\gamma}\gamma^n n .$$

Given that $\gamma < 1$, it follows that $\gamma^n \to 0$ as $n \to \infty$, and also that $n\gamma^n \to 0$ as $n \to \infty$, so that (33) holds. From the previous definitions of the parameters α, β and γ, it then follows

$$V_k = \frac{-c + \text{v}q\delta V_F}{1-\delta(1-\text{v}q)} + \frac{\Delta k}{1-\delta(1-\text{v}q)} + \frac{\Delta\delta\left(\text{v}q+(1-\text{v})p\right)}{\left(1-\delta(1-\text{v}q)\right)^2} \tag{35}$$

This expression is conditional on V_F, which satisfies (32). But for $k = 1$ we have:

$$V_1 = \frac{-c + \text{v}q\delta V_F}{1-\delta(1-\text{v}q)} + \frac{\Delta}{1-\delta(1-\text{v}q)}\left[\frac{1-\delta\left(1-2\text{v}q-(1-\text{v})p\right)}{1-\delta(1-\text{v}q)}\right] \tag{36}$$

Upon solving the system of equations given by (32) and (36) we obtain:

$$V_1 = \frac{-c\left(1-\delta\left[1-\text{v}q(1+\text{v})\right]\right)}{(1-\delta)\left(1-\delta(1-2\text{v}q)\right)} + \frac{\Delta}{(1-\delta)} + \frac{\Delta\left(\delta(1-\text{v})p\right)}{(1-\delta)\left(1-\delta(1-2\text{v}q)\right)} \tag{37}$$

$$V_F = \text{v}\left(\frac{\Delta q\delta\left[1-\delta(1-2\text{v}q-(1-\text{v})p)\right]}{(1-\delta)\left(1-\delta(1-2\text{v}q)\right)\left(1-\delta(1-\text{v}q)\right)} - \frac{c\left(1-\delta(1-(1+\text{v})q)\right)}{(1-\delta)\left(1-\delta(1-2\text{v}q)\right)}\right) \tag{38}$$

Equations (35) and (38) contain the results claimed in Lemma 1.

2.9.2 Proof of Proposition 1

Part (i). If both firms invest in every period, then, from the recursive equations (2) and (3), their value functions are given by

$$V_L(\sigma,k) = k\Delta - c + q\delta V_F + q\delta V_L(\sigma,k+1) + (1-2q)\delta V_L(\sigma,k) \tag{39}$$

$$V_F = -c + q\delta V_L(\sigma,1) + (1-q)\delta V_F \tag{40}$$

Consider the Leader first, and suppose that now the Leader deviates by not investing in state s. Then his expected payoff is

$$V_L(\hat{\sigma},s) = s\Delta + p\delta V_F + (1-p)\delta V_L(\hat{\sigma},s) \quad \Rightarrow \quad V_L(\hat{\sigma},s) = \frac{s\Delta + p\delta V_F}{1-\delta(1-p)} \tag{41}$$

Here $\hat{\sigma} = (\hat{\sigma}_L, \sigma_F)$ and $\hat{\sigma}_L(k) = \sigma_L(k)$ for all $k \neq s$. Assume that $s = 1$. Then the one-stage deviation under consideration would be profitable i.f.f. $V_L(\hat{\sigma},1) \geq V_L(\sigma,1)$. From Lemma 1, when $k = 1$ and both firms invest in every period, the value functions of Leader and Follower reduce to

$$V_L(\sigma,1) = \frac{\Delta - c}{(1-\delta)} \tag{42}$$

$$V_F(\sigma) = \frac{\Delta q\delta}{(1-\delta)\left(1-\delta(1-q)\right)} - \frac{c}{(1-\delta)} \tag{43}$$

By using these expressions and (41), we find that $V_L(\sigma,1) \geq V_L(\hat{\sigma},1)$ i.f.f.

$$\frac{c}{\Delta} \leq \frac{p\delta}{1-\delta(1-q)} \tag{44}$$

For the purposes of part (i) of Proposition 1 we observe that

$$x_2 \equiv \frac{q\delta}{1-\delta(1-q)} < \frac{p\delta}{1-\delta(1-q)} \quad . \tag{45}$$

Therefore we conclude that deviating by not investing in state $s=1$ cannot be profitable for the Leader when $c/\Delta \le x_2$. Since not investing in state $s=1$ yields a strictly lower payoff to the Leader, the Leader will not choose this action with positive probability in any arbitrary deviation when the lead is equal to one. Hence we conclude that the Leader has no profitable deviation in this state. Next, by using equation (5) of Lemma 1 we can write

$$V_L(\sigma,s+1)-V_L(\hat{\sigma},s+1)=V_L(\sigma,s)-V_L(\hat{\sigma},s)+\frac{\Delta\delta(p-q)}{\left(1-\delta(1-q)\right)\left(1-\delta(1-p)\right)} \tag{46}$$

If $V_L(\sigma,1) \ge V_L(\hat{\sigma},1)$, then, because $p>q$, it follows by induction that $V_L(\sigma,k) \ge V_L(\hat{\sigma},k), \forall k$. Thus, the Leader does not have a profitable deviation at any stage. Next consider the Follower. Conditional on the Leader investing in every period, the value to the Follower of investing in every period is V_F as given by (43), whereas the value of deviating to not investing in the first stage is $V_F\left(\hat{\sigma}\right)=\delta V_F\left(\sigma\right)$. Hence, $V_F(\sigma) \ge V_F(\hat{\sigma})$ whenever $V_F \ge 0$ which, from (43), is equivalent to $c/\Delta \le q\delta/\left(1-\delta(1-q)\right) \equiv x_2$.

Part (ii). Because the value of being a Follower does not depend on the state k of the game, the follower can follow the same stationary strategy at all states. Thus, consider the candidate equilibrium profile σ where Let $\sigma_F(k)=\phi, \forall k$ and $\sigma_L(k)=1, \forall k$, where $\text{v} \in [0,1]$. From part (i), $\text{v}=1$ i.f.f. $c/\Delta \le q\delta/\left(1-\delta(1-q)\right) \equiv x_2$. For $c/\Delta < x_2$ and close enough to x_2 suppose that $\text{v} \in (0,1)$. Then, in any one stage, the Follower must be indifferent between actions I and N (given that the rest of the game accords with the strategy profile σ), that is $V_F^I = V_F^N$ where

$$V_F^I = -c + q\delta V_1 + (1-q)\delta V_F$$

$$V_F^N = \delta V_F$$

By using the expressions derived in Lemma 1, we find that $V_F^I = V_F^N$ requires v to solve the quadratic equation (11). Note that $\text{v} \to 1$ as $c/\Delta \to x_2$ and $\text{v} \to 0$ as $c/\Delta \to x_1$. By construction, the Follower does not have a one-stage profitable deviation from $\sigma_F(k)=\phi, \forall k$. As for the Leader, the value of $\sigma_L(k)=1, \forall k$ when the Follower plays $\sigma_F(k)=\phi, \forall k$ is given by $V_L(\sigma,k)$ in Lemma 1. Deviating at stage s only by choosing action N at that stage yields payoff

$$V_L(\hat{\sigma},k) = \Delta k + \text{v}\, p\delta V_F + (1-\text{v}\, p)\delta V_L(\sigma,k)$$

Because, as shown, in the postulated mixed strategy equilibrium the Follower's payoff is $V_F = 0$, $V_L(\sigma,k) \geq V_L(\hat{\sigma},k)$ holds as long as $V_L(\sigma,k) \geq \Delta k / \left(1-\delta(1-\text{v}q)\right)$ which, by using the result of Lemma 1, is equivalent to

$$\frac{c}{\Delta} \leq \frac{\delta\left(\text{v}q + (1-\text{v})p\right)}{1-\delta(1-\text{v}q)} \tag{47}$$

This inequality can be shown to hold for all $\text{v} \in [0,1]$ that solve equation (11). Because equation (11) applies to $x_2 \leq c/\Delta \leq x_1$, then in this domain the Leader does not have a profitable deviation from $\sigma_L(k) = 1, \forall k$.

Part (iii). If $\sigma_F(k) = 0, \forall k$, then the situation is isomorphic to that of the FP protection environment and, as established earlier, it is indeed optimal for the Leader to invest whenever $c/\Delta \leq x_0$. Given $\sigma_L(k) = 1, \forall k$, it follows from the proof of part (ii) that the Follower does not have a profitable one-stage deviation when away $x_1 < c/\Delta$.

Part (iv). If the firms play according to the strategy profile $\sigma_L(k) = \sigma_F(k) = 0, \forall k$, then the payoffs are given by $V_L(\sigma,1) = \dfrac{\Delta}{1-\delta}$ and $V_F(\sigma) = 0$. Suppose that the Leader considers the strategy $\hat{\sigma}_L(k)$ such that $\hat{\sigma}_L(1) = 1$ and $\hat{\sigma}_L(k) = \sigma_L(k) = 0, \forall k > 1$ (i.e., the Leader deviates by investing in state $k = 1$ only). Then the Leader's expected payoff can be written as

$$V_L(\hat{\sigma}_L,\sigma_F,1) = V_L(\sigma_L,\sigma_F,1) - c + p\delta\frac{\Delta}{1-\delta} \tag{48}$$

Thus, $V_L(\hat{\sigma}_L,\sigma_F,1) - V_L(\sigma_L,\sigma_F,1) > 0$ holds i.f.f. $\Delta p\delta - c(1-\delta) > 0$, that is i.f.f. $c/\Delta < x_0$. We conclude that the Leader has no profitable one-state deviation in this case. Now, for the Follower, consider the strategy $\hat{\sigma}_F(k)$ such that $\hat{\sigma}_F(1) = 1$ and $\hat{\sigma}_F(k) = \sigma_F(k) = 0, \forall k > 1$ (i.e., the Follower deviates by investing in state $k = 1$ only). Then his expected payoff is given by

$$V_F(\sigma_L,\hat{\sigma}_F) = V_F(\sigma_L,\sigma_F) - c + p\delta\frac{\Delta}{1-\delta} \tag{49}$$

and again we find that $V_F(\sigma_L,\hat{\sigma}_F) - V_F(\sigma_L,\sigma_F) > 0 \iff c/\Delta < x_0$.

2.9.3 Proof of Proposition 2

Part (i). We will show that for each firm it is optimal not to invest, given that its rival does not invest. The winner of the investment game would obtain a payoff equal to $\Delta/(1-\delta)$, so that the payoff from investing in the initial game while the other firm does not invest is

$$V_0 = -c_0 + p\delta\frac{\Delta}{1-\delta} + (1-p)\delta V_0 \quad \Rightarrow \quad V_0 = \frac{1}{(1-(1-p)\delta)}\left(\frac{p\delta\Delta}{1-\delta} - c_0\right). \tag{50}$$

Therefore such a firm will invest i.f.f.

$$\frac{p\delta\Delta}{1-\delta} - c_0 \geq 0 \quad \Leftrightarrow \quad \frac{p\delta}{1-\delta} \geq \frac{c_0}{\Delta} \geq \frac{c}{\Delta}.$$

Because here $x_0 < c/\Delta$, the best response of such firm is not to invest.

Part (ii). We will show that no firm can deviate profitably by switching to $\sigma_0 = 1$. Because $c/\Delta \leq x_0$ by assumption, the payoff of the winner of the investment game is given by the V_M of equation (1) (with $k = 1$). Consider the payoff to the firm from playing $\sigma_0 = 1$ given that its rival plays $\sigma_0 = 0$. This satisfies

$$V_0 = -c_0 + p\delta V_M + (1-p)\delta V_0 \tag{51}$$

Therefore such a firm will find it profitable to i.f.f.

$$V_0 = \frac{p\delta V_M - c_0}{1-(1-p)\delta} \geq 0 \quad \Leftrightarrow \quad \frac{p\delta}{1-\delta}\left(\frac{1-\delta+p\delta}{1-\delta} - \frac{c}{\Delta}\right) \geq \frac{c_0}{\Delta} \tag{52}$$

Part (iii). Consider the situation in which both firms invest with probability one. Then each firm's value function is given by

$$V_0 = -c_0 + q\delta V_M + (1-2q)\delta V_0 \tag{53}$$

Because the firm that does not innovate obtains a zero payoff, both firms invest in equilibrium if

$$V_0 = \frac{q\delta V_M - c_0}{1-(1-2q)\delta} \geq 0 \quad \Leftrightarrow \quad \frac{q\delta}{1-\delta}\left(\frac{1-\delta+p\delta}{1-\delta} - \frac{c}{\Delta}\right) \geq \frac{c_0}{\Delta} \tag{54}$$

Part (iv). Because here we have $c_0/\Delta \leq H_1(c/\Delta)$, we know from (ii) that in the absence of competition each firm will find it profitable to invest. On the other hand, since $c_0/\Delta \geq H_2(c/\Delta)$, we know from (iii) that if its rival is investing a firm will find it profitable not to invest. This implies that there exist two pure-strategy Nash equilibria in this domain, which require the two firms to behave asymmetrically. But there also exist a pair of mixed strategies which, because of their symmetry, may be more appealing. To compute the symmetric mixed-strategy equilibrium, suppose that firm 2 randomizes between investing and not with probability σ_0. Then the payoff of firm 1, conditional on investing or not investing, respectively, satisfies the following recursive equations:

$$V_0^1 = \sigma_0\left(q\delta V_M + (1-2q)\delta V_0^1\right) + (1-\sigma_0)\left(p\delta V_M + (1-p)\delta V_0^1\right) - c_0 \quad (55)$$

$$V_0^1 = \sigma_0(1-p)\delta V_0^1 + (1-\sigma_0)\delta V_0^1 \quad (56)$$

From (56) it follows that $V_0^1 = 0$. In a non-degenerate mixed-strategy equilibrium each firm is indifferent between its two (pure) strategies. Hence, the second firm's equilibrium mixing probability must satisfy

$$\sigma_0 q\delta V_M + (1-\sigma_0)p\delta V_M - c_0 = 0 \qquad \Leftrightarrow \qquad \sigma_0 = \frac{p\delta V_M - c_0}{(p-q)\delta V_M}.$$

