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DYNAMIC IMPLICATIONS OF PATENTING FOR CROP GENETIC RESOURCES

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ABSTRACT

In a climate of rapid technological change, it is important to evaluate policies on the innovation incentives that result from the introduction of intellectual property rights as they relate to agricultural genetic resources. In this paper, we use a stylized model of cumulative innovation to explore the dynamics of introducing patent protection with licensing agreements, and then we contrast those results with the comparative-statics viewpoint. We also investigate the dynamic effects of claims on behalf of farmers on the profits of private crop breeders whose output is newly protected by patents.

We show that the choices about patent life and licensing share that optimize worldwide dynamic social welfare can be quite different from the values that maximize steady-state social welfare. Further, recognition of farmers' rights entails a dynamic welfare loss to producers and consumers that is not revealed in a comparative-statics analysis.

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DYNAMIC IMPLICATIONS OF PATENTING FOR CROP GENETIC RESOURCES

Bonwoo Koo and Brian Wright*

1. INTRODUCTION

Genetic resources have substantial economic value as repositories of genetic information that provide inputs into the development of plant varieties, drugs, and pharmaceuticals. It is estimated that about half of the world's medicines contain compounds from a natural origin (Schery 1972), while approximately half of the increased yield of major crops is commonly attributed to genetic improvement.[1] The high value of genetic resources available through certain plants and animals has long been recognized in the history of crop improvement (Juma 1989, Huffman and Evenson 1993).

Until the 1980s, the international trend was toward wider and easier access to wild and weedy plants and to farmers' crop varieties as the "common heritage of mankind," a concept encouraged by developed countries—the major users of such breeding material. Indeed, if investments were to be made in research into crop plant breeding, until recently, in most cases they were necessarily public. For plants like annual crops that have a short reproductive cycle with seed easily saved by farmers and planted again to breed true-to-type, a high premium for new breeding material—called germplasm—was infeasible.

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Changes in the technological, biological, legal, and political environments in which genetic resources are used have been dramatic over the past few decades. Advances in technology have sufficiently facilitated accurate identification of plant varieties and their parentage to enable laws against misappropriation to be enforced in circumstances where conventional observation would be indecisive. Advances in biotechnology have made it possible to identify genes associated with diverse traits—in particular resistance to pests and diseases—and to transfer these genes between different varieties and even between different species. These advances have encouraged the vision that countries in geographic centers of biodiversity might hold, within their borders, life forms highly attractive to developed countries, though the possible rewards from using those resources may be modest (Wright 1997).

Judicial and administrative decisions, particularly in the United States, have accelerated a trend toward privatization that was initiated earlier in the century through several means of protection for plant genetic resources, and the validation of utility patents on life forms and genetic materials.[2] The major elements of intellectual property protection for plants are more diverse than for most other subject areas. This fact may be at least partly explained by the need to develop substitutes for conventional patent protection in the years prior to availability of utility patent protection.

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[1] See, for example, Duvick (1984) for evidence on corn in the United States from trials comparing new and older varieties in yield tests.

[2] Rights to plant varieties and other life forms, or to their genetic materials, are now generally classified as "intellectual property rights," even though the information that is protected is not necessarily the product of intellectual effort, but rather genetic code that might not even be understood by the "inventor."

Internationally, developed countries have insisted that other participants commit to developing a system of intellectual property rights that covers life forms including plants and genes. Patents or other sui generis ("of their own kind") means of protection must now be adopted by many countries before a rapidly approaching deadline, unless current GATT (General Agreement on Tariffs and Trade) agreements are revised.[3] Developing countries, for their part, are asserting claims on genetic resources originating within their borders, ending the free access of plant breeders to genetic materials in situ in farmers' fields and other areas in centers of biodiversity. Though their efforts have not materialized in a legal sense, developing countries won endorsement of the concept of "farmers' rights" in the *FAO International Undertaking on Plant Genetic Resources* (FAO Resolution C 5/89).[4]

