Patents, Research Exemption, and the Incentive for Sequential Innovation

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We develop a quality ladder model to study the R&D incentive impacts of intellectual property rights with a "research exemption" or "experimental use" provision. The innovation process is sequential and cumulative and takes place alongside production in an infinite-horizon setting. We solve the model under two distinct intellectual property regimes, characterize the properties of the relevant Markov perfect equilibria, and investigate the profit and welfare effects of the research exemption. We find that firms, ex ante, *always prefer full patent protection. The welfare ranking of the two intellectual property regimes, on the other hand, depends on the relative magnitudes of the costs of initial innovation and improvements.*

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 an agreement that legally provided rights and institutions that 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 reflects the fact that IPRs, because they work by creating a degree of monopoly power, only provide a second-best solution to the market failures that arise in this context (Arrow, 1962). The prospect of monopoly

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profits can be a powerful *ex ante* incentive for the would-be innovator and can bring about innovations that would not otherwise take place, but the monopoly position granted by 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 new products and processes are the springboard for more innovations and discoveries (Scotchmer, 1991). When innovation is cumulative, the first inventors are not necessarily compensated for their contribution to the social value created by subsequent inventions. This problem is particularly evident when the first invention stems from basic research and constitutes a so-called research tool that is not directly of interest to final users. Addressing this intertemporal externality requires the transfer of profits from successful applications of a given patented innovation to the original inventor(s). A number of studies have investigated what the features of an IPR system should be to achieve that. Green and Scotchmer (1995) consider how patent breadth and patent length should be set in order to allow the first inventors to cover their cost, subject to the constraint that the second-generation innovation is profitable, and they highlight the critical role of licensing. This and related studies, including Scotchmer (1996), and Matutes et al. (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 research and development (R&D) races (Denicolò, 2000).

How one models the features of an IPR system is critical in this setting, 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. In quality ladder models of sequential innovation, this property is represented by the notion of "leading breadth"—the minimum size of quality improvement that makes a follow-on innovation noninfringing (O'Donoghue et al., 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 "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 US 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.

The intense debate that followed the CAFC ruling in *Madey v. Duke University* 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 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 question addressed in this paper is related to the analysis of Bessen and Maskin (2006), who find that when innovation is sequential, the need for the incentive effect of patent protection is greatly reduced in

1. The 2005 decision of the US 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).

a dynamic setting. Indeed, they find that, in such a situation, individual firms themselves may gain from being imitated. This result stems from the conjunction of two features: an appealing "complementarity" condition, meaning that having more firms engaged in the pursuit of a particular innovation raises the overall probability of success; and the recognition that, in a dynamic setting, an innovation has both an immediate value and an indirect value because it makes future innovations possible. Provided that imitation does not dissipate too much of the innovation gains that the firms share in, having rivals that increase the overall R&D success probability might be beneficial. We retain this basic approach but formulate an explicit quality ladder model in the tradition of the analyses of the optimal patent breadth discussed earlier—specifically, a fully dynamic model of an infinite-horizon stochastic innovation contest—whereby the dissipation and sharing of firms' profit are endogenously determined by the model's equilibrium. Related literature includes formal models of dynamic R&D competition between firms engaged in "patent races" (e.g., Tirole, 1988, Ch. 10). As with most contributions in this setting, we postulate a memoryless stochastic arrival of innovation, which is modeled by means of a geometric distribution (rather than with exponential distribution often used when modeling R&D races; e.g., Reinganum, 1989).

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 state-dependent (this is an attractive feature under typical market structures, yet it seems neglected in many a quality ladder model). Conversely, to keep the analysis tractable, here we consider a fixed number of firms (two) and thus do not address the question of entry in the R&D contest (an issue extensively studied in previous work). 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 using 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, *ex ante*, the firms themselves always prefer the full patent protection regime (unlike what happens in Bessen and Maskin, 2006). 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, and either regime may dominate from a welfare perspective. In particular, the research exemption is most likely to provide inadequate incentives when the cost of establishing a research program is large. On the other hand, when both initial and improvement costs are small relative to the expected returns, the weaker incentive to innovate is immaterial (firms engage in R&D anyway), and the research-exemption regime dominates.

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.

2.1 Plant Variety Protection, 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 US 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 IPRs, plant innovators can rely on trade secrets, the use of hybrids, and specific contractual arrangements (such as bag-label contracts). More important, in the United States plant breeders can now also rely on utility patents. The landmark 1980 US 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 US Supreme Court held that plant seeds and plants themselves (both traditionally bred or produced by genetic engineering) are patentable under US law (Janis and Kesan, 2002).

As noted earlier, the US 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 (whole genome) 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 US 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 breeders' 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.[2]

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, and that in turn is critically affected by whether or not one has access to existing successful varieties,

2. 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).

which in turn 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 prebreeding activities aimed at widening the germplasm diversity base (Donnenwirth et al., 2004).

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 knowledge base (e.g., same initial germplasm in plant innovation) and, upon investing in R&D, achieve success with some probability. 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 patent is randomly awarded (with equal probability) to one of them. If neither firm is successful, they can try again, which requires a new R&D investment.

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). Two activities characterize each stage of the improvement game: rent extraction through production, and (possibly) further R&D. Throughout the paper, production is the prerogative of the leader. This captures the idea that patents have breadth, so that mere imitation is not possible. Whether or not both firms can participate in the improvement game depends on the nature of IPRs, specifically on whether or not there exists a "research exemption." 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 by others only upon a license from the patent holder). Thus, the FP regime characterizes the environment of US 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 (including the follower) to use the current innovation in order to pursue the next innovation, although the patent gives the right to practice the innovation (and earn returns) 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.[3]

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 can participate in the follow-up R&D. Furthermore, under the RE regime, both firms have access to the same state-of-the-art technology in their pursuit of the next innovation. Thus, a success in a stage of the improvement game either reinforces the leader's dominant position or produces a change in the identity of the leader. For example, the first success in the improvement game can result either in the winner of the initial game (the current leader) owning two consecutive innovations or can end up with the loser of the initial game becoming the leader. Note that this structure reflects the strict sequential and cumulative nature of the innovation process that we wish to model: the current quality level is an essential input into the production of the next quality level.

We note, at this juncture, that our model ignores the possibility that the follower may risk infringement and participate in the improvement game under the FP regime anyway. This is because our primary interest is to compare and contrast a "strong" and a "weak" IPR regime, and thus we view the implicit full enforcement of the FP regime as part of the definition of strong IPRs. Also, our model does not allow the leader to prevent access to its innovation by foregoing patenting in favor of "trade secret" protection (e.g., Anton and Yao, 2004). The implicit assumption is that the new technology can be easily reversed engineered by the follower when marketed by the leader for the purpose of earning stage profit (this is certainly true for the plant innovation case discussed earlier, in which the innovation is embedded in the improved seeds that are sold).