2.9.4 Proof of Proposition 4

If both firms invest with probability one in the investment game, then the value function of each firm is given by

$$V_0 = -c_0 + q\delta V_1 + (1-2q)\delta V_0 \qquad \Leftrightarrow \qquad V_0 = \frac{q\delta V_1 - c_0}{1-(1-2q)\delta}.$$

On the other hand, if only one firm invests, then its value function is given by

$$V_0^I = -c_0 + p\delta V_1 + (1-p)\delta V_0^I \qquad \Leftrightarrow \qquad V_0^I = \frac{p\delta V_1 - c_0}{1-(1-p)\delta}$$

and the value function of the firm that does not invest (V_0^N) is equal to zero. Therefore, both firms invest in equilibrium if and only if $V_0 \geq V_0^N$, that is $\frac{q\delta V_1 - c_0}{1-(1-2q)\delta} \geq 0$. The last expression can be written as $q\delta V_1 \geq c_0$. By using equation (9), which implies that $V_1 = V_L(\sigma,1) = c/(q\delta)$, we can write this last condition simply as: $c \geq c_0$. By assumption we are limiting consideration to the case $c \leq c_0$, therefore firms will invest with probability one only when $c = c_0$. On the other hand, none of the firms invests in equilibrium if $V_0^I < 0$, that is $\frac{p\delta V_1 - c_0}{1-(1-p)\delta} < 0$. The last expression is equivalent to $p\delta V_1 < c_0$, or

$$H_5\left(\frac{c}{\Delta}\right) \equiv \frac{p}{q}\frac{c}{\Delta} < \frac{c_0}{\Delta}$$

Note that this implies that $H_5(x)$ is a linear function with $H_5(x_1) = H_1(x_1)$ and $H_5(x_2) = H_3(x_2)$ (see Figure 5). Finally, if $c/\Delta < c_0/\Delta \le H_5(c/\Delta)$ then both firms must randomize in a symmetric equilibrium. In such a symmetric mixed strategy equilibrium, if the second firm invests with probability σ_0, then for the first firm to be indifferent between investing and not we must have

$$\sigma_0 q\delta V_1 + (1-\sigma_0)p\delta V_1 - c_0 = 0 \quad \Leftrightarrow \quad \sigma_0 = \frac{p\delta V_1 - c_0}{(p-q)\delta V_1}.$$

2.9.5 Proof of Proposition 5

Part (i). If both firms invest with probability one in the investment game, then the value function of each firm is given by

$$V_0 = -c_0 + q\delta V_L + q\delta V_F + (1-2q)\delta V_0 \quad \Leftrightarrow \quad V_0 = \frac{q\delta(V_L + V_F) - c_0}{1-(1-2q)\delta} \tag{57}$$

On the other hand, if only one firm invests, then its value function is given by

$$V_0^I = -c_0 + p\delta V_L + (1-p)\delta V_0^I \quad \Leftrightarrow \quad V_0^I = \frac{p\delta V_L - c_0}{1-(1-p)\delta} \tag{58}$$

and the value function of the firm that does not invest is given by

$$V_0^N = p\delta V_F + (1-p)\delta V_0^N \quad \Leftrightarrow \quad V_0^N = \frac{p\delta V_F}{1-(1-p)\delta}. \tag{59}$$

Therefore, both firms invest in equilibrium if and only if

$$V_0 \ge V_0^N \quad \Leftrightarrow \quad \frac{q\delta(V_L + V_F) - c_0}{1-(1-2q)\delta} \ge \frac{p\delta V_F}{1-(1-p)\delta}$$

By using the expressions for V_L and V_F derived earlier, the last expression can be re-arranged to yield the claimed parametric domain.

Part (ii). Suppose that a firm faces a rival that does not invest. From (v) we know that such a firm will find it profitable to invest i.f.f.

$$V_0^I = \frac{p\delta V_L - c_0}{1-(1-p)\delta} \ge 0 \quad \Leftrightarrow \quad \frac{p\delta(\Delta - c)}{1-\delta} \ge c_0 \quad \Leftrightarrow \quad c_0/\Delta \le H_3(c/\Delta). \tag{60}$$

Part (iii). The results in (i) and (ii) imply that in this case a firm that faces no rival will find it optimal to invest. On the other hand if the rival is investing, then it is optimal not to invest. It is clear that the symmetric equilibrium must involve mixed strategies. To compute them, suppose that one of the firms invests in each period of the investment stage with probability $\sigma_0 \in [0,1]$. In equilibrium its rival must be indifferent between investing and not. In particular, we have

$$V_0^I = \sigma_0\left(-c_0 + q\delta V_L + q\delta V_F + (1-2q)\delta V_0^I\right) + (1-\sigma_0)\left(-c_0 + p\delta V_L + (1-p)\delta V_0^I\right)$$

$$\Leftrightarrow \quad V_0^I = \frac{(\sigma_0 q + (1-\sigma_0)p)\delta V_L + \sigma_0 q\delta V_F - c_0}{1-\delta(1-p)(1-\sigma_0 p)} \tag{61}$$

and

$$V_0^N = \sigma_0\left(p\delta V_F + (1-p)\delta V_0^N\right) + (1-\sigma_0)\delta V_0^N \quad \Leftrightarrow \quad V_0^N = \frac{\sigma_0 p\delta V_F}{1-\delta(1-\sigma_0 p)} \tag{62}$$

The equilibrium mixing probability must satisfy $V_0^I = V_0^N$, implying

$$\frac{(\sigma_0 q + (1-\sigma_0)p)\delta V_L + \sigma_0 q\delta V_F - c_0}{1-\delta(1-p)(1-\sigma_0 p)} = \frac{\sigma_0 p\delta V_F}{1-\delta(1-\sigma_0 p)} \tag{63}$$

This defines a quadratic equation in σ_0 of the form $a\cdot\sigma_0^{\,2} + b\cdot\sigma_0 + e = 0$, where

$$a \equiv -p\delta^2(p-q)(V_L - V_F) < 0 \tag{64}$$

$$b \equiv \delta\left[(p-q)\left(V_L(3\delta-1) - V_F(1+\delta)\right) - c_0 p\right] \tag{65}$$

$$e \equiv (1-\delta)(p\delta V_L - c_0) \geq 0 \tag{66}$$

and where V_F and $V_L \equiv V_L(\sigma,1)$ are given by equations (4) and (9), respectively. The equilibrium mixing probability is the root of this equation that belongs to the unit interval.

2.9.6 Completion of the Proof of Proposition 6

Note that(21) is monotonically increasing in σ_0, achieving its maximum on $[0,1]$ at $\sigma_0 = 1$. Thus, a sufficient condition for $\Pi^{FP} > \Pi^{RE}$ in this case is:

$$\frac{q\delta V_M - c_0}{1-(1-2q)\delta} > \frac{p\delta V_F}{1-\delta(1-p)} \quad \Rightarrow \quad \left(q\delta V_M - c_0\right)\left(1-\delta(1-p)\right) > \left(p\delta V_F\right)\left(1-(1-2q)\delta\right) \tag{67}$$

provided c_0 is such that we still are in region *D*, that is $\frac{c_0}{\Delta} \leq \frac{p\delta}{1-\delta}\left(1-\frac{c}{\Delta}\right) \equiv H_3\left(c/\Delta\right)$.

The LHS of the inequality in (67) is decreasing in c_0, so take the upper value $\overline{c}_0 = \frac{p\delta\Delta}{1-\delta}\left(1-\frac{c}{\Delta}\right)$.

Recalling the expressions for V_M and V_F (equation (1) and Lemma 1), and evaluating it at $\overline{c}_0$, the inequality of interest reduces to:

$$\frac{\delta}{(1-\delta)^2}\left[(q-p)(\Delta-c)(1-\delta)+qp\Delta\right]\left(1-\delta(1-p)\right) > p\delta\left[\frac{-c\left(1-\delta(1-q)\right)+q\delta\Delta}{(1-\delta)\left[1-\delta(1-q)\right]}\right]\left(1-(1-2q)\delta\right)$$

Note that the LHS is increasing in c and the RHS is decreasing in c. Hence, evaluate both at the lower bound $c=0$, so that the resulting sufficient condition simplifies to:

$$\left(1-\delta(1-p)\right)\left(1-\delta(1-q)\right) > \frac{(2-p)\delta}{(1+\delta-p)}\left(1-\delta\right)\left(1-\delta(1-2q)\right)$$

It is now verified that the inequality is always satisfied because, given that $p \in (0,1)$ and $\delta \in (0,1)$, we have $(2-p)\delta < (1+\delta-p)$ and

$$\left(1-\delta(1-p)\right)\left(1-\delta(1-q)\right) > \left(1-\delta\right)\left(1-\delta(1-2q)\right) \quad \Leftrightarrow \quad (1-\delta)(p-q)+\delta pq > 0 .$$

2.9.7 Derivation of the function W_ϕ

Suppose that the leader invests in all periods, and the follower invests with probability ϕ in each period and let $W_\phi(k)$ denote the expected total surplus at stage k. Then we have

$$W_\phi(k) = \Delta k - c(1+\phi) + \phi\left[2q\delta W_\phi(k+1) + (1-2q)\delta W_\phi(k)\right] + (1-\phi)\left[p\delta W_\phi(k+1) + (1-p)\delta W_\phi(k)\right]$$

This can be written as follows

$$W_\phi(k) = \alpha + \beta k + \gamma W_\phi(k+1) \qquad k = 1,2,...$$

where the parameters α, β and γ are defined as:

$$\alpha \equiv \frac{-c(1+\phi)}{\left(1-\phi\delta(1-2q)-(1-\phi)(1-p)\delta\right)}$$

$$\beta \equiv \frac{\Delta}{\left(1-\phi\delta(1-2q)-(1-\phi)(1-p)\delta\right)}$$

$$\gamma \equiv \frac{\phi 2q\delta + (1-\phi)p\delta}{\left(1-\phi\delta(1-2q)-(1-\phi)(1-p)\delta\right)} < 1$$

The general solution to the value of the leader can be written as:

$$W_\phi(k) = \frac{\alpha}{1-\gamma} + \frac{\beta k}{1-\gamma} + \frac{\beta\gamma}{(1-\gamma)^2} .$$

By using the definitions of the parameters α, β and γ given above, and simplifying for the case $k=1$, yields:

$$W_{\phi}(1)=\frac{\Delta-c(1+\phi)}{1-\delta}+\frac{\Delta(\phi 2q\delta+(1-\phi)p\delta)}{(1-\delta)^{2}}\equiv W_{\phi}.$$

CHAPTER 3. INTELLECTUAL PROPERTY RIGHTS AND CROP IMPROVING R&D UNDER ADAPTIVE DESTRUCTION

3.1 Introduction

Many commercially produced crops suffer significant yield reductions caused by pests and crop diseases. According to recent estimates, the damage in the U.S. agricultural sector ranges between $2 billion and $7 billion per year, with an additional $1.2 billion spent on various crop protection measures (Palumbi, 2001). Even though the development of biotechnology has led to the invention of innovative solutions in the fight against pests, it seems that no permanent solution to this problem is possible. The evolution of pest species inevitably leads to the emergence of resistance in the pest population, which then results in an increase in crop losses over time.

The dynamics of this process raises the question of which government policies may improve the outcome from efficiency and social welfare points of view. In particular, it is sometimes argued that farmers may lack incentives to take into account the consequences of their pest management practices, including planting decisions. For this reason, the U.S. Environmental Protection Agency has introduced in some cases (in particular in the cases of Bt cotton and Bt corn) regulations that require farmers to plant at least some of their land with crops that are not genetically modified (GM) to slow down the rate of resistance development (Fisher and Laxminarayan, 2005). The effectiveness of such policy creating "crop refuges" has been questioned on purely biological grounds, as well as more generally. Specifically, it has been argued that private breeders should have an incentive to take into account the problem of the evolution of pest resistance, because this process directly affects their profits (Noonan, 2002). Thus, private breeders would ensure that existing pest management techniques are used efficiently and would invest in the development of new technologies to overcome the resistance problem. Fisher and Laxminarayan (2004) note that Monsanto has already modified Bt technology, which now makes use of two proteins instead of one, making the development of insect resistance more difficult.

The problem of resistance management was first addressed formally by Hueth and Regev (1974), whose study generated considerable interest in the topic (e.g., Carlson and Wetzstein, 1993). Even though the literature on the excessive use of pesticides and the possibility of market failure when dealing with the pest resistance problem has yielded important insights, there is a need to move beyond the renewable or nonrenewable resource framework that has been used so far and to consider other important features of the economic environment (Alix-Garcia and

Zilberman, 2005). In particular, the incentive of private sector breeders to invest in crop innovations depends on the delineation of property rights in the various attributes of the new crop varieties, and, therefore, the issues of intellectual property rights and the resulting market structure should occupy a central place in this debate.

The interplay between social and private incentives to innovate in the context of the resistance problem has received considerable attention recently, and there are several interesting conclusions that arise out of this line of research. First, while society as a whole reaps a large benefit from technologies that decrease the scope of the resistance problem, the benefits of such technologies are dissipated among many users and thus may not attract sufficient private investments. This point was made by Goeschl and Swanson (2003b), who also note that the nature of the innovation in the context of the biological race against nature is different from the situations described in the standard quality ladder model used in many innovation and growth models. They coined the term "adaptive destruction" to characterize this process, emphasizing the analogy and difference with the Schumpeterian paradigm of "creative destruction" (in which each product is eventually superseded by a higher-quality one). Second, as shown by Goeschl and Swanson (2003a), private and social incentives to invest in research and development (R&D) might diverge with an increase in the degree of adaptive destruction, because the more severe is the resistance problem, the lower is the private benefit of crop R&D and the higher are the social returns from such investment. In addition to that, Goeschl and Swanson (2002) develop a model of an R&D race to compare the solution of the social planner problem in the context of antibiotic resistance with the equilibrium outcome of the race. They find that, in general, private incentives fall short of generating the first-best outcome.