In this new policy environment, the question of the merits of adopting intellectual property protection over plant genetic resources has become a major focus of political debate in both developing and developed countries, as well as in public agricultural institutions such as the International Agricultural Research Centers (CGIAR). The issue of the possible positive economic effects of intellectual property protection for plants is

[3] Article 27(1) on the 1994 Trade-related Aspects of Intellectual Property Rights (TRIPs) agreements states that "members are required to provide for the protection of plant varieties either by patents or by an effective *sui generis* system or by any combination thereof." The deadlines for the implementation of the protection over plant varieties are 1995 for developed countries, 2000 for developing countries, and 2005 for least developed countries. In general, a sui generis system implies plant breeders' rights such as Plant Variety Protection Act in the U.S. or UPOV Acts. See Leskien and Flitner (1997) for more detail.

[4] "Farmers' rights" are defined as rights arising from the past, present, and future contributions of farmers in the conservation and development of plant genetic resources. However, farmers' rights are a moral commitment rather than legal rights, and they did not grant farmers ownership of genetic resources.

obviously an important input into this larger policy debate. In this paper, we consider the effects of policy regarding property rights to plant genetic resources for agriculture, at a time when the rights of seed producers to protect their innovations from expropriation are being initially recognized or strengthened in most countries. Because of the cumulative nature of plant-breeding processes for yield enhancement, the issue is essentially a multiperiod one. Moreover, because we are considering policy changes in the intellectual property rights over plants, the issue is clearly dynamic. Thus, the issue we address is an example of policy change in a chain of cumulative innovation, in which links in the chain and evidence of progress and causality are more explicit than is usual in innovation markets. This example may prove instructive in forming intellectual property protection policy in more complex environments.

Using a necessarily highly stylized model, we explore the dynamics of the introduction of patent protection with licensing to subservient patents, and contrast the results with the comparative-statics viewpoint that has been the focus of the few infinite-horizon models of R&D and patenting available up to now. We also investigate the dynamic effects of a strong form of claims on farmers' rights to the profits of private crop breeders whose output is newly protected by patents. We show that recognition of farmers' rights entails a dynamic welfare loss to producers and consumers that is not revealed in a comparative-statics analysis. Further, the decisions about patent life and licensing share that optimize worldwide dynamic social welfare can be quite different from the values that maximize the steady-state social welfare.

The paper is organized in five main sections. First we review the nature and use of agricultural genetic resources in plant breeding, and then we introduce the model of cumulative innovation, leading to an analysis of the effects of alternative patent systems on the innovator's incentive using the argument of dynamic programming. Next we investigate the dynamic implications of patent systems and farmers' rights through numerical analysis, and finally offer some concluding remarks.

2. THE NATURE AND USE OF AGRICULTURAL GENETIC RESOURCES

To properly consider the questions of this paper, it is necessary to be more precise about the types of genetic resources we are considering. Speaking generally, useful plant genetic resources make contributions to innovation that fall into two classes. In the first class are plants that test positive for a specific *qualitative* trait, such as resistance to a pest or disease in the case of agricultural applications, or anticancer or antibiotic properties in the case of pharmaceuticals. With respect to potential pharmaceuticals, the relevant plant traits are commercialized either directly, by extraction from the wild plants, or indirectly via the development of synthetic substitutes for naturally occurring compounds. The consumer is the target market for these products. In agriculture, pest and disease resistance are often associated with one or a small number of genes that can be identified and transferred to plant breeders who incorporate these genes in plant varieties to be sold to agricultural producers. These genes are often direct substitutes for chemical pesticides.[5]

The second class of genetic resources are those valued for their *quantitative*—e.g., yield-increasing—traits. Such traits in general are not readily associated with specific genes; indeed they might only be apparent via their combined effects on crop yield.[6] While it is relatively simple to evaluate the contribution of a single gene in the development of pharmaceuticals or pest- and disease-resistant crops, it is extremely difficult to determine the relative contributions of genes to a quantitative trait that affects

[5] Herbicide resistance genes are now another important set of biotechnology products not found by selection.