2.3 The Stochastic Game

The model is formalized as an infinite-horizon stochastic game between two players (the two firms). At each stage of the initial game, the two firms simultaneously choose an action from the set $\{I, N\}$, where $I =$ invest and $N =$ no investment. Action I entails a cost to the firm of

3. 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.

$c_0 > 0$ 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 $q \equiv p(2 - p)/2$. The assumption of independent R&D outcomes is the simplest way to capture the notion of complementarity discussed in the Introduction.[4] 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, 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. The R&D structure of the improvement game is similar to that of the initial game: a single firm innovates with probability p, and when both firms invest, each wins the contest with probability q. But we wish to model the feature that the initial innovation is more important, in a well-defined sense, and thus we assume that the per-period cost of R&D in the improvement game is $c \leq c_0$. Again, if both firms fail to innovate in any one stage, the R&D contest does not end (both can try again).

On the demand side, as in other quality ladder models (e.g., O'Donoghue et al., 1998), we assume identical consumers (whose mass is normalized to one) who buy at most one unit of the good per period and, when the quality of the good is Q and pay price P, derive utility $Q - P$. Quality is improved by an amount $\Delta > c$ with each successful innovation (i.e., $Q = \Delta, 2\Delta, 3\Delta \ldots$). Hence, neglecting production costs, each additional innovation is worth an additional Δ, per period, to society. Under the FP regime the innovating firm can extract the entire surplus. Under the RE regime, on the other hand, both firms may have been successful at some point in the history leading up to a particular stage; that is, both firms may own valid patents on some innovations. The assumed demand structure implies that only the best product is sold in this market, so that only the current leader produces (and earns profit) at any one stage of the improvement game. Furthermore, the most the leader can charge is the marginal value over what the competitor can offer (i.e., Bertrand competition). For example, if two firms own patents on the m^{th} and n^{th} innovation steps, respectively, with $m > n$, in our model the firm with m steps is the one selling any product, with an *ex post* per-period return of $(m - n)\Delta$.

4. More generally, the critical condition is to rule out perfect positive correlation of outcomes so that the probability of at least one success is higher with two firms than with one firm (which here is reflected in the fact that $2q > p$).

The improvement game under the FP regime 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, with each distinguished by the number $k = 1, 2, 3, \ldots$ of innovation steps held by the leader (over those of the follower). Thus, at the end of the initial game we have $k = 1$. If the leader is the firm that also obtains the first innovation in the improvement game, then $k = 2$ 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 $k = 1$. At each stage of the improvement game under the RE regime, the leader earns a stage payoff determined by the assumed Bertrand competition: specifically, the leader collects $k\Delta$. 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.[5]

The analysis of the stochastic game is restricted to considering "Markov strategies," whereby the history of the game affects strategies only through state variables that summarize the payoff-relevant attributes of the strategic environment (Fudenberg and Tirole, 1991). The relevant equilibrium concept in this setting is that of *Markov Perfect Equilibrium* (MPE), that is, a profile of Markov strategies that yields a subgame perfect Nash equilibrium. Markov strategies, and the associated MPE notion, have a number of attractive features (Maskin and Tirole, 2001). The MPE constitutes the backbone of applied dynamic analyses of oligopolistic industries (Doraszelski and Pakes, 2007), and it is also routinely used in models of innovation races (e.g., Hörner, 2004; Bar, 2006).

In the context of our model, there are two state variables that affect Markov strategies. First, the number of leads held by the leader ($k = 1, 2, 3, \ldots$) is clearly one of the state variables of the game (recall that the stage payoff of the leader is $k\Delta$). The other payoff-relevant state variable is the identity of the leader. Alternatively, if instead of representing the strategies of the two firms we characterize the strategies of the two "types" of firms (leader and follower), then the only remaining state variable is the number of leads k, and that is the approach we take in

5. These are two recurrent concepts in patent race models (Tirole, 1988, Ch. 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.

what follows. A Markov strategy for the leader, denoted by $\sigma_L(k)$, thus is a probability distribution over available actions (I and N), conditional on the state variable k (and similarly for the strategy of the follower, denoted by $\sigma_F(k)$).[6]

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. 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.

3.1 Improvement Game under the Full Patent Regime

As noted, here we do not really have a game, but just an optimization problem because the firm is effectively a monopolist in the improvement game. If the firm chooses action I at any one stage, success will occur with probability p and hence the change in expected payoff due to choosing action I in that stage is $-c + p\delta\Delta/(1-\delta)$ (because success yields a stage payoff Δ forever starting next period). Hence action I is optimal in any one stage iff $c/\Delta \leq x_0$, where

$$x_0 \equiv \frac{\delta p}{(1-\delta)}. \tag{1}$$

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 (the investment rule does not depend on state k). Therefore, 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 is

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

If $c/\Delta > x_0$, on the other hand, the optimal action would be N, with payoff $k\Delta/(1-\delta)$.

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

3.2 Improvement Game(s) under the Research-Exemption Regime

In each possible improvement game under the RE regime, firms are asymmetric. The firm with the last success (the leader) earns returns from the market. Under our Bertrand pricing condition, only the highest quality of the product is sold in the market and the per-period (gross) return to the firm selling it is $k\Delta$. The other firm (the follower) does not earn current returns but has the same opportunities to engage in R&D as the other firm. Thus, 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 it lags behind 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 $\sigma \equiv (\sigma_L, \sigma_F)$, and for any stage with state k, we can write the payoff to the follower as $V_F(\sigma)$ and the payoff to the leader as $V_L(\sigma, k)$. These value functions must satisfy the following recursive equations:

$$\begin{aligned} V_L(\sigma, k) = \Delta k &+ \sigma_L\sigma_F\,[-c + q\delta V_L(\sigma, k+1) + q\delta V_F(\sigma) + (1-2q) \\ &\qquad \times \delta V_L(\sigma, k)] \\ &+ \sigma_L(1-\sigma_F)\,[-c + p\delta V_L(\sigma, k+1) + (1-p)\delta V_L(\sigma, k)] \\ &+ (1-\sigma_L)\,[\sigma_F\,(p\delta V_F(\sigma) + (1-p)\delta V_L(\sigma, k)) \\ &\qquad + (1-\sigma_F)\delta V_L(\sigma, k)] \end{aligned} \tag{3}$$

$$\begin{aligned} V_F(\sigma) = \sigma_F\sigma_L\,&[-c + q\delta V_L(\sigma, 1) + (1-q)\delta V_F(\sigma)] \\ &+ \sigma_F(1-\sigma_L)\,[-c + p\delta V_L(\sigma, 1) + (1-p)\delta V_F(\sigma)] \\ &+ (1-\sigma_F)\delta V_F(\sigma). \end{aligned} \tag{4}$$

To find the MPE, we start by characterizing a useful benchmark case.