In this paper we explore in more detail how the form and extent of intellectual property rights (IPRs) impact the incentive to innovate and the welfare consequences of innovation, in a context characterized by adaptive destruction. Specifically, we compare and contrast the effects of two alternative IPR regimes that capture the essential features of the current institutional setting. The strong IPR mode, referred to as the full patent (FP) regime, corresponds to the standard utility patents (as awarded in the United States by the U.S. Patent and Trademark Office). The relatively weaker IPR mode, referred to as the research exemption (RE) regime, corresponds to the so-called plant breeders' rights (PBRs), as implemented in the United States by plant variety protection certificates awarded by the U.S. Department of Agriculture. As discussed below in more detail, the critical difference between these two IPR modes concerns a feature that bears on the sequential and cumulative nature of innovation, which is a distinctive feature of agricultural and biotechnology innovations.

In addition to the consideration of alternative IPR regimes, in our analysis we also emphasize the importance of the market structure of the innovation industry, a feature largely ignored to date in the analysis of the biological resistance problem. In particular, we build a duopoly model of an R&D race in which the value of the final product is destroyed with exogenously given probability, thus making the duration of the monopoly power finite even under the (simplifying) assumption of an infinite patent life. Conceptually this model belongs to the class of symmetric stochastic R&D races in which innovations arrive according to a Poisson process (Reinganum, 1989, provides an early survey of this literature). In addition to addressing the resistance problem, our analysis contributes to the literature on IPR incentives for sequential innovation. Models in this area typically consider the effects of patent length and breadth on the division of profit between the owners of the first and second generations of innovation, both in a sequential setting (Green and Scotchmer, 1995) and in the context of R&D races (O'Donoghue, 1998; Denicolò, 2000). In contrast to most of these models, we assume that the second generation of the innovation is patentable and non-infringing and we concentrate on the question of whether the first innovator has the right to block all further R&D activities related to the patented product (i.e., whether or not there exists a research exemption).

In our setting, under the FP regime, the research on the patented product constitutes an infringement. Because of the sequential nature of the innovation process, with this kind of IPR protection the winner of the first race obtains an exclusive right to improve the product in the future. On the other hand, under the RE regime, firms cannot be excluded from participating in any improvement project, so that each improvement stage is a race between two firms. Throughout the analysis, we assume that no licensing takes place, in order to emphasize the effects of the IPR regimes on the incentives for innovation. In the next section, we provide a brief background that illustrates some critical features of our stylized model. We then describe the demand side of the model and lay out the structure of the R&D model that embeds, among other things, the notion of adaptive destruction. We characterize the Markov perfect equilibria that arise and study the incentive and welfare effects of the two IPR regimes of interest.

3.2 IPRs and Crop-Improving R&D in Agriculture

The need to account explicitly for the nature of IPRs is given more urgency by the dramatic changes that have characterized the R&D enterprise in crop improvements and biotechnology over the last quarter of a century. Intellectual property protection in these areas has been strengthened enormously, leading to what amounts to a revolution in the set of opportunities facing innovators (Wright and Pardey, 2006). In the United States, following the 1980 landmark

U.S. Supreme Court decision in *Diamond v. Chakrabarty*, a major change has been the extension of the applicability of standard utility patents to virtually any biologically based invention, if obtained through human intervention. That utility patents can be used for the products of plant breeding and biotechnology in agriculture was confirmed by the 2001 U.S. Supreme Court ruling in *J.E.M. Ag Supply, Inc. v. Pioneer Hi-Bred International, Inc.*, which held that plant seeds and plants themselves (both traditionally bred or produced by genetic engineering) are patentable under U.S. law (Janis and Kesan, 2002).

Whereas the availability of utility patents for plant and animal innovations has also been introduced in many other developed countries, in most developing countries PBRs remain the strongest IPR protection instrument available. Indeed, in the international context the impetus to harmonize and strengthen IPRs in agriculture has resulted from the implementation of the TRIPS (trade related aspects of intellectual property rights) agreement of the World Trade Organization (WTO) (Moschini, 2004). A crucial feature of TRIPS is that it mandates that minimum standards of IPR protection be provided by each WTO member in each of the main areas of intellectual property that it covers. Specifically, patent protection must be accorded for both products and processes, for at least 20 years, in almost all fields of technology. But agriculture-related innovations enjoy a somewhat special treatment within TRIPS because plant and animal innovations need not be protected by patents, as long as a suitable *sui generis* protection is offered. Modern agriculture-related R&D relies heavily on biotechnology innovations, as in the development of GM crop varieties, and it turns out that the flexibility provided by TRIPS extends further than plant and animal innovation: "essentially biological processes" may also be excluded from patentability (although patents must be provided for microorganisms, and for microbiological processes for producing plants or animals).

As noted, if plants and animals are excluded from patentability then under TRIPS a *sui generis* IPR system must be provided. PBRs are commonly used internationally for plant varieties and appear to be the *sui generis* IPR system of choice for many countries, including virtually all developing countries. But, unlike utility patents, PBRs allow for a well-defined "research exception." That is, a protected variety may be used by others in their breeding program aimed at developing a new variety. Thus, PBRs are clearly a weaker IPR protection instrument than patents, and whether the feature that separates these two IPR protection modes has important consequences for the innovation enterprise appears to be an important and yet unsettled question.

Concomitant with the rise of the importance of IPRs for agricultural R&D, the last few decades have also witnessed a number of other critical developments. The secular trend in the decline of public R&D relative to private R&D (Fuglie et al., 1996) has intensified, and at present the private sector provides the bulk of biological research efforts in agriculture. Furthermore, the agricultural seed and chemical industry has undergone a tremendous consolidation. The earlier emphasis on the "life sciences" concept was abandoned because of a perceived lack of sufficient synergies between plant and human-health biotechnology. What has emerged, instead, is a strong consolidation between the seed and the agrochemical industrial segments aimed at exploiting the way modern GM varieties can complement and/or substitute for more traditional herbicide and pesticide products. A wave of acquisitions has resulted in a highly concentrated and integrated agro-chemical sector (UNCTAD, 2006).

In what follows, we develop a stylized model of innovation that features the biological resistance problem and the notion of adaptive destruction, and we do so in a more realistic institutional context that is consistent with the critical role played by IPRs and the market structure of the relevant industry. In particular, we compare and contrast the effects of two IPR regimes that differ precisely with respect to the presence of a research exemption, and, based on the foregoing discussion of consolidation in the agro-chemical sector, we cast the analysis in an imperfectly competitive setting (specifically, a duopoly).

3.3 A Model of Sequential Innovation

We imagine a situation in which a biological innovation, such as an improved seed variety resistant to a particular pest, can be developed upon a costly and risky R&D process. Once developed, this innovation is adopted by a competitive sector, which we represent as made up of heterogeneous agents (e.g., farmers), that is, a population of potential costumers with differing willingness to pay for the innovation. Consistent with the notion of adaptive destruction discussed in the introduction, we also postulate that the value of the innovation is stochastically reduced to zero as time goes by. After the value of the existing innovation is thus destroyed, a new R&D process can start to re-introduce the resistance trait of interest into the variety. Whether both firms can take part in this new innovation effort or only the firm that developed the improved variety in the initial innovations state depends on the nature of the IPR system. With an RE regime, both firms can participate in follow-on research. But if the IPR system does not allow for a research exemption (i.e., the FP regime), then we presume that only the winner of the initial stage can engage in efforts to restore the value of the variety after the onset of pest resistance. In either case, the winner of each race becomes the monopolist for the duration of the period in which innovation has a positive market value.

3.3.1 Demand for innovation

The derived demand $D(p)$ for the innovated product protected by IPRs is presumed downward sloping, as in Figure 1 where v denotes the choke price. Given the exclusivity afforded by IPRs, the innovator can price monopolistically at p^M so that, at the quantity demanded by users at that price, the marginal production cost mc equals the marginal revenue mr. *Ex post*, therefore, the innovator can extract a profit equal to π, but some of the innovation's benefits also accrue to users, and relative to the *ex post* first-best use of the innovation there is also a deadweight loss—these two effects are labeled cs and dwl in Figure 1 (e.g., Langinier and Moschini, 2002). To make the model tractable, we postulate that there is a unit mass of end-users whose valuation of the new product is distributed uniformly on the interval $[0, v]$. For any given price of a new product, only users with valuations above that price will make a purchase. This implies that the monopolist faces a linear demand function of the form $D(p) = 1 - p/v$. If the marginal cost of production is constant, as in Figure 1, then without further loss of generality we can write $mc = 0$. Under these assumptions, the monopolist's profit per unit of time is given by $\pi = v/4$. Given this simplified demand structure, the surplus accruing to consumers under this (uniform) monopolistic pricing satisfies $cs = \pi/2$.

3.3.2 Stochastic production of innovation

At the start of the R&D contest, or after the value of innovation is reduced to zero, the firms engage in an R&D race in which the time of discovery is stochastic. As in other strategic R&D models (e.g., Reinganum, 1989), we assume that innovations arrive according to a Poisson process with arrival rate x. Specifically, each firm that incurs a fixed R&D cost c at the start of a race has an instantaneous probability of producing a new product equal to x (Denicolò, 1999), and the resulting stochastic time of the arrival of the innovation $\tau(x)$ is distributed exponentially so that its cumulative distribution function is given by $\Pr\left[\tau(x) \le z\right] = 1 - \exp(-xz)$.

The expected profit of a firm, when the total number of competitors is equal to n, is derived as follows. Denote by τ_i the random time of arrival of innovation for firm i and let $\tau_{\min} = \min\{\tau_1, ..., \tau_n\}$. Then the probability that at least one of firm i's rivals has made a discovery at time z is given by

$$\Pr\left[\tau_{\min} \le z\right] = 1 - e^{-(n-1)xz}. \quad (1)$$

The expected profit of firm i can now be found by integrating the joint density of $(\tau_i, \tau_{\min})$ over the subset of the support in which $\tau_i \le \tau_{\min}$. Let W denote the payoff to the winner of the race.

Then, if r denotes the common discount rate of all firms, the expected profit of firm i when n firms participate in the R&D contest is given by

$$V_i^0 = \int_0^{\infty} \int_s^{\infty} e^{-rs} Wx(n-1)e^{-x(n-1)z} xe^{-xs} dzds - c \tag{2}$$

where, again, c is the fixed R&D cost. Thus,

$$V_i^0 = \frac{xW}{nx+r} - c . \tag{3}$$

3.3.3 Adaptive destruction

A critical element of our model is the explicit modeling of the possible devaluation of the innovation due to pest adaptation. Such an "adaptive destruction" feature is captured by postulating that the value of the new product can be reduced to zero at each point in time with instantaneous probability b. That is, the stochastic arrival of adaptive destruction time τ_{AD} is distributed exponentially so that $\Pr\left[\tau_{AD} \le z\right] = 1 - \exp(-bz)$. Admittedly, this convenient way to parameterize adaptive destruction is somewhat special, and there are other reasonable ways to model this process. In particular, some may find it desirable to postulate that the stochastic process of adaptive destruction leads to a gradual erosion of value. Our assumption that adaptive destruction follows a Poisson process with constant instantaneous probability, however, does capture the essence of biological adaptation while keeping the model tractable. Our specification is also consistent with the parameterization used by Goeschl and Swanson (2003), although they do allow the adaptive destruction to be affected by some variables endogenous to the model (e.g., adoption). Such an extension is not crucial in our setting because our model does not emphasize the diffusion phase of innovation but instead focuses on the R&D strategic interactions brought about by different IPR regimes.

3.4. Duopoly Model of Innovation

As noted in the introduction, we capture the imperfectly competitive industry structure by postulating that there are at most two firms in any stage of the game. At the beginning of each stage both firms decide whether to take part in the race. The winner of each race obtains IPRs that afford exclusivity in the final product market. Upon the onset of adaptive destruction, leading to the loss of market value for the innovated product, the race to produce a new product starts again. In this setting we interpret the RE regime as allowing both firms to enter the improvement race after the value of the innovated crop variety has been reduced to zero by adaptive destruction.

Similarly, we interpret the stronger FP regime as restricting access to the improvement stage that follows adaptive destruction, so that only the winner of the first race has the right to practice the innovation for subsequent improvements. These interpretations are certainly consistent with the distinction between PBRs and patents discussed in the introduction, namely, that a patent gives full control of the improved variety to the innovator whereas PBRs allow others to use the variety for the development of further improvement. In what follows, we characterize the symmetric stationary equilibrium of the infinite horizon game under these two IPR regimes.