[6] Dwarfing genes, important in modern high-yield wheat and rice varieties, are prominent exceptions.

the overall performance of a given plant variety. Traits can only be readily transferred via their presence in elite parent lines using traditional breeding methods. It appears that the quantitative-yield trait has no comparable significance in the pharmaceutical industry.

Thus, a modern high-yield crop variety represents the latest achievement in a long, cumulative sequence of yield improvements over the landraces and perhaps the wild varieties that are its ancestors. Small portions of genetic material associated with specific traits may have been added from otherwise undesirable varieties, but the continued development of higher-yield varieties is essentially a cumulative process of incremental improvements on the genetic resources responsible for current yield levels.

In the context of this cumulative innovative chain, the implications of changes in the intellectual property protection can be quite different from those revealed in the common one-period (Nordhaus, 1969; Gilbert and Shapiro, 1990; and Klemperer, 1990) or two-period (Scotchmer, 1991, 1996; Green and Scotchmer, 1995; Chang, 1995; and Matutes et al., 1996) models, or in the available multiperiod models that take a comparative-statics approach (Horowitz and Lai, 1996; O’Donoghue, 1998; and O’Donoghue et al., 1998). We substantiate these claims in the next section, using a simple, and necessarily stylized, dynamic model.

3. A MODEL OF CUMULATIVE INNOVATION

ASSUMPTIONS

We assume an infinite sequence of innovation process, where each innovation is based upon previous innovations.[7] Innovations occur stochastically, and each innovation is the product of an *innovation race*. During each innovation race, n homogeneous innovators compete to be the first to develop an innovation whose flow value is v. The value v can be regarded as the amount of the "willingness-to-pay" by consumers who demand one unit of the product per period, or as the amount of quality improvement. In this model, we interpret v as the value of the reduction in production cost from each innovation. Another simplifying assumption, following O'Donoghue et al. (1998), and in contrast to Horowitz and Lai (1996), is that successful innovators place zero probability on the event that they will also be first to find the next innovation based on their innovation. Each successful innovator obtains a patent to appropriate any rent from his or her innovation; that is, the possibility of trade secret as an alternative means of protection is assumed away.

Patents affect an innovator's incentive, which in turn changes the rate of innovation in the industry. We assume that the scope of the patent is broad enough, and the durability of the technological advantage strong enough, to make the effective patent life equal to the statutory patent life T.[8] This implies that every innovation under the

[7] Scotchmer (1991) points out three possible relationships between successive innovations: the first innovation a) is a necessary condition for the following innovation, b) reduces the cost of achieving the following innovation, or c) accelerates the development of the following innovation. Our model assumes the first relationship.

[8] O'Donoghue et al. (1998) defines *effective patent life* as the length of time for which a patent enables a firm to receive a share of market profits. A patent effectively

overhang of previous patents is infringing, and each innovator should pay licensing fees to previous innovators until their patents are expired. Note that licenses are not given for use of the patented product, but for permission to work the next innovation while it is subservient to the patent on the current innovation.[9]

The royalty rate α can be set by the government through compulsory licensing, or sequentially by each innovator as the Stackelberg leader of subsequent innovators, or by innovators as the result of efficient bargaining. In the following analysis, we simply assume a flat royalty rate that is exogenous to each innovator. One interpretation of this assumption is that the royalty rate is regarded as the proxy of patent scope set by the government (or the court).[10] In the following analysis, we simply assume a flat royalty rate that is exogenous to each innovator. For tractability, we assume a simple licensing scheme—i.e., each innovator pays a license fee solely to the previous innovator, during the life of the previous patent, by a share, α, of all income the current innovator receives from exploiting his or her innovation and from the license fee of the subsequent innovation.[11]

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terminates either when it expires or when the new innovation is outside the scope of previous patents.

[9] To focus on effective changes in the intellectual property rights, we ignore costs of information, contracting, and enforcement that can be crucial in determining the market structure.

[10] For plant genetic materials, the value of each material is too low to make individual agreements, and the public-good nature of some crop varieties may justify the use of compulsory licensing.