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*

$$(i)\ V_F(\sigma) = \frac{\phi\Delta q\delta\,[1 - \delta(1 - 2\phi q - (1-\phi)p)]}{(1-\delta)(1-\delta(1-2\phi q))(1-\delta(1-\phi q))} - \frac{\phi c\,(1 - \delta(1-(1+\phi)q))}{(1-\delta)(1-\delta(1-2\phi q))}, \tag{5}$$

$$(ii)\ \ V_L(\sigma, k) = \frac{-c + \phi q \delta V_F}{1 - \delta(1 - \phi q)} + \frac{\Delta k}{1 - \delta(1 - \phi q)} + \frac{\Delta \delta\,(\phi q + (1 - \phi)p)}{(1 - \delta(1 - \phi q))^2}. \quad (6)$$

The proof of this result is confined to the Appendix. Thus, when the leader invests in every period with probability one whereas the follower invests with the same probability $\phi \in [0, 1]$ in every period, Lemma 1 provides close-form expressions 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 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 it is successful in the stage R&D race, the new leader obtains a one-step lead over the other firm (under our Bertrand pricing condition). 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 invests in the equilibrium of the improvement games. For that purpose, in addition to x_0 defined in equation (1), we define the threshold levels:

$$x_1 \equiv \frac{q\delta\,(1 - \delta(1 - p))}{(1 - \delta)\,(1 - \delta(1 - q))}, \quad (7)$$

$$x_2 \equiv \frac{q\delta}{(1 - \delta(1 - q))}. \quad (8)$$

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

Proposition 1: *For all $k = 1, 2, \ldots$, the MPE of the improvement game under the RE regime satisfies:*

(i) If $c/\Delta \leq x_2$, then $\sigma_L(k) = 1$ and $\sigma_F(k) = 1$.
(ii) If $x_2 \leq c/\Delta \leq x_1$, then $\sigma_L(k) = 1$ and $\sigma_F(k) = \phi \in [0, 1]$.
(iii) If $x_1 \leq c/\Delta \leq x_0$, then $\sigma_L(k) = 1$ and $\sigma_F(k) = 0$.
(iv) If $x_0 \leq c/\Delta$, then $\sigma_L(k) = \sigma_F(k) = 0$.

The proof, confined to the Appendix, relies on establishing that neither leader nor follower has a one-stage deviation from the proposed strategy that would increase its 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 a 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.

From Proposition 1, therefore, we find that 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

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

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

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, $V_F \geq 0$ when $c/\Delta \leq x_2$ and $V_F \to 0$ 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 (2). Hence, if the firm that is a follower in any one stage believes that future followers always choose action N, 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 $c/\Delta > x_2$ and c/Δ is close to x_2. The MPE in the domain $x_2 \leq c/\Delta \leq x_1$, in fact, entails the use of a mixed strategy whereby the follower invests with probability $\phi \in [0, 1]$. As derived in the Appendix, the mixing probability ϕ in this domain is the positive root that solves the quadratic equation

$$\begin{aligned} &-c\,[1-\delta\,(1-q(1+\phi))]\,(1-\delta(1-\phi q)) \\ &\quad +\Delta q\delta\,(1-\delta(1-2q\phi)+\delta(1-\phi)p) = 0. \end{aligned} \tag{11}$$

At $c/\Delta = x_1$, equation (11) yields $\phi = 0$. At this point the follower drops out of the improvement game and only the leader finds it profitable to invest. Note that, when evaluated at $c/\Delta = x_1$ and $\phi = 0$, 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 $c/\Delta > x_0$ no firm invests. Thus, for $c/\Delta \geq x_1$ the FP regime and the RE regimes are equivalent as far as the improvement game is concerned.

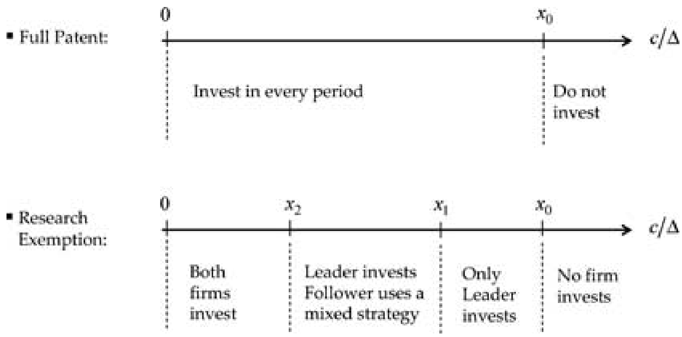

FIGURE 1. TYPES OF MARKOV PERFECT EQUILIBRIA IN THE IMPROVEMENT GAMES

The conclusions of Proposition 1 are illustrated in Figure 1, 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 regime (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 is of some interest. For the follower, because of its use of mixed strategies, we of course find that $V_F = 0$ in the domain $x_2 \leq c/\Delta \leq x_1$. As for the leader, it is clear that its payoff must be increasing on some part of the domain when $c/\Delta \geq x_2$ because, by using equations (2) and (9), we find

$$V_M(k)|_{c/\Delta=x_0} = \frac{k\Delta}{(1-\delta)} > \frac{k\Delta}{(1-\delta(1-q))} = V_L(\sigma, k)|_{c/\Delta=x_2}\,. \tag{12}$$

In fact, at the mixed-strategy parameter ϕ that solves equation (11), the leader's payoff is

$$V_L(\sigma, k) = \frac{c}{q\delta} + \frac{(k-1)\Delta}{1-\delta(1-\phi q)}. \tag{13}$$

Thus, in the domain $x_2 \leq c/\Delta \leq x_1$, 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 outweighs the direct negative impact of R&D cost.