3.4.1 Research exemption

Under an RE regime, both firms can enter the race after the value of the crop has been reduced to zero. This implies that the game is essentially a sequence of identical races with two firms in each contest. The solution concept we employ in this paper is that of a Markov perfect equilibrium, i.e., we assume that strategies of the firms can depend only on the current state of the game (Fudenberg and Tirole, 1991). Let $(\sigma_i, \sigma_j) \in [0,1] \times [0,1]$ denote a stationary strategy profile of this game and let $V_0(\sigma_i, \sigma_j)$ denote the expected payoff of firm i at the beginning of the race (i.e., when no firm has yet produced an innovation). Upon arrival of the innovation, the successful firm (which we label the "leader") can market the innovation. But because of the adaptive destruction feature discussed earlier, the value of this innovation is eventually destroyed. When that happens, a new innovation race can start, and under the RE regime both firms can participate. This means that the firm that is not successful in the firm innovation (which we label the "follower") still obtains value from the opportunity to take part in future innovation rounds. Thus, let $V_L(\sigma_i, \sigma_j)$ and $V_F(\sigma_i, \sigma_j)$ denote the expected payoffs of firm i when it is the leader and when it is the follower, respectively. Then these functions are determined by the following conditions:

$$V_0(\sigma_i, \sigma_j) = \sigma_i \sigma_j \left(\frac{xV_L(\sigma_i, \sigma_j) + xV_F(\sigma_i, \sigma_j)}{2x + r} - c \right) + (1-\sigma_i)\sigma_j \frac{xV_F(\sigma_i, \sigma_j)}{x + r} + (1-\sigma_j)\sigma_i \left(\frac{xV_L(\sigma_i, \sigma_j)}{x + r} - c \right) \quad (4)$$

$$rV_L(\sigma_i, \sigma_j) = \pi + b\big(V_0(\sigma_i, \sigma_j) - V_L(\sigma_i, \sigma_j)\big) \quad (5)$$

$$rV_F(\sigma_i, \sigma_j) = b\big(V_0(\sigma_i, \sigma_j) - V_F(\sigma_i, \sigma_j)\big). \quad (6)$$

Equation (4) is the expected profit of firm i for a given strategy profile (σ_i, σ_j). Equation (5) is a standard Bellman equation, which says that the instantaneous return to being the innovation leader in this duopoly equals the flow of profit π from marketing the innovation while it obtains plus the expected loss of value caused by the possibility of adaptive destruction. The Bellman equation (6) exhibits the property that there is value to being in this duopoly industry, even without any marketable product, because the possibility of adaptive destruction entails (in the RE regime) the possibility of taking part in future (and potentially profitable) R&D contests. The following proposition characterizes the Markov perfect equilibrium (MPE) of the game under the RE regime.

Proposition 1. The symmetric MPE under the RE regime is given by the strategy profile $(\sigma_{RE}, \sigma_{RE})$ that satisfies the following conditions:

(i) $\sigma_{RE} = 1$, if $\frac{c}{\pi} \le t_1^{RE}$

(ii) $\sigma_{RE} \in (0,1)$, if $t_1^{RE} < \frac{c}{\pi} < t_0$

(iii) $\sigma_{RE} = 0$, if $\frac{c}{\pi} \ge t_0$

where

$$t_1^{RE} \equiv \frac{x}{(r+b)(2x+r)} \tag{7}$$

$$t_0 \equiv \frac{x}{(r+b)(x+r)}. \tag{8}$$

A detailed proof of this result is provided in the Appendix, which also reports an explicit expression for the σ_{RE} that applies to the case (ii).

The fact that the two firms are *ex ante* identical justifies interest in the symmetric MPE. In such a context, a pure strategy equilibrium in which both firms invest with probability one emerges when the R&D cost c is sufficiently low (relative to the per-period payoff π), that is, when $c/\pi \le t_1^{RE}$. Similarly, when R&D cost is too high, that is, when $c/\pi \ge t_0$, both firms abstain from investing. Finally, for intermediate values of the R&D cost, that is, when $t_1^{RE} < c/\pi < t_0$, either firm would be willing to invest conditional on the other firm abstaining. In addition to such asymmetric pure strategy equilibria, there is a symmetric mixed strategy MPE in which each firm invests with probability $\sigma_{RE} \in (0,1)$, as per Proposition 1. The particular value of this probability, as well as the value of the threshold levels t_1^{RE} and t_0, of course depends on the primitive parameters of the model (i.e., the Poisson arrival rates x and b, and the discount rate r).

3.4.2 Full patent

Under the FP regime, the winner of the first race is the only one who has the right to practice the innovation for subsequent improvements. Let V_m denote the value to the monopolist who has the property rights for the (existing) improved variety that is sold in the market, and let V_0^{FP} denote the expected profit of the firm that has the exclusive right (because of the FP regime) to engage in the R&D process in order to produce the next generation of a product. Recalling equation (3), these value functions must satisfy

$$V_0^{FP} = \frac{xV_m}{x+r} - c \tag{9}$$

as well as the asset equation

$$rV_m = \pi + b\left(V_0^{FP} - V_m\right). \tag{10}$$

Solving for the value functions we obtain

$$V_m = \frac{(\pi - bc)(x+r)}{(r+b)(x+r)-bx}, \tag{11}$$

$$V_0^{FP} = \frac{(\pi - bc)x - c(r+b)(x+r) - bx}{(r+b)(x+r)-bx}. \tag{12}$$

Recall that under the FP regime there is only one race at the start of the game, the winner of which will exclude the other firm from trying to improve the product in the future. In order to solve for the equilibrium we need to find the optimal strategies of the two firms in the initial race. The equilibrium under the FP regime is described in the following proposition.

Proposition 2. The symmetric MPE under FP regime is given by the strategy profile $(\sigma_{FP}, \sigma_{FP})$ that satisfies the following conditions:

(i) $\sigma_{FP} = 1$, if $\frac{c}{\pi} \leq t_1^{FP}$

(ii) $\sigma_{FP} \in (0,1)$, if $t_1^{FP} < \frac{c}{\pi} < t_0$

(iii) $\sigma_{FP} = 0$, if $\frac{c}{\pi} \geq t_0$

where t_0 is still defined as in equation (8), and

$$t_1^{FP} \equiv \frac{x(x+r)}{(2x+r)(x+r+b)r+bx(x+r)}. \qquad (13)$$

A detailed proof of this result is provided in the Appendix, which also reports an explicit expression for the σ_{FP} that applies to the case (ii).

As for the case of the RE regime, we find that the symmetric MPE can involve pure strategies with both firms investing when the R&D cost is low enough (relative to the per-period payoff π), or with both firms not investing when the R&D cost is too high. For a specific domain of the cost-to-profit ratio, specifically $t_1^{FP} < c/\pi < t_0$, the two firms follow an equilibrium mixed strategy. It is informative to observe the relationship between threshold levels under the two regimes. First, note that the parameter t_0 is common to both regimes. Next, from the expressions given in (7) and (13) it can be verified that $t_1^{FP} > t_1^{RE}$. This result is intuitive because it implies that the level of the cost-to-profit ratio at which both firms start to invest with probability one is higher when the winner becomes a monopolist in the improvement game. A comparison of the two IPR regimes' equilibria is given in Figure 2.

3.5 Comparing IPR Alternatives: *Ex Ante* Profits

Having characterized the various equilibria that can emerge in our R&D model, we can now compare the economic implications of the two IPR regimes of interest. Consider first the *ex ante* expected payoff to the two firms. When firms follow a non-degenerate mixed strategy, they must be indifferent between the actions upon which they are randomizing. Given that not investing entails a zero expected payoff, it follows that the expected payoff of a mixed strategy that assigns nonzero probability to not investing is itself zero. Hence, we know that (a) in the interval $[t_1^{FP}, t_0]$, profits are zero under both IPR regimes; (b) in the interval $[t_1^{RE}, t_1^{FP}]$, profits are zero under the RE regime, and positive under the FP regime; and (c) in the interval $[0, t_1^{RE}]$, profits are positive under both IPR regimes.

In the interval $[0, t_1^{FP}]$, both firms invest with probability one under the FP regime. Recalling equation (3), the *ex ante* expected profit of each firm in this case is given by

$$\Pi_0^{FP} = \frac{V_m x}{2x+r} - c \qquad (14)$$

where V_m is the value of being the monopolist of the innovation (and of the right to pursue further innovations, upon the onset of pest resistance), as defined earlier. By using equation (11) we find that the *ex ante* expected profit can be written as $\Pi_0^{FP} = \pi\alpha_{FP} - c\beta_{FP}$, where

$$\alpha_{FP} \equiv \frac{x(x+r)}{(2x+r)(r+b+x)r} \tag{15}$$

and $\beta_{FP} \equiv 1 + b\alpha_{FP}$.

Similarly, in the interval $[0, t_1^{RE}]$, both firms invest with probability one under the RE regime. By using the expression of the proof of Proposition 1 in the Appendix, when $\sigma_i = \sigma_j = 1$, the *ex ante* expected profit of each firm can be written as $\Pi_0^{RE} = \pi\alpha_{RE} - c\beta_{RE}$, where

$$\alpha_{RE} \equiv \frac{x}{(2x+r+b)r} \tag{16}$$

$$\beta_{RE} \equiv \frac{(2x+r)(r+b)}{(2x+r+b)r}. \tag{17}$$

From the foregoing equations it follows that $\alpha_{RE} > \alpha_{FP}$, and also that $\beta_{RE} > \beta_{FP}$. It follows that, for a given π, for low values of the cost parameter c the *ex ante* expected profit is higher under the RE regimes, whereas for higher values of the cost parameter the FP regime yields higher *ex ante* expected profit. More specifically, the ranking of *ex ante* expected profit under the two IPR regimes can be summarized as in the following proposition.

Proposition 3. The firm's expected profit under the RE regime is higher than the expected profit under the FP regime if and only if $\frac{c}{\pi} \leq \frac{\alpha_{RE} - \alpha_{FP}}{\beta_{RE} - \beta_{FP}} \equiv \tilde{t}$.

Figure 3 illustrates the expected profit functions under the two IPR regimes for a given level of the per-period profit (i.e., varying only the cost parameter while keeping the profit parameter fixed). In this graph, the threshold $\tilde{t}$, as defined in Proposition 3, is the point at which $\Pi_0^{RE} = \Pi_0^{FP}$. As established in Proposition 3, Figure 3 shows that firms will *ex ante* prefer the RE regime—the weaker of the two IPR regimes—if c is low enough, that is, as long as $c/\pi \leq \tilde{t}$.

The intuition for this result can be obtained by considering the objective functions of each firm under the two IPR regimes when both firms invest with probability one in equilibrium, which happens in the interval $[0, \tilde{t}]$. From equation (4) we know that when both firms invest with probability one the *ex ante* expected profit can be written as

$$\Pi_0^{RE} = \frac{2x\left(0.5V_L(1,1) + 0.5V_F(1,1)\right)}{2x+r} - c \tag{18}$$

where $V_L(1,1)$ and $V_F(1,1)$ are defined in equations (5) and (6). Note that this can be interpreted as if each firm could pay amount c to get a lottery with equal chances of becoming the leader and the follower, with corresponding expected payoff discounted by the factor $\frac{2x}{2x+r}$. On the other hand, from equation (14) we can write

$$\Pi_0^{FP} = \frac{2x\left(0.5V_m\right)}{2x+r} - c. \tag{19}$$

Similarly to the RE regime, this can be interpreted as each firm obtaining a lottery with equal probabilities of becoming a monopolist and dropping out of the race.

By comparing equations (18) and (19), it is now clear that the firm's *ex ante* profits are higher under the RE regime if and only if

$$V_L(1,1) + V_F(1,1) \geq V_m. \tag{20}$$

In other words, this would be the case when the expected payoff of the industry with two firms both investing with probability one is higher than the expected payoff of the industry with only one firm investing with probability one. Note that industry with two firms will have both higher R&D costs and a higher arrival rate of innovation, resulting in larger total profit when the R&D cost is close to zero, as was previously shown.

This finding that firms may, *ex ante*, prefer the RE regimes is similar to the result of Bessen and Maskin (2002), who show that sometimes firms might prefer a weaker IP regime before the start of a race. This result in Bessen and Maskin arises because of the authors' assumption that innovations are complementary (diversity of innovation increases the probability of discovery, which is essential to keep the innovation process going). In our model, the downside of the FP regime from a firm's *ex ante* perspective is that losing the first innovation stage forecloses the possibility of profitable innovations in the future. This lost opportunity is particularly valuable when the R&D cost is relatively low.

3.6 Comparing IPR Alternatives: Welfare

In addition to the profit flowing to the firms, for the welfare comparison of the two IPR regimes we need to account for the surplus that flows to consumers whenever an innovation is commercialized (recall Figure 1).

3.6.1 Expected consumer surplus

Considering the RE regime first, let S_0^{RE} denote the *ex ante* expected surplus to consumers when the IPR system allows for a research exemption. Also, let S_1^{RE} denote the expected consumer surplus, under this regime, whenever a successful innovation is achieved. Then S_0^{RE} and S_1^{RE} must satisfy the following asset equations:

$$S_0^{RE} = (\sigma_{RE})^2 \frac{2xS_1^{RE}}{2x+r} + 2\sigma_{RE}(1-\sigma_{RE})\frac{xS_1^{RE}}{x+r} \tag{21}$$

$$rS_1^{RE} = \frac{\pi}{2} + b(S_0^{RE} - S_1^{RE}). \tag{22}$$

As can be seen from the equation (21), the expected *ex ante* surplus depends on the number of firms investing in R&D. With probability $(\sigma_{RE})^2$ both firms invest in R&D, and with probability $2\sigma_{RE}(1-\sigma_{RE})$ there is a single firm in the race. In the latter case the expected time until the arrival of innovation is longer, with instantaneous probability of discovery equal to x (as opposed to $2x$ when both firms invest). Equation (22) is a standard Bellman equation and represents the flow of consumer surplus from the existing innovation. According to this equation, the instantaneous expected return to consumers to having an innovation (i.e., rS_1^{RE}) is equal to the flow of consumer surplus while the innovation lasts (i.e., $\pi/2$) plus the expected loss of this surplus due to the possibility of adaptive destruction (i.e., $b(S_0^{RE} - S_1^{RE})$).