[11] This scheme of transfer simplifies the calculation and captures the intertemporal transfer of license fees among successive innovators. In a sequence of innovations t, t+1, t+2, …, for example, this scheme is analogous to the case where the t innovator gets α of the t+1 innovator's payoff, an order of α^2 of the t+2 innovator's payoff, and so on.

With this licensing structure, the payoff from an innovation at a certain time depends on the time difference between that innovation and the one that immediately precedes it (called "overhang"). Unlike the open-loop investment decision of existing models (Loury, 1979; Lee and Wilde, 1980; and Dasgupta and Stiglitz, 1980),[12] the decision in our model is closed-loop, in which innovators have to revise the maximization problem at each instant of time during an innovation race. Innovation occurs according to a Poisson process with a hazard rate $\lambda(x)$, where x is the amount of R&D expenditure. Each innovator is assumed to be risk neutral and faces the same discount rate r.

AN INNOVATOR'S DECISION

An innovator's problem at time t is to choose the level of R&D expenditure x_t to maximize the expected profit.

$$\max_{x_t} \Pi_t = \lambda(x_t)V_t(T,\alpha) - x_t$$

where t is the distance of the innovation from the timing of the previous innovation, and $V_t(T, \alpha)$ is the total payoff from an innovation at time t, discussed below. Assuming that each innovator ignores the effect of his or her decision on the aggregate hazard rate (Dasgupta and Stiglitz 1980), we derive the first-order condition as follows:

$$\lambda'(x_t)V_t(T,\alpha) = 1 \qquad (1)$$

The shape of innovation technology (i.e., the form of the hazard-rate function) is crucial in the rates of successive innovations, and different assumptions have been made in existing models. Loury (1979) and Lee and Wilde (1980) assume that the hazard-rate

[12] Loury (1979), for example, assumes that firm i purchases the expected date of success with R&D cost at the *beginning* of innovation race.

function displays decreasing returns beyond some expenditure level, and Grossman and Helpman (1991) assume a linear hazard-rate function in which innovation can be accelerated indefinitely by spending more on R&D. Following Stokey (1995), we assume a hazard-rate function with decreasing returns to scale. For computational purposes, we will use the Cobb-Douglas functional form: $\lambda(x) = \theta x^{\varepsilon}$, where $\theta > 0$ and $0 < \varepsilon < 1$. With this specification, the hazard rate at time t, which satisfies the first-order condition (1), is[13]

$$\lambda_t^*(T,\alpha) = \theta\left[\theta\varepsilon V_t(T,\alpha)\right]^{\frac{\varepsilon}{1-\varepsilon}} \qquad (2)$$

From equation (2), it is clear that the optimal hazard rate at time t depends both on the patent life and on the royalty rate through the total payoff, V_t.[14] When there is a change in the patent life, the effect on the hazard rate at time t is expressed as follows:

$$\frac{\partial \lambda_t}{\partial T} = M \frac{\partial V_t}{\partial T}$$

where $M \equiv \frac{(\varepsilon\theta)^2}{1-\varepsilon}\left[\theta\varepsilon V_t(T,\alpha)\right]^{\frac{2\varepsilon-1}{1-\varepsilon}} > 0$. The sign of $\partial\lambda_t/\partial T$ is the same as that of $\partial V_t/\partial T$, and a similar argument applies to the effect of a change in the royalty rate α.

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[13] From the first-order condition $\theta\varepsilon x^{\varepsilon-1}V_t(T,\alpha) = 1$, we can derive that $x^* = \left[\theta\varepsilon V_t(T,\alpha)\right]^{\frac{1}{1-\varepsilon}}$. By substituting x^* into the Cobb-Douglas hazard-rate function $\lambda = \theta x^{\varepsilon}$, we get equation (2).

[14] The optimal hazard-rate function can also be interpreted as the innovation supply function, which relates the total payoff to the intensity of R&D. As $\varepsilon \to 0$, the slope of this supply function becomes vertical, implying that R&D intensity is not responsive to the change of the total payoff. As $\varepsilon \to 1$, however, the innovation becomes very responsive to the change of the total payoff.