The equilibrium payoffs to the leader and the follower are illustrated in Figure 2. The threshold levels x_0, x_1, and x_2 that we

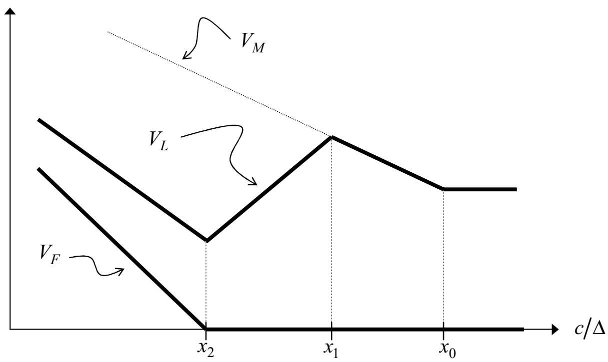

FIGURE 2. EQUILIBRIUM PAYOFFS IN THE IMPROVEMENT GAMES

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 et al. (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 its 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 $k\Delta$.

4. Equilibria in the Initial Game

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

4.1 Full Patent Regime

The types of equilibria that arise are characterized in Proposition 2, wherein the regions of interest, in the parameter space $(c/\Delta\,,\,c_0/\Delta)$, are defined by the functions:

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

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

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 game.

Proposition 2: *The symmetric equilibrium of the initial 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* $\sigma_0 = \frac{p\delta V_M - c_0}{(p-q)\delta V_M}$.

Details of the proof are in the Appendix (V_M here is given by equation (2) with $k = 1$). The parameter space of interest is illustrated in Figure 3 (which will also be used for the RE regime below). Under the FP regime, Proposition 2 indicates that both firms invest with probability one in the initial game in regions C_1, C_2, C_3, B_1 and B_3; a mixed-strategy equilibrium applies for regions C_4, B_4, B_2, and A; and neither firm invests everywhere else. Thus, we find that the equilibrium depends critically on the postulated asymmetry in cost/returns between initial innovation and follow-on improvements. For a given (low enough) value of c, relatively low values of initial R&D cost c_0 induce both firms to invest with probability one. If the R&D cost parameters c and/or c_0 are large enough, on the other hand, neither firm invests.

For intermediate values of the R&D cost parameters (part (iv) of Proposition 2), each firm would want to invest if the other does not. Thus, in this domain we have two (asymmetric) pure-strategy equilibria, as well as a (symmetric) mixed-strategy equilibrium. The pure-strategy equilibria predict that the two firms behave differently and enjoy different outcomes (one invests and makes positive profit whereas the other does not and makes zero profit), even though the firms are *ex ante* identical. In the absence of any coordination argument (and we have built none into our model), this asymmetry is not very appealing. In the mixed-strategy equilibrium, by contrast, the two firms follow the same strategy and enjoy the same outcome. Because of this attractive feature, the equilibrium in mixed strategies is the one that

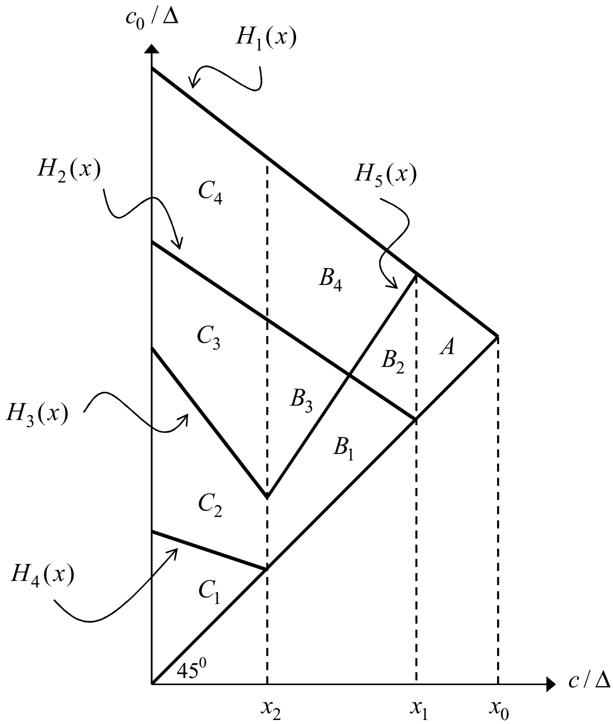

FIGURE 3. PARAMETRIC REGIONS FOR THE MPE OF THE INITIAL GAME

is emphasized in part (iv). 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 $c_0/\Delta \to H_2(c/\Delta)$.

4.2 Research-Exemption Regime

Under the RE regime one can distinguish three intervals for c/Δ in which the equilibrium in the improvement game is qualitatively different (recall Figure 1), and thus Proposition 3 analyzes the equilibrium of the initial game separately for these domains. The various possibilities that arise can be illustrated with the aid of Figure 3. The parametric regions of interest are defined by the functions $H_1(x)$ and $H_2(x)$ defined earlier, and by the functions:

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

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

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

PROPOSITION 3: *Given $c \leq c_0$, the strategy profile (σ_0, σ_0) that constitutes the symmetric equilibrium of the initial game under the RE regime satisfies:*

(i) If $c/\Delta > x_0$, or if $c_0/\Delta > H_1(c/\Delta)$, then $\sigma_0 = 0$.
(ii) If $x_1 \leq c/\Delta \leq x_0$ and $c_0/\Delta \leq H_1(c/\Delta)$ (region A), then $\sigma_0 = \frac{p\delta V_M - c_0}{(p-q)\delta V_M}$.
(iii) If $x_2 \leq c/\Delta \leq x_1$ and $c_0/\Delta \leq H_5(c/\Delta)$ (regions B_1 and B_2), then $\sigma_0 = \frac{p\delta V_1 - c_0}{(p-q)\delta V_1}$.
(iv) If $x_2 \leq c/\Delta \leq x_1$ and $c_0/\Delta > H_5(c/\Delta)$(regions B_3 and B_4), then $\sigma_0 = 0$.
(v) If $c/\Delta \leq x_2$ and $c_0/\Delta \leq H_4(c/\Delta)$(region C_1), then $\sigma_0 = 1$.
(vi) If $c/\Delta \leq x_2$ and $c_0/\Delta > H_3(c/\Delta)$(regions C_3 and C_4), then $\sigma_0 = 0$.
(vii) If $c/\Delta \leq x_2$ and $H_4(c/\Delta) \leq c_0/\Delta \leq H_3(c/\Delta)$ (region C_2), then $0 \leq \sigma_0 \leq 1$.