Solving equations (21) and (22) yields

$$S_0^{RE} = \frac{\pi x\left[\sigma_{RE}(2x+r) - (\sigma_{RE})^2 x\right]}{(r+b)(2x+r)(x+r) - 2bx\left[\sigma_{RE}(2x+r) - (\sigma_{RE})^2 x\right]}, \tag{23}$$

To derive the consumer surplus under the FP alternative, consider the moment at which a firm has won the initial R&D contest such that this firm can now market the innovation at a profit flow of π (as long as resistance does not arise). Upon the onset of resistance, the FP regime gives the firm the sole right to research for an improvement that overcomes the resistance. In such a setting, let S_1^{FP} denote the expected consumer surplus when there is an innovation at hand, and let S_m denote the expected consumer surplus when no innovation is available and only one firm (a monopoly) has the right to invest in R&D. Then S_1^{FP} and S_m must satisfy the following asset equations:

$$S_m = \frac{xS_1^{FP}}{x+r} \tag{24}$$

$$rS_1^{FP} = \frac{\pi}{2} + b(S_m - S_1^{FP})\,. \tag{25}$$

Solving these two equations yields

$$S_1^{FP} = \left(\frac{\pi}{2}\right)\frac{x+r}{(x+r+b)r}\,. \tag{26}$$

Now let S_0^{FP} denote the *ex ante* expected consumer surplus under the FP regime. Given the equilibrium strategy profile, this expected consumer surplus would be equal to

$$S_0^{FP} = (\sigma_{FP})^2 \frac{2xS_1^{FP}}{2x+r} + 2\sigma_{FP}(1-\sigma_{FP})\frac{xS_1^{FP}}{x+r}\,. \tag{27}$$

Using the solution in equation (26), it follows that

$$S_0^{FP} = \frac{\pi x}{(x+r+b)r}\left(\frac{\sigma_{FP}(2x+r)-(\sigma_{FP})^2 x}{(2x+r)}\right). \tag{28}$$

3.6.2 Welfare comparison: Analytic results

By using the foregoing derivation for S_0^{RE} and S_0^{FP}, we can unambiguously rank social welfare when the cost of R&D, relative to the potential payoff of the innovation, in not too high.

Proposition 4. The RE regime results in a higher level of social welfare if $\frac{c}{\pi} \in [0, \tilde{t}\,]$.

To see why this result must hold, evaluate equations (23) and (28) at $\sigma_{FP} = \sigma_{RE} = 1$. It can then be verified that when both firms invest with probability one, the consumer surplus functions satisfy $S_0^{RE}(1) > S_0^{FP}(1)$, and so we conclude that in the domain of interest, the RE regime results in a higher level of social welfare. This result is very intuitive. Because both firms invest with probability one under either regime in the domain $c/\pi \in [0, t_1^{RE}]$, the RE regime results in a higher rate of innovation for all improvement stages (after the onset of resistance), and so in this domain consumers are necessarily better off under the RE regime. Furthermore, as long as $c/\pi \in [0, \tilde{t}\,]$, we have shown that firms also *ex ante* prefer the RE regime. Because $\tilde{t} < t_1^{RE}$, we can then conclude that in the domain of interest social welfare is higher with the RE regime.

3.6.3 Welfare comparison: Numerical results

Proposition 4 does not rank the two IPR regimes when R&D cost is sufficiently high, that is, when $c/\pi \in [\tilde{t}, t_0]$. To compare social welfare in this domain, we need to take into account the types of equilibria that can occur. In particular, we have to distinguish three cases:

(A) $\frac{c}{\pi} \in [t_1^{FP}, t_0]$. In this interval, firms' profits are equal to zero under both regimes, so the social welfare under both regimes is equal to the corresponding consumer surplus.

(B) $\frac{c}{\pi} \in [t_1^{RE}, t_1^{FP}]$. In this interval, firms make positive profit under the FP regime, and social welfare under the FP regime is equal to the sum of profits and consumer surplus.

(C) $\frac{c}{\pi} \in [\tilde{t}, t_1^{FP}]$. In this interval, firms make positive profit under both regimes, and both welfare functions are equal to the sum of profit and consumer surplus.

Because the equilibrium strategies σ_{FP} and σ_{RE} are in general functions of π and c parameters (see the Appendix), it does not appear possible to provide an analytic result that would establish unambiguously the welfare ranking of the two IPR regimes. To gain some insights, here we resort to comparing welfare numerically. In particular, we normalize profit to be equal to one $(\pi = 1)$ and study social welfare as a function of c for a given set of parameter values. We calibrate the model so that the resulting durations of an innovation race and the useful life of a new variety are broadly consistent with what is observed in the plant breeding industry. In particular, we perform our numerical analysis for the following parameters values. The discount factor is fixed at $r = 0.05$. The arrival rate of innovation x is equal to either 0.25 or 0.125, which corresponds to the expected times until discovery of 4 or 8 years, respectively. The destruction rate b is equal to 0.2, 0.1, or 0.05, which corresponds to the expected lifetime of a new variety of 5, 10, or 20 years, respectively. The resulting threshold values (which determine the domains of equilibria A, B, and C for which numerical analysis is performed) are given in Table 1.

For each pair (x, b) we computed the social welfare functions under RE and under the FP regimes on the interval $c \in [\tilde{t}, t_0]$ (we already know the welfare ranking for the range $c \in [0, \tilde{t}]$ from Proposition 4). These computed welfare levels are graphed in Figure 4, where welfare is measured on the vertical axes and R&D cost on the horizontal axes (welfare under the RE regimes is represented by the dashed line and welfare under the FP regime is represented by the solid line).

Consistent with what was established in Proposition 4, at $c = \tilde{t}$ social welfare is higher under the RE regime. But as c increases, the numerical analysis shows that at some point the FP regime dominates. Hence, this suggests the general conclusion that for the parameter values, which reflect the nature of the plant breeding industry, the FP regime is socially optimal when the cost of innovation is relatively high. In this case the stronger incentives provided by the FP regime lead to a higher flow of innovations and higher social welfare. On the other hand, when the cost of R&D is relatively low, a weaker intellectual property regime such as RE is beneficial from the social point of view. Additional numerical analysis, not reported here, shows that this general conclusion appears robust to changes in the underlying parameter values well outside the range explored in Figure 4.

3.7 Conclusion

The analysis of this paper contributes to the discussion of economic policies that may mitigate problems caused by pest resistance. In contrast to much of the previous literature, which deals with this issue within the renewable or non-renewable resource framework, this study has focused on the role of an institutional factor that is having an increasing influence on the R&D process in plant breeding, namely, the nature of intellectual property rights. In particular, we construct an explicit model of the two types of intellectual property regimes that are widely used to protect plant innovations and study the effect of the resulting market structure on the incentive to invest in plant breeding R&D and social welfare. The two types of intellectual property protection in question are those provided by utility patents and those provided by Plant Variety Protection certificates. The latter intellectual property regime results in a weaker form of protection because it allows for a well-defined research exemption provision. We specifically focus on the adaptive destruction process, which arises because of the reduction of the market value of the crops due to pest adaptation.

The model that we have analyzed is necessarily very stylized, yet it yields some interesting analytic and numerical results. Specifically, we find that the welfare ranking of the intellectual property regimes depends on the cost-to-profit ratio. In our model, the R&D activity requires a fixed outlay at the start of the innovation race, which can be interpreted as the cost of starting and maintaining a new plant breeding program. The analytic results established in this paper imply that when the cost is relatively low, the research exemption regime yields a higher welfare. Our numerical results suggest that for a high cost-to-profit ratio it is the full patent regime that provides better incentives to invest in R&D and yields higher social welfare. These results are established by calibrating the model so that the expected durations of innovation and adaptive destruction processes are broadly representative of the plant breeding industry. An additional result established in this paper implies that when the value of the cost-to-profit ratio is low, firms *ex ante* prefer the research exemption regime, even though it is a weaker form of protection (this conclusion is similar to that obtained by Bessen and Maskin [2002] in a different model of sequential innovation).

In addition to deriving the profit and welfare effects of alternative intellectual property regimes used in the plant breeding, the analysis of this paper also emphasizes that the form of intellectual property rights defines the market structure of the industry, and that this market structure will not necessarily coincide with the two extreme cases of monopoly and perfect competition that have been the focus of the majority of previous studies. Future work toward the derivation of cogent implications for policymakers concerned with the adaptive destruction problem, therefore, may need to account more explicitly for the (sometimes subtle) effects of alternative institutions that establish and strengthen intellectual property rights.

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3.9 Tables

Table 1. Threshold values

$x = 0.125, b = 0.1$	$\tilde{t} = 1.32$	$t_1^{RE} = 2.78$	$t_1^{FP} = 3.47$	$t_0 = 4.76$
$x = 0.25, b = 0.1$	$\tilde{t} = 1.02$	$t_1^{RE} = 3.03$	$t_1^{FP} = 4.05$	$t_0 = 5.56$
$x = 0.125, b = 0.05$	$\tilde{t} = 1.69$	$t_1^{RE} = 4.17$	$t_1^{FP} = 4.89$	$t_0 = 7.14$
$x = 0.25, b = 0.05$	$\tilde{t} = 1.22$	$t_1^{RE} = 4.55$	$t_1^{FP} = 5.61$	$t_0 = 8.33$
$x = 0.125, b = 0.2$	$\tilde{t} = 0.91$	$t_1^{RE} = 1.67$	$t_1^{FP} = 2.19$	$t_0 = 2.86$
$x = 0.25, b = 0.2$	$\tilde{t} = 0.77$	$t_1^{RE} = 1.82$	$t_1^{FP} = 2.61$	$t_0 = 3.33$