THE PAYOFF FUNCTION

The total payoff of an innovator at time t consists of the *current payoff* from exploiting the current innovation (V_t^c) and the *expected payoff* from a license fee for the subsequent innovation (V_t^e): i.e., $V_t = V_t^c + V_t^e$. We define the *first innovator* as the one who has no previous innovation and does not pay any licensing fee. Since the decision of the first innovator does not depend on the previous patent, his or her total payoff is constant regardless of the innovation's timing. The *steady-state innovator* is defined as the one who pays licensing fee to the previous innovator. That innovator's total payoff and hazard-rate change as the period of the overhang from the previous patent declines. Every innovator except the first can be regarded as a steady-state innovator in our model. This non-stationarity distinguishes our model from existing models (Horowitz and Lai, 1996; O'Donoghue, 1998; and O'Donoghue et al., 1998), none of which consider the first innovation.

The Current Payoff

With a flow profit v, the current payoff from an innovation during the patent life T, when there is no overhang from the previous patent, is

$$V^c = \int_0^T v e^{-r\tau} \, d\tau \qquad (3)$$

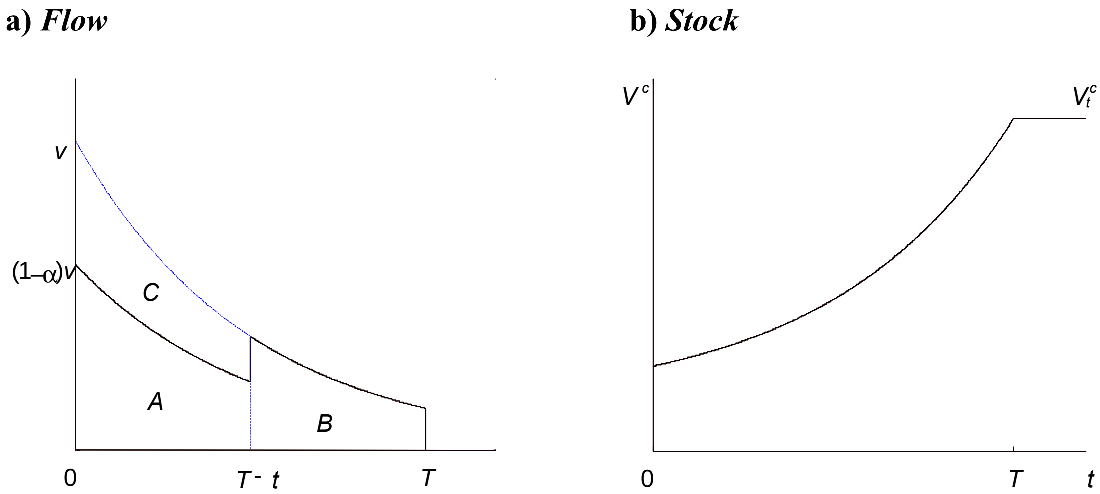
This is the payoff of the first innovator or of the steady-state innovator who is outside the previous overhang ($t \geq T$). The current payoff of a steady-state innovator who is under the overhang of the previous patent, with the royalty rate α, is

$$V_t^c = (1-\alpha)\int_0^{T-t} v e^{-r\tau} \, d\tau + \int_{T-t}^{T} v e^{-r\tau} \, d\tau \qquad (4)$$

The first term on the right-hand side (RHS) of equation (4) is the payoff during the overhang period $[0, T - t]$, in which the innovator receives $(1 - \alpha)$ of his or her profit (area A in Figure 1a). The second term on the RHS is the payoff outside of overhang $[T - t, T]$, in which the innovator receives the full profit (area B). The area C in Figure 1a is the amount of licensing fee transferred to the previous innovator during the overhang period. Either the first innovator or the innovator who is outside of previous patent can capture area C as well as area A and B.