The proof of this proposition is given in the Appendix, wherein the quadratic equation defining σ_0 for part (vii) is also explicitly derived (V_1 in part (iii) is the leader's payoff, as given by equation (9), when $k = 1$). With respect to Figure 3, therefore, pure strategies are used in the parameter regions labeled C_1, and symmetric mixed strategies are used in regions A, B_1, B_2, and C_2 (as noted earlier, in this domain there also exist asymmetric pure-strategy equilibria). 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 invest whenever $c/\Delta > x_1$ (Figure 1). If this condition is satisfied, once one of the firms succeeds in completing the first innovation step, its rival will drop out of the race. This type of equilibrium is similar to the one obtained by Fudenberg et al. (1983) in the context of a race with a known finish line, and by Hörner (2004) in an infinite-horizon setting.

Comparing the equilibrium outcomes under the FT and RE regimes, we note that in the parameter regions C_4 and B_4 of Figure 3 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 3 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. As one would expect, firms have higher incentives to invest in R&D when they compete for the entire market, that is, when the winner of the initial game faces no competition afterward. Thus, it is apparent that the presence of an RE clause unambiguously weakens the initial incentive of firms to invest in R&D. The welfare consequences of this weakened investment incentive are analyzed next.

5. Welfare Comparisons

Having characterized the MPE of the model, we can now turn to 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.

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 are illustrated in Figure 3). Our findings are as follows.

Proposition 4: *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 profits 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 whenever $c/\Delta < x_1$ *and* $c_0/\Delta \leq H_2(c/\Delta)$.

The domain of part (i) encompasses the parameter space labeled as A,B_2, B_4, and C_4 in Figure 3. In areas A and B_2 the firms follow mixed strategies in the initial game under both regimes (and thus both earn zero-expected profit). In areas B_4 and C_4 firms also earn zero-expected profit under either regime, but for different reasons (no firm invests in the MPE of the initial game under the RE regime, whereas firms follow mixed strategies in the MPE of the initial game under the FP regime). For the parametric regions B_3 and C_3 of the domain of part (ii), *ex ante* expected profits are positive under the FP regime and zero under the RE regime (because none of the firms invests in the initial game). For the parametric regions B_1 and C_2, *ex ante* expected profits are again positive under the FP regime and zero under the RE regime (because a mixed-strategy equilibrium applies). Finally, in the parametric region C_1 both firms invest with probability one under either regime (in both the initial game and the improvement games). Because firms have the same probability of success, it follows that both firms prefer the FP regime, *ex ante*, iff $V_M(1) \geq V_L(\sigma, 1) + V_F(\sigma)$. By using equations (2), (5) and (6) (for $k = 1$ and $\phi = 1$), it is readily verified that this condition is satisfied.

Thus, Proposition 4 establishes that firms, *ex ante*, would never prefer the RE regime over the FP regime. This result differs from that of Bessen and Maskin (2006), in which the absence of patents, in a similar sequential innovation setting, can produce higher *ex ante* returns to the innovating firms than a standard patent system. This result reflects a quintessential feature of sequential innovation in a dynamic setting: in addition to an immediate use value, an innovation also carries an option value because an invention makes future inventions possible.[7] Furthermore, the complementarity assumption discussed earlier ensures that the presence of a competitor increases the probability that future improvements may be undertaken. Thus, whereas the presence of a competitor erodes a firm's expected profit in a given stage of the innovation race, it also increases the total option value of the innovation that is shared by the firms. The latter effect counters the former (standard) effect and, according to Bessen and Maskin (2006), can lead to a firm benefiting from the presence of an R&D competitor. Our model also maintains the appealing complementarity condition, and our dynamic setting clearly embeds the option value of making future innovations possible. But that is not enough because dynamic R&D competition entails too much profit dissipation (which, in our model, is endogenously determined). Specifically, whereas the FP regime allows the innovator to capture the entire social value of the innovation, under the RE regime some of the surplus spills over to consumers each time the follower overtakes the leader (as a result of the Bertrand pricing condition).

5.2 Welfare

Welfare evaluation under the RE requires that we take into account consumer surplus, in addition to the firms' *ex ante* expected profit. To that end, we first compute the expected social welfare starting at the beginning of the (first) improvement game. Let W_i denote this welfare measure when, in the equilibrium of the improvement game, there are i firms ($i = 1, 2$) that invest in every stage. Similarly, let W_ϕ denote this welfare measure when the leader invests with probability one and the

7. In Bessen and Maskin (2000) this dynamic option value is represented by postulating that improvement possibilities are exhausted if all firms fail to innovate in any given period.

follower invests with probability ϕ in each stage of the improvement game. Clearly, $W_1 = V_M$, where V_M is given by equation (2) with $k = 1$. On the other hand, from the social point of view, the situation in which two firms invest in every stage is the same as the situation in which there is only one investing firm (i.e., a monopolist) with cost $2c$ and success probability $2q > p$. Hence, the sum of firms' profits and consumer surplus is equal to the profits of such a (fictitious) monopolist. Therefore,

$$W_2 = \frac{\Delta - 2c}{1-\delta} + \frac{2q\delta\Delta}{(1-\delta)^2}. \tag{19}$$

The measure of social welfare when the follower randomizes over its actions, with probability ϕ in every stage, is given by the following expression (see the Appendix):

$$W_\phi = \frac{\Delta - c(1+\phi)}{1-\delta} + \frac{\Delta(\phi 2q\delta + (1-\phi)p\delta)}{(1-\delta)^2}. \tag{20}$$

Note that $W_\phi = W_1$ when $\phi = 0$, and $W_\phi = W_2$ when $\phi = 1$. Similar to the equilibrium analysis of the initial game, the comparison of welfare under the two IPR regimes needs to distinguish alternative possible parametric cases in the space $(c/\Delta, c_0/\Delta)$. It turns out that it is possible to welfare-rank the two IPR regimes only for a subset of these cases.