3.10 Figures

Figure 1. Demand for innovation

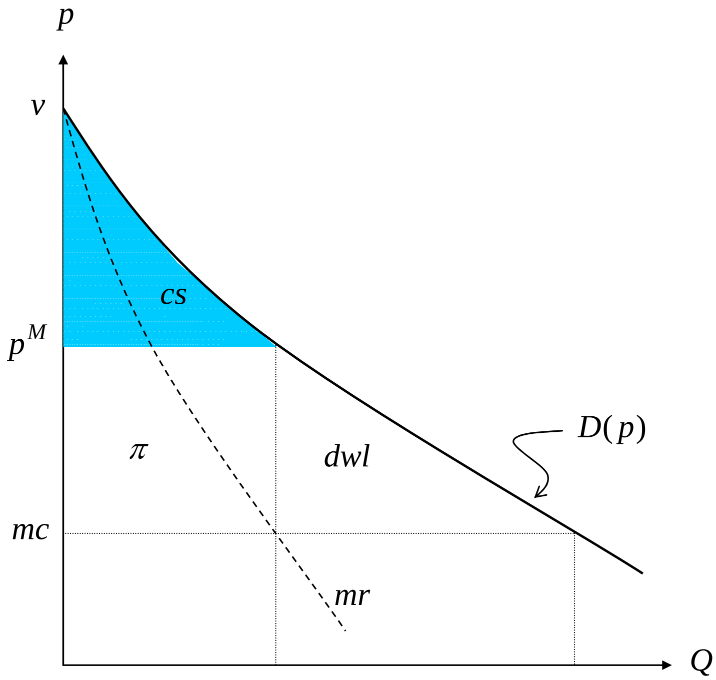


Figure 2. Equilibria under the two IPR alternatives

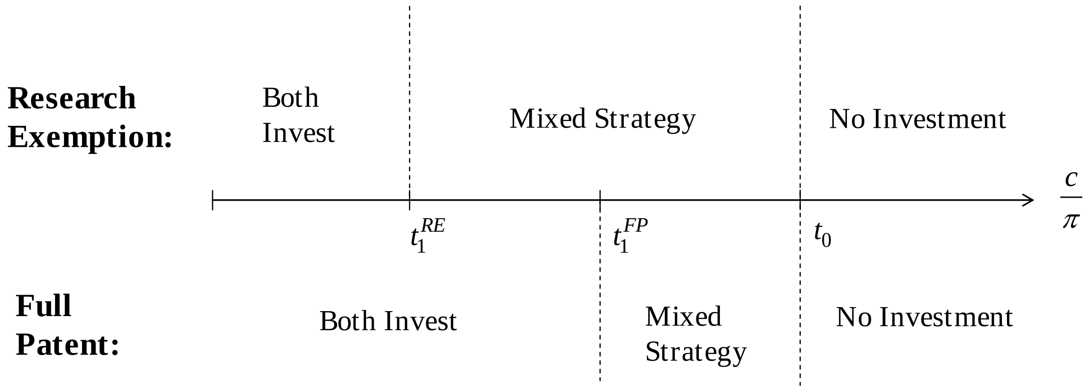


Figure 3. Comparison of *ex ante* profits

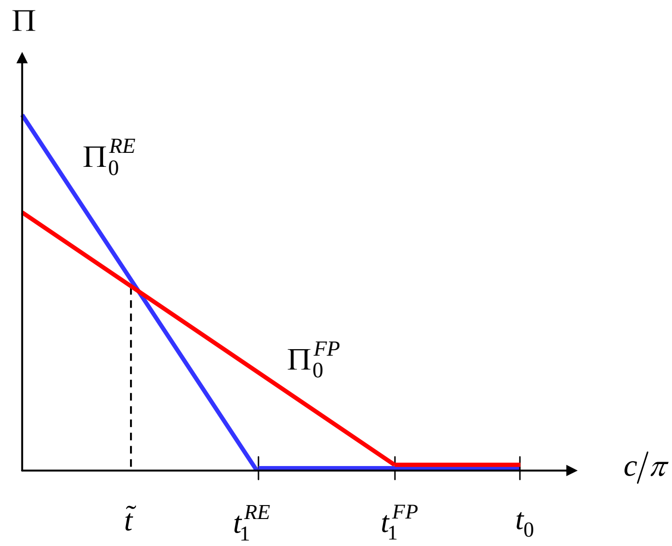
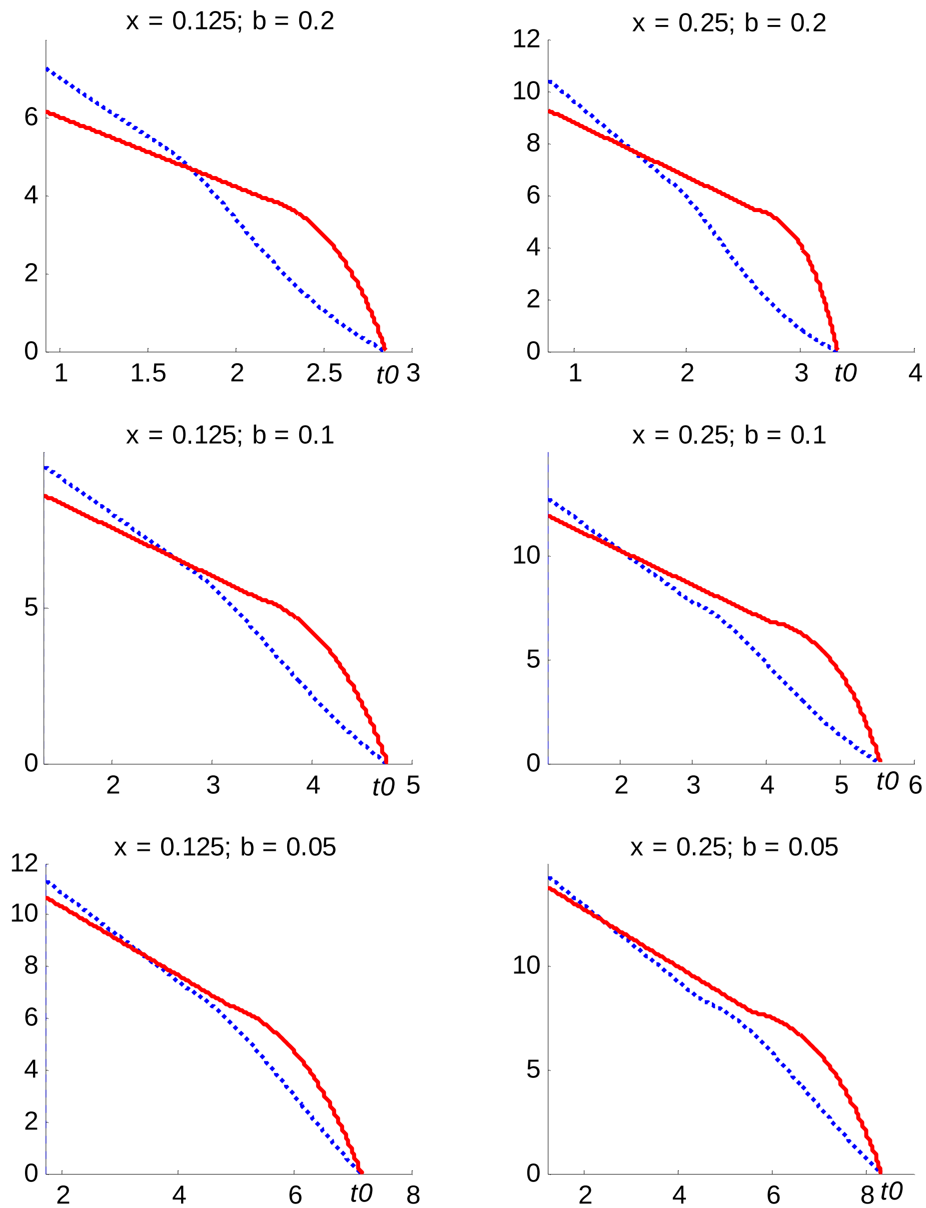


Figure 4. Welfare under FP (solid line) and RE (dashed line) regimes



3.11 Appendix

3.11.1 Proof of Proposition 1 (RE regime)

Substituting (5) and (6) into (4) we obtain

$$V_0(\sigma_i,\sigma_j)=\sigma_i\sigma_j\left(\frac{x}{(2x+r)}\frac{\pi}{(r+b)}+\frac{2x}{(2x+r)}\frac{bV_0(\sigma_i,\sigma_j)}{(r+b)}\right)+(1-\sigma_i)\sigma_j\left(\frac{x}{x+r}\right)\frac{bV_0(\sigma_i,\sigma_j)}{r+b}$$
$$+(1-\sigma_j)\sigma_i\left(\frac{x}{x+r}\frac{\pi+bV_0(\sigma_i,\sigma_j)}{r+b}\right)-c(\sigma_i\sigma_j+(1-\sigma_j)\sigma_i)$$

Rearranging:

$$V_0(\sigma_i,\sigma_j)=\frac{1}{\Phi(\sigma_i,\sigma_j)}\left[\sigma_i\sigma_j\frac{x}{(2x+r)}\frac{\pi}{(r+b)}+(1-\sigma_j)\sigma_i\frac{x}{(x+r)}\frac{\pi}{(r+b)}-c\sigma_i\right],$$

where

$$\Phi(\sigma_i,\sigma_j)\equiv 1-\frac{2xb\sigma_i\sigma_j}{(2x+r)(r+b)}-\frac{xb\left((1-\sigma_i)\sigma_j+(1-\sigma_j)\sigma_i\right)}{(x+r)(r+b)}.$$

Part (i). First note that if $\sigma_j=1$, then

$$V_0(\sigma_i,\sigma_j)=\frac{\sigma_i}{\Phi(\sigma_i,1)}\left[\frac{x}{(2x+r)}\frac{\pi}{(r+b)}-c\right].$$

Note also that the first term $\frac{\sigma_i}{\Phi(\sigma_i,1)}=\sigma_i\left(1-\frac{xb}{(x+r)(r+b)}\left(1+\frac{r\sigma_i}{2x+r}\right)\right)^{-1}$, is increasing in σ_i.

This implies that if $\frac{x}{(2x+r)}\frac{1}{(r+b)}>\frac{c}{\pi}$ then $\sigma_i=1$ is the best response and both firms invest with probability 1 in equilibrium.

Part (ii). For notational simplicity let $\sigma_{RE}\equiv\sigma^*$. In the interior equilibrium, firm i is indifferent between investing and not for any given σ_j. Then the equilibrium symmetric strategy $\sigma_i=\sigma_j=\sigma^*$ must satisfy $V_0(1,\sigma^*)=V_0(0,\sigma^*)$, that is,

$$\frac{1}{\Phi(1,\sigma^*)}\left[\sigma^*\frac{x}{(2x+r)}\frac{\pi}{(r+b)}+(1-\sigma^*)\frac{x}{(x+r)}\frac{\pi}{(r+b)}-c\right]=0$$

from which we can solve

$$\sigma^*=\frac{(2x+r)}{x}\left(1-\frac{c}{\pi}\frac{(r+b)(x+r)}{x}\right).$$

Next, the condition $0<\sigma^*<1$ implies that this solution applies if and only if

$$\frac{x}{(r+b)(2x+r)} < \frac{c}{\pi} < \frac{x}{(r+b)(x+r)}.$$

Part (iii). Note that if $\sigma_j = 0$ then

$$V_0(\sigma_i, \sigma_j) = \frac{\sigma_i}{\Phi(\sigma_i, 0)} \left[\frac{x}{(x+r)} \frac{\pi}{(r+b)} - c \right].$$

Clearly, if $\frac{x}{(x+r)} \frac{1}{(r+b)} < \frac{c}{\pi}$, then $\sigma_i = 0$ is a best response and none of the firms invests in equilibrium.

3.11.2 Proof of Proposition 2 (FP regime)

Consider the initial stage of the game. For a given strategy profile $(\sigma_i, \sigma_j) \in [0,1]^2$ the payoff of firm i in the initial stage is given by

$$V_0(\sigma_i, \sigma_j) = \sigma_i \sigma_j \left(\frac{V_m x}{2x+r} - c \right) + \sigma_i (1 - \sigma_j) \left(\frac{V_m x}{x+r} - c \right),$$

or, rearranging,

$$V_0(\sigma_i, \sigma_j) = \sigma_i \left(\frac{V_m x}{x+r} \left(1 - \frac{\sigma_j x}{2x+r} \right) - c \right).$$

Part (i). Note that if $\sigma_j = 1$ we have

$$V_0(\sigma_i, \sigma_j) = \sigma_i \left(\frac{V_m x}{2x+r} - c \right).$$

This implies that if $\frac{V_m x}{2x+r} \geq c$ then $\sigma_i = 1$ is the best response and both firms invest with probability 1 in equilibrium. Substituting for V_m yields

$$\frac{c}{\pi} \leq \frac{x(x+r)}{(2x+r)(x+r+b)r + bx(x+r)}.$$

Part (ii). For notational simplicity let $\sigma_{FP} \equiv \sigma^*$. In the interior equilibrium, firm i is indifferent between investing and not for any given σ_j. Then the equilibrium symmetric strategy profile $\sigma_i = \sigma_j = \sigma^*$ must satisfy $V_0(1, \sigma^*) = V_0(0, \sigma^*)$, from which we obtain

$$\sigma^* = \frac{V_m x - c(x+r)}{V_m x} \left(\frac{2x+r}{x} \right).$$

Again, the condition $0 < \sigma^* < 1$ implies that this solution applies if and only if

$$\frac{x(x+r)}{(2x+r)(x+r+b)r+bx(x+r)} < \frac{c}{\pi} < \frac{x}{(r+b)(x+r)}.$$

Part (iii). Note that if $\sigma_j = 0$, then

$$V_0(\sigma_i, \sigma_j) = \sigma_i \left(\frac{V_m x}{x+r} - c \right).$$

This implies that if $\frac{V_m x}{x+r} \le c$ then $\sigma_i = 0$ is the best response and none of the firms invests in equilibrium. This condition can be further simplified, by using the expression for V_m, to obtain

$$\frac{c}{\pi} \ge \frac{x}{(x+r)(r+b)}.$$

CHAPTER 4. UNOBSERVED HETEROGENEITY AND THE URBAN WAGE PREMIUM

4.1 Introduction

It has been long established that workers in large metropolitan areas earn higher wages than observationally equivalent workers living elsewhere. In a recent study Glaeser and Mare (2001) report that workers residing in metropolitan areas receive an average wage premium ranging from 19% to 33% over workers living in non-metro areas, and point out that the magnitude of the premium is larger than, for example, the racial wage gap. Whereas the existence of a urban wage premium is well documented, understanding the forces behind this phenomenon is still an open question. It is clear that any possible explanation of the urban wage premium must address two obvious questions. First, why do workers in non-metro areas not take advantage of the urban wage premium by migrating to larger cities? Second, why do firms stay in cities if the price of labor is much lower in non-metro areas?

In most empirical studies, the first question is often dealt with by arguing that after accounting for cost of living and site-specific amenities, real wages are the same in urban and non-urban regions. This argument, first proposed by Roback (1982), undoubtedly explains at least some part of the wage premium. While theoretically appealing, this hypothesis has little empirical content because it is difficult to refute it in practice. Indeed, if the wage premium remains after accounting for various area specific characteristics, one can always claim that some unobserved factors were omitted from the consideration (Glaeser and Mare (2001)). On the other hand, alternative explanations of differences between labor quality across different geographical labor markets (Johnson(1953)) have received little systematic attention in the literature. As we will argue below, if workers' unobserved ability is not independent of the place of residence, then empirical studies that ignore this possibility might produce misleading results.

The second question (why do firms stay in cities) has been subjected to an extensive theoretical analysis. In particular, various forms of agglomeration economies, such as lower transportation cost, faster learning and knowledge spillovers all offer a rationale for the higher marginal product of labor in densely populated areas. These theories usually deliver precise testable implications. For example, if lower input cost and knowledge spillovers make firms more productive in densely populated areas (Ciccone and Hall (1996)), then workers moving from non-urban to urban areas must experience discontinuous wage increases. On the other hand, if higher urban density facilitates more productive interactions between people (Glaeser (1999)) or results in low search frictions, then the wages of workers who move into urban areas must increase gradually over time.

These theories enjoy some degree of empirical support. For example, both Glaeser and Mare (2001) and Yankow (2006) find that movers into large cities tend to experience faster wage growth. Similarly, Wheeler (2006) finds evidence of faster wage growth in urban areas using the National Longitudinal Survey of Youth (NLSY) data set. He argues that this effect is mostly due to the large number of job-to-job transitions, as opposed to the faster wage growth on the same job. This evidence supports the theory that the average quality of a match is higher and search frictions are lower in the urban areas.

It must be noted that the way these studies address potential difference in unobserved ability levels across urban and non-urban areas raises concerns about the validity of such empirical findings. In particular, these studies tend to concentrate on measuring various forms of agglomeration effects while leaving the location decisions of individual workers in the background. In this paper we will argue that subjecting the location decisions of workers to careful analysis might improve our understanding the urban wage premium. In particular, it is widely agreed that the labor migration process is best viewed as endogenous and related to individual workers' characteristics. This naturally leads to the possibility that the urban wage premium might result, at least in part, from differences in workers' quality across the two regions. For example, Fucsh (1967) argues that ``... one of the most promising hypotheses to explain the city-size differential is that it reflects differences in labor quality not captured by standardization for color, age, sex, and education. This might take the form of better quality schooling, more on-the-job training, selective in-migration to the big cities of more ambitious and hard working persons, or other forms."

This difference in unobserved ability of the workforce, however, is difficult to control for in a simple regression setting because of the possible correlation between unobserved ability and location preferences. Such correlation is quite likely for several reasons. First, various consumption externalities that are present in big cities tend to cater to the richer and more educated segment of the population. Second, higher competition in the dense labor markets of large metropolitan areas naturally attracts the more ambitious and able workers. Careful empirical analysis of the urban wage premium, therefore, must take into account the potential location endogeneity problem. Such an endogeneity makes it difficult to distinguish empirically between the agglomeration externalities present in dense labor markets and the composition effects arising because of the non-random selection of workers into cities of different sizes.

Whereas the possibility of an endogeneity bias is widely acknowledged in the urban wage premium literature, it is rarely dealt with systematically. It is usually either ignored or, if panel data are used, wage regressions with fixed effects are estimated. However, if residential switching is endogenous then both of these estimation methods produce biased and inconsistent estimates. In addition, if workers' skills are priced differently at the margin in urban and non-urban areas, fixed effects will be biased even in the absence of self-selection: for example if skills have higher value in cities, the estimated wage premium will overstate the expected wage increase from moving to the urban area (Yankow (2006)). The direction of the bias is uncertain in general, which makes the interpretation of the obtained estimates of the wage premium difficult.