As the distance from the timing of the previous patent increases, or the period of overhang decreases, area C becomes smaller and the current payoff increases, given the patent life and the royalty rate. Figure 1b shows the current payoff as a function of the time t, in which the height at time t corresponds to the areas A and B at time t of Figure 1a. The current payoff increases from the lowest level at $t = 0$ (i.e., under the complete overhang), and stays at the maximum when $t \geq T$ (outside of overhang). When there is no licensing agreement among innovators ($\alpha = 0$) or the previous patent has expired, the current payoff is constant at the level of the first innovator.

Figure 1 The current payoff



The Expected Payoff

Another important portion of the payoff comes from subsequent innovators through licensing fees. When an innovation occurs during the patent life of the previous innovation on which it was based, the current innovator should pay a licensing fee for the remainder of the previous innovation's patent life. The derivation of the expected payoff can be conceptualized as a two-step decision process: an innovator first calculates the total expected payoff without royalty payment to the previous innovator, and then determines his or her portion of the total expected payoff based on the duration of the overhang.

First, let $f(s) \equiv [1 - F(s)]n\lambda(s)$ be the probability that the last innovation occurs at time s, and consider the decision of the second-last innovator.[15] The expected payoff of the second-last innovator, who is outside of the previous overhang, is the weighted average of the licensing fee from the last innovator from 0 to T (e.g., area C in Figure 1a).

$$V^e = \int_0^T L(s) f(s) e^{-rs} ds \tag{5}$$

where $L(s) \equiv \alpha v \left(1 - e^{-r(T-s)}\right) / r$ is the amount of the licensing fee when the last innovation occurs at time s. If the last innovation occurs earlier (i.e., $f(s)$ is skewed more to the left), the expected payoff of the second-last innovator increases due to the longer stream of licensing fee, *ceteris paribus*.

If the second-last innovation is under the overhang of the third-last patent, the second-last innovator should transfer some portion of the expected payoff (including the licensing revenue from the last innovator) to the third-last innovator during the overhang period. When the last innovation occurs within the overhang of the third-last patent ($0 < s < T - t$), the second-last innovator gets $L(s) - \alpha L(s + t)$, transferring $\alpha L(s + t)$ to the third-last innovator. When the last innovation occurs outside of the previous patent ($T - t < s < T$), however, the last innovator keeps the full licensing fee $L(s)$. The expected payoff of the second-last innovator at time t is

$$V_t^e = \int_0^T L(s) f(s) e^{-rs} ds - \int_0^{T-t} \alpha L(s+t) f(s) e^{-rs} ds \tag{6}$$

[15] This does not mean that everyone knows that a last innovator exists, or that the model is finite. We need an initial condition to solve the dynamic programming problem, thus we start from the case where the expected payoff is zero, which happens to be the definition of the last innovator.

The total payoff of the second-last innovator at time *t*—the addition of the current payoff (equation (4)) and the expected payoff (equation (6))—determines his or her hazard rate through equation (2). This hazard rate is used for the derivation of the expected payoff of the third-last innovation in a similar way. If we continue this process of backward induction, we can derive the expected payoff and the hazard rate of a steady-state innovator. The hazard rate of the first innovator can be derived using equation (3) and the expected payoff of a steady-state innovator without overhang, analogous to equation (5).

The hazard rate is endogenously determined, and this intertemporal correlation among successive innovators makes it difficult to derive a simple analytic form of the payoff function (and hazard rate) for the steady-state innovation. A numerical calculation using the dynamic-programming approach is required to analyze the effect of patent systems on the incentive for innovation. In the next section, before examining the numerical solution, we will first sketch the possible effects of the changes in patent system on the hazard rates of a first and a steady-state innovator.

4. THE EFFECTS OF PATENT LIFE AND ROYALTY RATE

THE EFFECT OF A CHANGE IN THE PATENT LIFE

The payoff from an innovation depends on the policy parameters (i.e., patent life T and royalty rate α), as well as the timing of the innovation t. Longer patent life increases the current payoff V^c by lengthening the stream of the payoff. However, an innovator also has to pay licensing fees to the previous innovator for a longer period of time, thus making the net effect ambiguous for a steady-state innovator. For the first innovator, however, longer patent life always increases the current payoff since that innovator receives royalty fees for a longer period of time.