Proposition 5: *The welfare ranking of the two IPR regimes is as follows:*

- *(i) If $c/\Delta \in [0, x_2]$ and $H_3(c/\Delta) < c_0/\Delta < H_2(c/\Delta)$ (region C_3) the FP regime dominates.*
- *(ii) If $c/\Delta \in [0, x_2]$ and $c_0/\Delta \leq H_4(c/\Delta)$ (region C_1) then:*
  - (a) *if $(1-p)(2-p) \geq (1-\delta)/\delta$, the RE regime dominates;*
  - (b) *if $(1-p)(2-p) < (1-\delta)/\delta$, the FP regime dominates if $(1-p)x_0 < c/\Delta \leq x_2$, but the RE regime dominates if $0 \leq c/\Delta \leq (1-p)x_0$.*
- *(iii) If $c/\Delta \in [x_2, x_1]$ and $H_5(c/\Delta) < c_0/\Delta < H_2(c/\Delta)$(region B_3) the FP regime dominates.*
- *(iv) If $c/\Delta \in [x_2, x_1]$ and $H_2(c/\Delta) < c_0/\Delta < H_5(c/\Delta)$ (region B_2) the RE regime dominates.*
- *(v) If $c/\Delta \in [0, x_1]$ and $\max\{H_2(c/\Delta), H_5(c/\Delta)\} < c_0/\Delta < H_1(c/\Delta)$ (regions C_4 and B_4) the two IPR regimes are equivalent.*
- *(vi) If $c/\Delta \in [x_1, x_0]$ and $c_0/\Delta \leq H_1(c/\Delta)$ (region A) the two IPR regimes are equivalent.*

For parts (i) and (iii), 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, in the improvement game, it is better to have two firms (as under the RE regime) or one firm (as under the FP regime). Thus, the RE regime yields higher welfare if $W_2 \geq W_1$, that is, whenever $c/\Delta \leq x_0(1-p)$. In the region of interest here, $c/\Delta \leq x_2$. Recalling the definitions of x_0 and x_2 given earlier, we conclude that in this region the RE regime will yield a higher welfare as long as parameter values satisfy the inequality $(1-p)(2-p) \geq (1-\delta)/\delta$. For part (iv), firms randomize in the initial game under both IP regimes. Even though expected profits are zero under both IP regimes, the RE regime yields a higher welfare because firms do not appropriate the whole consumer surplus (under our Bertrand pricing condition). For part (v), firms randomize under the FP regime (earning zero-expected profit), and there is no investment under the RE regime, and thus welfare is equal to zero in both cases. Finally, for part (vi) the FP and RE regimes entail exactly the same equilibrium (and therefore the same welfare outcomes) in both initial and improvement games.

Proposition 5 does not say anything conclusive about the welfare ranking of the two IPR regimes when the parameters of interest fall in parametric areas C_2 and B_1 of Figure 3. It turns out that either welfare ranking is possible in these domains, depending on parameter values, a conclusion that is readily verified by evaluating equilibrium welfare, under the two regimes, for alternative values of the model's parameters.

The main conclusion, therefore, is that either IPR regime may dominate from a welfare perspective. In particular, the stronger protection of the FP regime is not necessarily preferred, and the weaker RE regime may actually be desirable. Specifically, this happens when the costs of innovation c and c_0 are not too high, so that the incentive for firms to invest exists regardless of whether or not there is an RE provision. In such a case the RE provision entails more R&D in the follow-up innovations, which increases the rate of innovation. Although this increased activity does not benefit the firms themselves (as shown earlier, they have an *ex ante* preference for the FP regime), it may benefit society through an increased consumer welfare. The RE provision can also dominate the FP regimes with higher innovations costs, specifically when, in equilibrium, firms follow a mixed strategy under either regime (region B_2). In such a case the firms' expected profits are dissipated in equilibrium, but the

RE regime yields higher welfare because it provides for some spillover to consumers (via the Bertrand pricing condition).[8]

The fact that the parameter space in which the RE regime dominates is disjoint exhibits, to a certain extent, one of the simplifying features of the model: the assumption that there is no surplus to consumers under the monopolistic pricing of the FP regime. Hence, the limited avenue for R&D benefit spillover to consumers that we allow in our model might slant the comparison in favor of the RE regime. Nonetheless, there is also a sizeable region of the parameter space with $c_0 > c$, and with high-enough costs of innovation, in which the FP regime yields higher welfare. In this parametric region the RE is not attractive from society's perspective because it does not provide enough incentive for firms to undertake the initial innovation (the positive externality that the initial innovator conveys to follow-up innovators is not adequately internalized).

5.3 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 is a central theme in studies of cumulative innovation (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 noninfringing). Under the FP regime, on the other hand, the winner of the initial game would find it profitable to license the right to innovate

8. A question raised during the review process concerns the robustness of the welfare results to relaxing one of the model's simplifying assumptions, namely that of reducing the firms' R&D decisions to a binary choice (to invest or not to invest). In a dynamic setting similar to ours, Bessen and Maskin (2006, footnote 10) explain that their results are expected to generalize to the case in which firms can also vary the intensity of their R&D effort, and such a presumption holds here as well.

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 5 we have shown that two firms are better than one iff $c/\Delta \leq (1-p)x_0$. 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).

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 et al., 2004; Thomas, 2004; Rimmer, 2005). Conversely, for the case of plant breeders' 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 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 welfare properties of full patent and research-exemption regimes.

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

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 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 dominates 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 of establishing a research program, as is arguably the case for the plant breeding industry (in which 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 discussed by Bessen and Maskin, 2000), the weaker incentive to innovate is immaterial (firms engage in R&D anyway), and the research-exemption regime results in a higher social payoff.

The model developed in this paper deals with innovation settings characterized by both complementarity and sequentiality, attributes that are present in a number of high-technology industries (e.g., computer software, biotechnology, and pharmaceutical industries). There are, naturally, related situations that do not fit well into the framework of our model. For example, if the initial innovation can be used as input in many subsequent innovations that do not compete directly with each other in the final use market, as is the case for some biotechnology research tools (e.g., the Cohen–Boyer recombinant DNA technique), then the particular structure of our model may not capture the relevant stylized facts. But for research settings in which the model's assumptions apply, our analysis offers useful insights with some policy relevance. For example, one of the shortcomings of the patent system as a way to spur private R&D investments concerns its one-size-fits-all nature (Scotchmer, 2004, p. 117). That is, the attributes that define the protection afforded by patents (e.g., patent length and breadth) are not tailored to the specific innovation environment (i.e., "difficult" and "easy" innovation are not treated differently). Contemplating an RE provision could be viewed as a way to relax somewhat the one-size-fits-all nature of the patent system. Specifically, it could help to explicitly differentiate the innovation incentive needs that characterize dynamic R&D settings which, as emphasized by Bessen and Maskin (2006), can be quite different from their static counterparts. Conversely, our results show that a patent system with an RE provision may not provide enough incentives for difficult (costly) initial innovations. This suggests that, whenever an RE provision characterizes the relevant IPR system (as in the case of PBRs discussed earlier), there exists a clear role for public research that complements private R&D efforts by focusing on such initial innovations.