The goal of this paper is to provide selectivity corrected estimates of the urban wage premium by taking into account the potential endogeneity of workers' location decision. We start by estimating a simple two-equation endogenous treatment model using data from the first wave of the National Survey of Families and Households, which provides data from a nationally representative sample of working age individuals and their families. Using the number of children under the age of eighteen as an instrument for residential choice, we show that although the estimate of the urban wage premium is equal to 17% if estimated by OLS regression, after controlling for possible endogenous selection it becomes negative (but not significantly different from zero at the 5% level). We also find that the hypothesis of no correlation between errors in the wage and selection equations is rejected.

Next, we generalize our results by estimating a two-sector version of the Roy (1951) model which allows for a more general pattern of correlation of the sector-specific errors in the wage equations. We find substantial evidence of non-random selection into urban and non-urban areas. More importantly, we show that estimates of the urban wage premium are highly sensitive to the random selection assumption. In addition, we find that the returns to observable characteristics differ markedly between urban and non-urban sectors. In general, these results suggest the presence of an endogeneity bias in OLS estimates and indicate that selection on unobservables can potentially explain a substantial part of the observed urban wage premium.

The rest of the paper proceeds as follows: section 2 presents some preliminary evidence that suggests that ability levels might differ across urban and non-urban areas. Section 3 outlines two econometric models that could be used to estimate the magnitude of the urban wage premium while controlling for endogenous selection. Section 4 describes the data used in the analysis. Section 5 discusses empirical findings and section 6 concludes.

4.2 Preliminary Evidence

To obtain a preliminary view of the extent of potential ability bias we follow the formal argument outlined by Glaeser and Mare (2001) in their study of the urban wage premium. In particular, let ϕ_j denote the efficiency units of labor of individual j. In this context ϕ_j represents a measure of ability of person j, broadly defined to include both observed and unobserved ability. Let w_i denote the price per efficiency unit of labor in location i and P_i be the consumer price level at this location. Then, as shown by Glaeser and Mare (2001) the following equality must hold in equilibrium

$$\hat{W}_i - \hat{W}_k = \hat{\phi}_i - \hat{\phi}_k + \ln(P_i / P_k)$$

where $\hat{W}_s$ and $\hat{\phi}_s$ denote the logarithm of the geometric mean of wages and ability levels in city s, respectively. This equation implies that if the real wages are different between metro and non-metro areas, then it must be the case that ability levels are different between these areas.

We use data from the Regional Economic Information System database to conduct a rough test of the hypothesis that cities are equal in the average levels of workers' unobserved ability. The cost of living index developed by DuMond, Hirsch and MacPherson (1999) is used to compare real wages in 1990 in a cross section of major U.S. urban areas and in order to partially adjust for the impact of the city-specific amenities we use data on climatic conditions from Burchfield et al (2006). The results presented in Table 1 indicate that after including cooling and heating degree days, the coefficient on city size increases in magnitude and remains statistically significant. While other city-specific factors affect real wages in that location, it is not possible to predict the direction of the omitted variable bias in the estimates presented above. In particular, while such city characteristics as cultural diversity and product variety are positively correlated with city size, others (such as traffic congestion) are negatively correlated. Furthermore, it must be noted that while city-specific characteristics can potentially explain the difference in real wages, this theory is testable only to the extent that *all* possible amenities can be measured and included in the model. At the same time, these differences are not incompatible with the situation in which the quality of the labor pool differs systematically from one geographical area to the other.

This evidence suggests that the hypothesis that self-selected migration can explain a substantial part of the urban wage premium deserves a closer examination. We proceed by proposing two models which take the endogenous migration decisions into account and estimate them by using the NSFH data.

4.3 Econometric Specification

The simplest approach to estimating urban wage premium employed in the literature is to estimate the following equation

$$W_i = \beta_0 + x_i'\beta_1 + \alpha T_i + \varepsilon_i \tag{1}$$

where W_i is the log of the hourly wage of individual i, x_i is the set of observable characteristics and T_i is a binary variable which is equal to one if a person resides in an urban area and is equal to zero otherwise. If the urban dummy T_i and all other variables are uncorrelated with the error term, then OLS estimator of α provides a consistent estimate of the premium in hourly wage received by a person who lives in an urban area compared with an observationally equivalent worker in the non-urban environment.

There are good reasons, however, to believe that the location decision should be properly viewed as endogenous and possibly correlated with some unobserved (or incompletely observed) worker characteristics, such as ability. In particular, let z_i denote the set of characteristics which influence the location decision (note that z_i may overlap with x_i). Then one way to model the location decision of person i is to assume that T_i is determined by the following condition

$$T_i = I(z_i'\gamma + u_i > 0) \tag{2}$$

where u_i is a random error term and $I(S)$ is an indicator function which is equal to one if the statement S is true and equal to zero otherwise. Then the urban dummy T_i is endogenous if the error terms ε_i and u_i are correlated. In what follows, we will assume that they have a bivariate normal distribution. In particular, let σ_ε denote the variance of ε_i and $\sigma_{u\varepsilon}$ denote the covariance between the two error terms. The variance of the error term in the selection equation is normalized to one. In this model the conditional expectations of the wage equation are given by

$$E(W_i \mid x_i, z_i, T_i = 1) = \beta_0 + \alpha + x_i'\beta_1 + E(\varepsilon_i \mid u_i < -z_i'\gamma) \tag{3}$$

$$E(W_i \mid x_i, z_i, T_i = 1) = \beta_0 + x_i'\beta_1 + E(\varepsilon_i \mid u_i > -z_i'\gamma) \tag{4}$$

Because the error term is truncated, OLS estimation of the equation (1) produces inconsistent estimates. This problem can be avoided by using the two-stage procedure proposed in Heckman (1978) and Heckman (1979). In particular, the conditional expectations on the right hand side can be approximated by the selection term $\sigma_{u\varepsilon}\lambda_i$, where λ_i is defined as

$$\lambda_i(z_i'\gamma) = E(\varepsilon_i \mid z_i, T_i) = (1-T_i)\frac{-\phi(z_i'\gamma)}{\Phi(-z_i'\gamma)} + T_i \frac{\phi(-z_i'\gamma)}{1-\Phi(-z_i'\gamma)}$$

Thus, λ_i is the selectivity correction term obtained from the probit selection equation, where $\Phi(\cdot)$ and $\phi(\cdot)$ are standard normal cumulative distribution and density functions, respectively.

The two-step estimation procedure can be implemented as follows. First, the probit selection model is used to obtain the estimates of $\hat{\gamma}$. Second, the estimated value of λ_i is included in the wage regression which is then estimated by OLS:

$$W_i = \beta_0 + x_i'\beta_1 + \alpha T_i + \sigma_{u\varepsilon}\lambda_i + e_i \tag{5}$$

The coefficient on the selection term is an estimate of the covariance between ε_i and u_i. The standard errors in this equation must be corrected for heteroskedasticity and the use of the predicted selectivity variable. Alternatively, one can estimate the model directly using standard MLE procedures. Both two-step and ML methods produce estimates of the wage premium which takes into account endogeneity of the location choice.

It must be noted that the foregoing model imposes some rather strong restrictions on the nature of the data generating process. In particular, it implies that the error terms in the wage equation are perfectly correlated across the urban and rural sectors. One can relax this restriction by estimating a simple two-sector selection model first proposed by Roy (1951). In particular, let subscripts 1 and 2 denote non-urban and urban sectors, respectively. Then, assuming that the wage equations have sector-specific error terms, we can specify the model as follows. The sectoral wage equations are given by

$$W_{1i} = x_{1i}'\beta_1 + \varepsilon_{1i} \tag{6}$$

$$W_{2i} = x_{2i}'\beta_2 + \varepsilon_{2i} \tag{7}$$

As before, the location decision is determined by the selection equation of the form

$$T_i = I(z_i'\gamma + u_i > 0) \tag{8}$$

If the sector-specific errors are not correlated with u_i the model can be estimated by OLS. However, as discussed above, this assumption is unlikely to hold in the case of location decisions. In order to complete the model we impose the standard assumption of joint normality of the error terms (Heckman and Honore (1990)). In particular, we assume that $(\varepsilon_{1i}, \varepsilon_{2i}, u_i \mid x) \sim N(0, \Sigma)$, where

$$\Sigma = \begin{pmatrix} \sigma_1^2 & \sigma_{12} & \sigma_{1u} \\ \sigma_{12} & \sigma_2^2 & \sigma_{2u} \\ \sigma_{1u} & \sigma_{2u} & 1 \end{pmatrix}$$

Note that in this model the covariance term σ_{12} is not identified because wages of individual i in the two sectors cannot be observed simultaneously. This model can be estimated either by applying the two-step procedure or directly, by maximizing the following likelihood function

$$\ln L = \sum_{i=1}^{n} (T_i[\ln(F(\theta_{1i})) + \ln(f(\varepsilon_{1i}/\sigma_1)/\sigma_1)] + (1-T_i)[\ln(1-F(\theta_{2i})) + \ln(f(\varepsilon_{1i}/\sigma_2)/\sigma_2)])$$

where F and f are cumulative and density functions of the standard normal distribution, and

$$\theta_{ji} = \frac{(z_i'\gamma + \rho_j \varepsilon_{ij} / \sigma_j)}{\sqrt{1-\rho_j^2}}$$

where ρ_j is the correlation coefficient between ε_{ji} and u_i, for $j = 1, 2$. The expectations of the wage of worker i in the two sectors conditional on sector choice are given by

$$E(W_{1i} \mid T_i = 1, x_{1i}) = x_{1i}'\beta_1 + \lambda_1 f(z_i'\gamma)/F(z_i'\gamma) \quad (9)$$

$$E(W_{1i} \mid T_i = 0, x_{1i}) = x_{1i}'\beta_1 + \lambda_1 f(z_i'\gamma)/(1-F(z_i'\gamma)) \quad (10)$$

$$E(W_{2i} \mid T_i = 1, x_{2i}) = x_{2i}'\beta_2 + \lambda_2 f(z_i'\gamma)/F(z_i'\gamma) \quad (11)$$

$$E(W_{2i} \mid T_i = 0, x_{2i}) = x_{2i}'\beta_2 + \lambda_2 f(z_i'\gamma)/(1-F(z_i'\gamma)) \quad (12)$$

where $\lambda_j = \sigma_j \rho_j$ for $j = 1, 2$. Using these equations we can derive the counterfactual predictions of the model. In particular, we are interested in the expected wage gain (or loss) from switching sectors, which are given by $E(W_{1i} \mid T_i = 1, x_{1i}) - E(W_{1i} \mid T_i = 0, x_{1i})$ for non-urban workers, and $E(W_{2i} \mid T_i = 1, x_{2i}) - E(W_{2i} \mid T_i = 0, x_{2i})$ for urban workers. These quantities correspond to the sector specific wage premiums which are corrected for possible endogeneity of the sector choice.

4.4 Data Description

The data come from the first wave of the National Survey of Families and Households (NFSH). The NSFH consists of a nationally representative sample of individuals, aged 19 or older living in households and able to speak English or Spanish. In this study we use the data from first wave of NFSH, which were collected in 1987-1988. The sample we use consists of male respondents between 19 and 65 year old who work full time (defined as working at least 35 hours per week). After restricting the sample to those for whom wage information is available we are left with 3088 observations (implicitly we assume that wage information is missing completely at random for those individuals for whom wage data are not available). An individual's place of residence is defined as urban if he lives in a Metropolitan Statistical Area, and non-urban otherwise. Available data allow us to construct a measure of actual work experience for each individual. In addition we utilize other personal characteristics such as marital status, race and industry of employment.

To control for the occupational differences we use the occupation's intelligence requirement (OIR) measure developed by Ingram and Neumann (2006). This measure was constructed using the data from the Dictionary of Occupational Titles (DOT) and Current Population Survey (CPS). DOT provides data on various occupational characteristics, that allows to use factor analysis in order to develop several broad measures which characterize occupations according to intellectual requirements, physical strength, etc. We use the Occupation's Intelligence Requirement developed in this study as a proxy for occupational skill complexity. This allows us to control for differences in occupational characteristics and measure the returns to skills in urban and non-urban labor markets.

4.5 Empirical Results

First we estimate the one-sector model by categorizing the observation according to whether respondent lives in a MSA ("Urban" = 1) or not ("Urban" = 0). Both OLS and ML estimates are presented in Table 2, and the estimates of the selection equation are given in the Appendix (Table 9). Even though the model is identified without exclusion restrictions, it is generally advisable to have at least one. We include the number of children living in respondent's household as an explanatory variable in the selection equation. The dependent variable in both equations is the natural logarithm of the nominal hourly wage. In addition to the variables presented in the table, each regression contains a set of industry controls.

The OLS regression produces the urban wage premium of about 16%, which implies that observationally equivalent workers living in MSAs earn on average 16% more than their counterparts in non-metro areas. Next we estimate the wage premium controlling for possible endogenous selection (equation (5)). In this case, the coefficient on the urban dummy is negative (-0.149) but it is not statistically significant at the 5% level. Also, the maximum likelihood estimates imply that the errors in the wage and selection equations have a positive covariance, with implied correlation coefficient $\rho = 0.43$. The likelihood ratio test rejects the null of independent equations (p-value = 0.01). These results suggest that OLS will not produce consistent estimates of the urban wage premium because of the endogeneity of migration decisions.

These results are further extended by estimating the two-sector model which allows for sector specific unobserved influences in the wage equations. The results of the maximum likelihood estimation of the wage and selection equations are given in Tables 3 and 4. The dependent variable is the log of hourly wage. In general these findings suggest that returns to observable worker characteristics differ significantly between urban and non-urban areas. The marginal effect of one additional year of education is 6% for workers living in MSA's and 4.7% for their non-urban counterparts. The return to occupational complexity, as measured by the OIR variable, is much larger in the urban sector (12% vs. 7.8% in non-metro areas). On the other hand, the marriage premium is much larger in non-urban areas (10% vs. 5.4% in cities). Returns to experience seem to be equal in both sectors. This last finding is at odds with wage premium theories which emphasize that urban workers experience a higher wage growth.