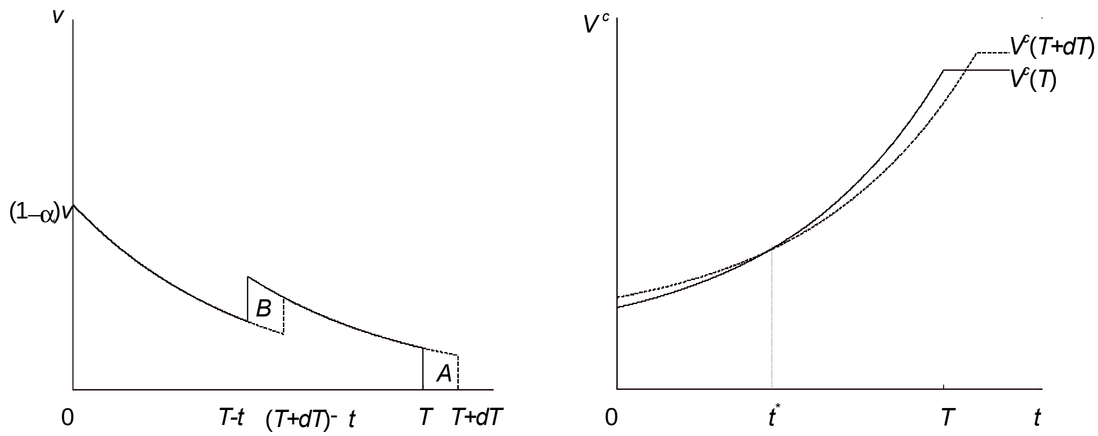
Similar argument is applied to the expected payoff V^e—i.e., longer patent life lengthens the stream of licensing income as well as the royalty payment to the previous innovator. However, there is an additional effect—i.e., a change in the patent life changes the probability of making the next innovation ($f(s)$) at each time. Thus, the net effect of a change in the patent life on the expected payoff of a steady-state innovator, and even of the first innovator, is ambiguous.

To see the effect of a change in the patent life more rigorously, we follow the argument of dynamic programming. Let's start from the last innovator whose payoff consists only of his or her current payoff. The effect of a change in the patent life on the current payoff at time t is

$$\frac{\partial V_t^c}{\partial T} = v\left(e^{-rT} - \alpha e^{-r(T-t)}\right) \tag{7}$$

Figure 2 The effect of a change in the patent life

(a) Flow **(b) Stock**



The first term on the RHS of equation (7) shows the increased stream of payoff due to the longer patent life, which corresponds to area A in Figure 2a. However, he or she also has to pay the royalty fee to the previous innovator for a longer period of time by area B (the second term of equation (7)). The net effect depends on the relative sizes of area A and B. The timing t where these two effects cancel and the change of a patent life has no effect on the current payoff is

$$t^* = -\frac{ln\alpha}{r} \tag{8}$$

For $t < t^*$, the patent life has a positive effect on the current payoff, and the opposite is true for $t > t^*$ (Figure 2b). That is, when there is a complete overhang from the previous patent, an increase in the patent life always increases the current payoff. If the "timing of crossing" occurs outside the patent life ($t^* > T$), which is likely to hold for a high discount rate r or a low royalty rate α, longer patent life always increases the current payoff. We assume $0 < t^* < T$ in the following analysis.

The change in the last innovator's payoff affects the expected payoff of the second-last innovator. The effect on the second-last innovator's expected payoff is derived from equation (5).[16]

$$\frac{\partial V^e}{\partial T} = \int_0^T \left[\frac{\partial L(s,T)}{\partial T} f(s,T) + L(s,T) \frac{\partial f(s,T)}{\partial T} \right] e^{-rs} ds \tag{9}$$

The first term in the integrand is the *direct effect* through the change in the total licensing income from the last innovator. Since the second-last innovator gets licensing fee for a longer period of time, the sign of this term is non-negative for all s—i.e., $\partial L(s,T)/\partial T = \alpha v e^{-r(T-s)} \geq 0$. The second term is the *indirect effect* through the change in the probability of making the last innovation. When the last innovator's hazard rate is changed, the probability of the last innovation at each time s is changed, which in turn affects the stream of licensing fee received by the second-last innovator. The change in the probability is negative for $s > t^*$ and positive for $s < t^*$.