Appendix

Proof of Lemma 1. To simplify notation, write $V_k \equiv V_L(\sigma_L(k), \sigma_F(k), k)$. Then from equations (3) and (4) we have

$$\begin{aligned} V_k = \Delta k - c + \phi\,[q\,\delta V_{k+1} + q\,\delta V_F + (1-2q)\delta V_k] \\ + (1-\phi)\,[p\delta V_{k+1} + (1-p)\delta V_k]\,, \end{aligned} \tag{A1}$$

$$V_F = \phi\,[-c + q\,\delta V_1 + (1-q)\delta V_F] + (1-\phi)\delta V_F\,. \tag{A2}$$

Hence, the leader's value function in equation (A1) can be written as:

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

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

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

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

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

Because it can be verified that the following convergence condition holds,

$$\lim_{n\to\infty} \gamma^n V_{k+n} \to 0,$$

the general solution to the value of the Leader can be written as:

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

Given the previous definitions of the parameters α, β, and γ, it then follows that:

$$V_k = \frac{-c + \phi q \delta V_F}{1 - \delta(1-\phi q)} + \frac{\Delta k}{1 - \delta(1-\phi q)} + \frac{\Delta\delta(\phi q + (1-\phi)p)}{(1-\delta(1-\phi q))^2}. \tag{A3}$$

This expression is conditional on V_F, which satisfies (A2). Upon solving the system of equations given by (A2) and (A3) we obtain the results claimed in Lemma 1.

Proof of Proposition 1

Part (i). If both firms invest in every period, their value functions are given by equations (9) and (10). Let $\hat{\sigma}$ denote the strategy profile in which only the leader deviates by not investing in only one given stage of state s. Then its expected payoff is

$$V_L(\hat{\sigma}, s) = s\Delta + p\delta V_F + (1-p)\delta V_L(\sigma, s).$$

Using equations (9) and (10), $V_F = V_L(\sigma, s) - s\Delta/(1 - \delta(1-q))$, and so

$$V_L(\sigma, s) - V_L(\hat{\sigma}, s) = -c + \frac{\delta q\Delta + \delta s\Delta(p-q)}{(1-\delta(1-q))}.$$

Therefore, $V_L(\sigma, s) \geq V_L(\hat{\sigma}, s)$ iff

$$\frac{c}{\Delta} \leq \frac{\delta q + \delta s(p-q)}{(1-\delta(1-q))},$$

Because $p > q$, if the condition is satisfied at $s = 1$ it will hold for all $s > 1$. At $s = 1$, this condition reduces to $c/\Delta \leq p\delta/(1-\delta(1-q))$. We finally observe that $x_2 < p\delta/(1-\delta(1-q))$. Thus, deviating by not investing in one stage of state $s = 1$ cannot be profitable for the leader when $c/\Delta \leq x_2$. Next consider the follower, and let $\hat{\sigma}$ now denote the strategy profile in which only the follower deviates in only one stage. The value of deviating is simply $V_F(\hat{\sigma}) = \delta V_F(\sigma)$. Hence, $V_F(\sigma) \geq V_F(\hat{\sigma})$ whenever $V_F \geq 0$ which, from equation (10), is equivalent to $c/\Delta \leq q\delta/(1-\delta(1-q)) \equiv x_2$.

Part (ii). Consider the candidate equilibrium profile $\sigma \equiv (\sigma_L, \sigma_F)$ where $\sigma_F(k) = \phi \in [0, 1]$, $\forall k$ and $\sigma_L(k) = 1$, $\forall k$. From part (i), $\phi = 1$ iff $c/\Delta \leq x_2$. For $c/\Delta > x_2$ and close enough to x_2, suppose that $\phi \in (0, 1)$. Then, in any one stage, the follower must be indifferent between actions I and N, that is, $V_F^I = V_F^N$ where $V_F^I = -c + q\delta V_1 + (1-q)\delta V_F$ and $V_F^N = \delta V_F$.

By using the expressions derived in Lemma 1, we find that $V_F^I = V_F^N$ requires ϕ to solve the quadratic equation (11). Note that $\phi \to 1$ as $c/\Delta \to x_2$ and $\phi \to 0$ 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 playing $\sigma_L(k) = 1, \forall k$ when the follower plays $\sigma_F(k) = \phi, \forall k$ is given by $V_L(\sigma, k)$ in Lemma 1. Deviating at one stage (only) of state s, by choosing action N at that stage, yields payoff $V_L(\hat{\sigma}, s) = \Delta s + \phi p \delta V_F + (1 - \phi p)\delta V_L(\sigma, s)$. Because $V_F = 0$ in the postulated mixed-strategy equilibrium, $V_L(\sigma, s) \geq V_L(\hat{\sigma}, s)$ holds as long as $V_L(\sigma, s) \geq \Delta s/(1 - \delta(1 - \phi q))$, which, by using the result of Lemma 1, is equivalent to

$$\frac{c}{\Delta} \leq \frac{\delta\,(\phi q + (1 - \phi)p)}{1 - \delta(1 - \phi q)}.$$

This condition, in the domain $x_2 \leq c/\Delta \leq x_1$, holds for all $\phi \in [0, 1]$.

Part (iii). If $\sigma_F(k) = 0, \forall k$, then the situation is isomorphic to that of the FP protection 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 $c/\Delta > x_1$.

Part (iv). If in the strategy profile σ both firms do not invest,$\forall k$, then $V_L(\sigma, 1) = \Delta/(1 - \delta)$ and $V_F(\sigma) = 0$. If $\hat{\sigma}$ denotes the strategy in which the leader invests at only one stage of state s, then the leader's payoff can be written as

$$V_L(\hat{\sigma}, s) = V_L(\sigma, s) - c + p\delta\frac{\Delta}{1 - \delta},$$

so that $V_L(\sigma, s) \geq V_L(\hat{\sigma}, s)$ if $c/\Delta \geq x_0$. Thus, in this domain the leader does not have a one-stage profitable deviation, and a similar argument establishes that the follower does not either.

Proof of Proposition 2

Part (i). We show that for each firm it is optimal not to invest given that its rival does not invest. The payoff from investing in the initial game, when the other firm does not, satisfies

$$V_0 = -c_0 + p\delta\frac{\Delta}{1 - \delta} + (1 - p)\delta V_0.$$

Thus $V_0 \geq 0$ iff $c_0/\Delta \leq p\delta/(1-\delta) \equiv x_0$. Because $c_0 \geq c$, in the domain of interest here the best response of each firm is not to invest.