The variance of the error terms in the wage equations are of similar magnitude. Most importantly, we find evidence of positive correlation between unobserved ability and location choice. In particular, the correlation between errors in the wage equations in the urban sector and the selection equation (ρ_1) is equal to 0.36 and it is statistically significant. This implies that workers with high unobserved ability in the urban sector tend to choose that sector as a place of work. A similar conclusion about the non-urban sector is suggested by the sign of the ρ_2 term, although this coefficient is not statistically significant. Finally the likelihood ratio test rejects the null hypothesis of independent equations at the 5% significance level. Consequently, it seems that both OLS and fixed-effects methods, that ignore the problem of self-selection, employed in the studies of the urban wage premium, produce biased and inconsistent estimates. Turning to the selection equation, we see that years of education and occupation complexity tend to increase the probability of living in metropolitan area. Years of experience, marriage and number of children have the opposite effect. All of these findings are consistent with prior expectations.

Next we study some counterfactual predictions of the model. In particular, we are interested in estimating the wage gain or loss that a person would receive by switching between the two sectors. These quantities can be computed using equations (9) to (12), i.e., these are the selectivity corrected estimates which take into account the expected values of the sector-specific shocks estimated from the model. Table 5 presents the sample averages and standard deviations of the predicted wages.

In equilibrium we should expect that, on average, none of the workers could gain by switching from one sector to the other. The model confirms this intuition and predicts that both urban and non-urban workers would experience a wage loss upon changing their sector. In particular, the average urban worker would lose about 35% of his wage by moving to the non-urban location. The corresponding loss for the workers currently residing outside of metropolitan areas is equal to 12%. This finding is consistent with the existence of systematic differences in unobserved abilities between the two sectors.

4.6 Conclusion

This paper provides selectivity-corrected estimates of the urban wage premium that use a nationally representative sample of the working age population. A first look at the data indicates that workers residing in Metropolitan Statistical Areas earn on average 17% more than their counterparts in non-urban areas, after controlling for occupational and individual characteristics. This estimate is similar in magnitude to the ones obtained in previous studies of the urban wage premium. However, after taking into account the potential bias introduced by the workers' endogenous migration decisions, we show that this estimate of the premium can be interpreted as resulting from the selection of more able workers into urban areas.

A richer set of conclusions is obtained by estimating the two-sector Roy model which allows for a general pattern of correlation between the sector-specific shocks (switching regression). In this setting we find that returns to education and skills, as measured by the occupation's intelligence requirement, are higher in the urban areas, and that sector specific shocks are correlated with the error term in the selection equation. In addition, both urban and non-urban workers would on average experience a wage loss by switching the location of occupation, with the average wage loss higher for urban workers moving out of the urban areas. We interpret this as evidence in favor of positive selection, under which workers choose to work in the sector where they are more productive.

The main empirical result of this study is that estimates of the urban wage premium are highly sensitive to the assumption of an exogenous location choice. At the same time, the results obtained in this study suggest that the hypothesis that the urban wage premium might result from the selection of workers with above-average ability (both observed and unobserved) into the urban areas must be subjected to careful empirical examination. In particular, estimation methods controlling for endogenous selection which go beyond the joint normality assumption imposed by the Roy model might be potentially useful in improving our understanding of urban labor markets.

4.7 References

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4.8 Tables

Table 1. Real Wage, MSA Population and Climatic Conditions

	(1)		(2)	
Variable	Coef.	St. Error	Coef.	St. Error
Log Population	609.5	126.4	658.8	127.7
Cooling Degree Days			0.631	0.373
Heating Degree Days			0.381	0.162
Constant	13003.68	1663.7	9767.18	2181.3
R^2	0.12		0.16	
Observations	175		175	

Table 2. Urban Wage Premium

	OLS (1)		ML	
Variable	Coef.	St. Error	Coef.	St. Error
Urban	0.159	0.020	-0.149	0.077
Education	0.057	0.004	0.063	0.004
Experience	0.036	0.002	0.034	0.003
Experience2/100	-0.055	0.006	-0.052	0.006
OIR	0.110	0.009	0.118	0.009
Married	0.066	0.017	0.047	0.019
Black	-0.091	0.023	-0.059	0.025
Hispanic	-0.105	0.032	-0.02	0.04
Constant	1.050	0.078	1.25	0.09
ρ			0.40	0.089
R^2	0.41			
Observations	3088		3088	

Table 3. ML Estimates of the Wage Equation

	MSA		non-MSA	
Variable	Coef.	St. Error	Coef.	St. Error
Education	0.062	0.004	0.047	0.012
Experience	0.034	0.003	0.038	0.006
Experience2/100	-0.053	0.007	-0.057	0.013
OIR	0.120	0.010	0.078	0.023
Married	0.054	0.020	0.099	0.049
Black	-0.052	0.027	-0.220	0.075
Hispanic	-0.035	0.039	-0.045	0.249
Constant	1.06	0.082	1.32	0.24
σ_j	0.45	0.01	0.41	0.03
ρ_j	0.36	0.11	-0.25	0.40
Log-likelihood	-3206.47			
Observations	3088			

Table 4. Selection Equation

Variable	Coef.	St. Error
Education	0.072	0.013
Number of Children	-0.107	0.0265
Experience	-0.007	0.009
Experience2/100	0.019	0.0211
OIR	0.099	0.030
Married	-0.149	0.066
Black	0.434	0.082
Hispanic	1.535	0.168
Constant	0.288	0.244
Observations	3088	

Table 5. Predicted Wages in the Two Sectors

Variable	Observations	Mean	St. Deviation
$E(W_1 \mid T=1)$	2449	2.31	0.36
$E(W_2 \mid T=0)$	639	2.10	0.35
$E(W_1 \mid T=0)$	2449	1.96	0.37
$E(W_2 \mid T=1)$	639	1.98	0.33

Table 6. Summary Statistics, Full Sample, n=3088

Variable	Mean	Std. Dev.	Min	Max
Log Wage	2.27	0.57	0	4.63
Urban	0.79	0.41	0	1
Education	13.23	2.83	0	20
Experience	15.63	10.91	0	51.1
Experience sqrd.	363.23	461.45	0	2609.5
IRO	0.20	1.10	-1.80	2.43
Married	0.63	0.48	0	1
Number of Children	0.85	1.16	0	8
Black	0.15	0.36	0	1
Hispanic	0.08	0.27	0	1
Agriculture	0.03	0.17	0	1
Mining	0.01	0.09	0	1
Construction	0.10	0.30	0	1
Manufacturing	0.24	0.43	0	1
Transportation	0.10	0.30	0	1
Wholesale Trade	0.07	0.25	0	1
Retail Trade	0.12	0.33	0	1
Business Rep. Services	0.07	0.25	0	1
Personal Services	0.02	0.13	0	1
Entertainment	0.01	0.11	0	1
Professional Services	0.12	0.33	0	1
Public Administration	0.07	0.25	0	1

Table 7. Summary Statistics, MSA Sub-Sample, n=2449

Variable	Mean	Std. Dev.	Min	Max
Log Wage	2.31	0.57	0	4.6
Education	13.4	2.87	0	20
Experience	15.47	10.9	0	49.75
Experience sqrd.	358	456	0	2475
IRO	0.26	1.1	-1.8	2.4
Married	0.61	0.49	0	1
Number of Children	0.8	1.13	0	7
Black	0.16	0.37	0	1
Hispanic	0.099	0.3	0	1
Agriculture	0.018	0.13	0	1
Mining	0.004	0.06	0	1
Construction	0.09	0.29	0	1
Manufacturing	0.23	0.42	0	1
Transportation	0.11	0.31	0	1
Wholesale Trade	0.07	0.25	0	1
Retail Trade	0.12	0.33	0	1
Business Rep. Services	0.07	0.26	0	1
Personal Services	0.017	0.13	0	1
Entertainment	0.014	0.119	0	1
Professional Services	0.13	0.34	0	1
Public Administration	0.07	0.25	0	1

Table 8. Summary Statistics, non-MSA Sub-Sample, n=639

Variable	Mean	Std. Dev.	Min	Max
Log Wage	2.1	0.53	0.14	3.75
Education	12.5	2.53	3	20
Experience	16.23	10	0	51.1
Experience sqrd.	382.36	481.7	0	2609.5
IRO	-0.03	1.06	-1.64	2.18
Married	0.7	0.45	0	1
Number of Children	1.07	1.24	0	8
Black	0.11	0.32	0	1
Hispanic	0.014	0.12	0	1
Agriculture	0.075	0.26	0	1
Mining	0.028	0.17	0	1
Construction	0.13	0.34	0	1
Manufacturing	0.28	0.45	0	1
Transportation	0.08	0.28	0	1
Wholesale Trade	0.06	0.23	0	1
Retail Trade	0.12	0.33	0	1
Business Rep. Services	0.04	0.20	0	1
Personal Services	0.01	0.12	0	1
Entertainment	0.01	0.08	0	1
Professional Services	0.08	0.27	0	1
Public Administration	0.05	0.22	0	1

Table 9. Probit Selection Equation, n=3008

Variable	Coef.	Std. Dev.	z	p-value
Constant	0.251	0.239	1.05	0.293
Number of Children	-0.102	0.025	-4.03	0.000
Education	0.071	0.013	5.40	0.000
Experience	-0.008	0.009	-0.88	0.377
Experience sqrd.	0.021	0.021	1.01	0.312
IRO	0.103	0.031	3.36	0.001
Married	-0.151	0.065	-2.32	0.021
Black	0.444	0.082	5.44	0.000
Hispanic	1.484	0.163	9.12	0.000
Agriculture	-1.114	0.199	-5.57	0.000
Mining	-1.253	0.288	-4.35	0.000
Construction	-0.345	0.165	-2.09	0.037
Manufacturing	-0.345	0.154	-2.24	0.025
Transportation	-0.060	0.169	-0.36	0.721
Wholesale Trade	-0.112	0.180	-0.62	0.535
Retail Trade	-0.271	0.163	-1.66	0.096
Business Rep. Services	0.048	0.183	0.26	0.792
Personal Services	-0.209	0.265	-0.79	0.430
Entertainment	0.157	0.320	0.49	0.624
Professional Services	-0.225	0.167	-1.35	0.177
Public Administration	-0.182	0.179	-1.02	0.310

CHAPTER 5. GENERAL CONCLUSION

In my dissertation I studied three specific questions in the economics of intellectual property rights and regional economics. Although all chapters are self-contained, they are related in a broad sense by the underlying theme of evaluating potential ways in which public policy could be used to improve market outcomes in presence of externalities in production of new goods and ideas. In addition, the first two essays share a common focus of the analysis of welfare properties of the research exemption, which is defined as a right to use patented inventions in the research process.

In the first essay, the importance of understanding the welfare properties of research exemption is emphasized by arguing that this is one of the major issues which will bear upon the evolution of the global system of intellectual property rights in such areas as plant innovation and potentially many others. To further our understanding of the incentives to innovate in the intellectual property systems with and without research exemption a fully dynamic model of R&D race is constructed and analyzed. First, the full characterization of Markov Perfect Equilibria of the stochastic game defining the R&D race is achieved, which serves to demonstrate the ability of the model to produce rich set of equilibria, depending on the underlying parameter structure. Next the welfare properties of the two intellectual property regimes, with and without research exemptions are studied. The main conclusion that arises in this process is that there exists a potential scope for the research exemption, but only in the case when the R&D cost structure is such that initial innovation is not much more costly than the follow up improvements. For other industries which are characterized by the high initial cost and low improvement cost (e.g. plant breeding) it is shown that the system which eschews research exemption altogether will be socially advantageous because it is more efficient in providing adequate incentives to invest in the research and development in this case.

The second essay continues the analysis of the research exemption provision by concentrating specifically on biological inventions which are subject to loss of value due to the adaptation of pathogens, such as in the case of new crop varieties or vaccines. We go beyond the traditional analysis of this problem, which relies on the insights from the literature on the optimal use of the non-renewable resource, by developing a new framework that emphasizes consideration of market power brought about by the intellectual property rights and the resulting strategic interactions between several firms. The simple model of R&D race with adaptive destruction delivers several interesting conclusions. First, firms themselves might prefer a weaker intellectual property regime *ex ante*, if the cost of innovation is small enough. Second, the implications of research exemption for the social welfare in the presence of adaptive destruction are qualitatively similar to the fully dynamic model analyzed in the first essay: both weaker and stronger intellectual property regimes can be socially optimal depending on the magnitude of the R&D cost.

The third essay of my dissertation is devoted to the problem of understanding the so called urban wage premium, i.e. the fact that observed characteristics of the workers living in urban and non-urban areas do not explain the differences in the level of wages they receive. In particular, it is well documented that urban residence results in the wage advantage of 25-33%, which cannot be reduced below 20% by accounting for differences in education, experience and other worker attributes. Clearly, if such differences result from faster learning and knowledge spillovers in densely populated areas, there is a scope for public policy aimed at promoting innovation by subsidizing various forms of industrial agglomeration in the innovative industries such as high-tech and biotechnology. If however, these differences do not stem from the external effects but are fully internalized by the agents, the scope for policy is much more limited. This essay addresses the urban wage premium puzzle by emphasizing that careful accounting for unobserved heterogeneity of the labor force across various locations is essential in order to understand this phenomenon. In contrast to previous studies, I estimate two econometric models that are designed to control for possible selection on unobserved characteristics (such as unobserved ability) across different geographical areas. I find that after controlling for the endogeneity of the location, we find little evidence of the wage advantage of the workers in urban areas, suggesting that explicit accounting for the self-selection is essential when studying the urban wage premium.

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