Part (ii). We 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 initial game is given by V_M of equation (2) (with $k = 1$). The payoff to the firm playing $\sigma_0 = 1$ when its rival plays $\sigma_0 = 0$ satisfies

$$V_0 = -c_0 + p\delta V_M + (1-p)\delta V_0.$$

By using the expression V_M in equation (2), $V_0 \geq 0$ iff

$$\frac{c_0}{\Delta} \leq \frac{p\delta}{1-\delta}\left(\frac{1-\delta+p\delta}{1-\delta} - \frac{c}{\Delta}\right) \equiv H_1\left(\frac{c}{\Delta}\right).$$

Part (iii). When both firms invest with probability one, each firm's value function satisfies

$$V_0 = -c_0 + q\delta V_M + (1-2q)\delta V_0.$$

Because the firm that does not invest obtains a zero payoff, both firms invest in equilibrium if $V_0 \geq 0$. By using the expression V_M in equation (2), $V_0 \geq 0$ requires

$$\frac{c_0}{\Delta} \leq \frac{q\delta}{1-\delta}\left(\frac{1-\delta+p\delta}{1-\delta} - \frac{c}{\Delta}\right) \equiv H_2\left(\frac{c}{\Delta}\right).$$

Part (iv). Because here we have $c_0/\Delta \leq H_1(c/\Delta)$, then from (ii) each firm finds it profitable to invest if the other firm does not. On the other hand, because $c_0/\Delta \geq H_2(c/\Delta)$, then from (iii) it is best for a firm not to invest if its rival does. This implies that there exist two (asymmetric) pure-strategy Nash equilibria. There exists also a mixed-strategy equilibrium. Suppose that firm 2 randomizes between investing and not with probability σ_0. Then the payoff of firm 1 if it does not invest is $V_0^N = 0$, whereas the payoff to investing satisfies the recursive equation:

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

In a nondegenerate mixed-strategy equilibrium, $V_0^I = 0$, and so firm 2's equilibrium mixing probability must satisfy

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

Proof of Proposition 3

Parts (i) and (ii). In this parametric domain there is no difference in the improvement game between the FP and RE regimes, and thus the analysis of Proposition 2 applies.

Part (iii). If both firms invest with probability one, then the value function of each firm satisfies

$$V_0 = -c_0 + q\delta V_1 + (1-2q)\delta V_0,$$

and the value function of the firm that does not invest is $V_0^N = 0$. Therefore, both firms invest in equilibrium iff $V_0 \geq 0$, that is, $q\delta V_1 \geq c_0$. By using equation (13), which implies that here $V_1 = V_L(\sigma, 1) = c/(q\delta)$, this last condition reduces to $c \geq c_0$. Because we are limiting consideration to the case $c \leq c_0$, firms here invest with probability one only when $c = c_0$. From the foregoing, if $c/\Delta < c_0/\Delta \leq H_5(c/\Delta)$ then both firms must randomize in a (symmetric) equilibrium. If firm 2 invests with probability σ_0, then for firm 1 to be indifferent between investing and not we must have

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

Part (iv). If only one firm invests, then its value function satisfies

$$V_0^I = -c_0 + p\delta V_1 + (1-p)\delta V_0^I.$$

Thus, no firm invests in equilibrium if $V_0^I < 0$, that is, $p\delta V_1 < c_0$, or $c_0/\Delta > pc/q\Delta \equiv H_5(c/\Delta)$.

Part (v). If both firms invest with probability one in the initial game, then the value function of each firm satisfies

$$V_0 = -c_0 + q\delta V_1 + q\delta V_F + (1-2q)\delta V_0. \tag{A4}$$

When only one firm invests, the value function of the firm that does not invest satisfies

$$V_0^N = p\delta V_F + (1-p)\delta V_0^N. \tag{A5}$$

Both firms invest in equilibrium iff $V_0 \geq V_0^N$ which, from (A4) and (A5), requires that

$$\frac{q\delta(V_1 + V_F) - c_0}{1-(1-2q)\delta} \geq \frac{p\delta V_F}{1-(1-p)\delta}.$$

By using the expressions for V_1 and V_F derived earlier, the last condition can be rearranged to yield the claimed parametric domain.

Part (vi). When only one firm invests, its value function satisfies

$$V_0^I = -c_0 + p\delta V_1 + (1-p)\delta V_0^I.$$

Given that the rival does not invest, investing is not profitable if $V_0^I < 0$, that is (by using the expressions for V_1 derived earlier) iff $c_0/\Delta > (1 - c/\Delta)(p\delta/(1-\delta)) \equiv H_3(c/\Delta)$.

Part (vii). 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. In addition to these (asymmetric) pure-strategy equilibria, there exists a symmetric equilibrium in mixed strategies. Suppose that one firm invests with probability $\sigma_0 \in [0, 1]$. The rival's payoff from investing and not investing, respectively, satisfy

$$\begin{aligned} V_0^I &= \sigma_0 \left(-c_0 + q\delta V_1 + q\delta V_F + (1-2q)\delta V_0^I\right) \\ &\quad + (1-\sigma_0)\left(-c_0 + p\delta V_1 + (1-p)\delta V_0^I\right), \\ V_0^N &= \sigma_0\left(p\delta V_F + (1-p)\delta V_0^N\right) + (1-\sigma_0)\,\delta V_0^N. \end{aligned}$$

In a mixed-strategy equilibrium, $V_0^I = V_0^N$, implying

$$\frac{(\sigma_0 q + (1-\sigma_0)p)\delta V_1 + \sigma_0 q\delta V_F - c_0}{1-\delta(1-p)(1-\sigma_0 p)} = \frac{\sigma_0 p\delta V_F}{1-\delta(1-\sigma_0 p)}, \tag{A6}$$

where V_F and $V_1 \equiv V_L(\sigma, 1)$ are given by equations (10) and (9), respectively. This defines a quadratic equation in σ_0 of the form $a\cdot\sigma_0^2 + b\cdot\sigma_0 + e = 0$, where the coefficients $a < 0$, b, and $e \geq 0$ are implicitly defined in equation (A6). The equilibrium mixing probability is the root of this quadratic equation that belongs to the unit interval.

Derivation of the function W_ϕ in equation (20)

Suppose the leader invests with probability one and the follower invests with probability ϕ in each stage of the improvement game. Let $W_\phi(k)$ denote the expected surplus at state k. Then,

$$\begin{aligned} W_\phi(k) &= \Delta k - c(1+\phi) + \phi\left[2q\delta W_\phi(k+1) + (1-2q)\delta W_\phi(k)\right] \\ &\quad + (1-\phi)\left[p\delta W_\phi(k+1) + (1-p)\delta W_\phi(k)\right]. \end{aligned}$$

This difference equation can be solved and, for $k = 1$, yields the expression in equation (20).

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