If we continue the backward induction, we can show the patent life has an ambiguous effect on the innovation incentive of each innovator. However, there exists a specific parameter space in which the change in the patent life has no effect on the expected payoff ($\partial V^e/\partial T = 0$). In this case, we only need to analyze the effect on the current payoff for a steady-state innovator and the first innovator. This case is more likely to hold when the timing t^* is fairly small. For a small t^*, the size of the indirect negative effect is large enough to compensate the size of the direct positive effect. For other parts of the parameter space that make $\partial V^e/\partial T > 0$, an increase in the patent life has a positive effect on the second-last innovator's expected payoff, which in turn reinforces the positive effect on the third ast innovator's expected payoff. By backward induction, the patent life has a positive effect on the expected payoff of a steady-state innovator when the timing t^*, defined in equation (8), is large. The opposite result holds for a very small t^*, which makes $\partial V^e/\partial T < 0$. The actual size of the change depends on the functional form of the hazard-rate function, as well as parameter values, and thus the numerical analysis is necessary.

THE EFFECT OF A CHANGE IN THE ROYALTY RATE

The effect of a change in the royalty rate on the last innovator's current payoff at time t is

$$\frac{\partial V_t^c}{\partial \alpha} = -\frac{v}{r}\left(1 - e^{-r(T-t)}\right) \tag{10}$$

Equation (10) shows that a higher royalty rate unambiguously reduces the current payoff of the last innovator regardless of the timing of his or her innovation (Figure 3a). Thus, the last innovator's R&D expenditure will reduce, and thus the hazard rate of the last innovation will be decreased. The effect on the current payoff is the same for all innovators except the first.

While the current payoff is decreased from a higher royalty rate, the expected payoff may increase, since the subsequent innovator pays a higher royalty rate. However,

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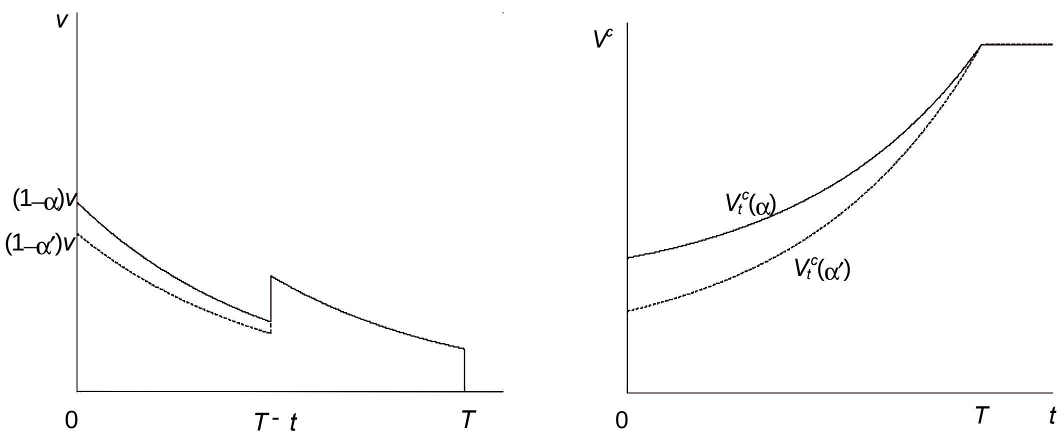
[16] Due to the two-stage process in the determination of the expected payoff, we can simplify the calculation by using equation (5) instead of equation (6).

Figure 2 The effect of a change in the royalty rate

(a) Flow **(b) Stock**



lower-hazard rates of the subsequent innovators have a negative effect on the expected payoff. The effect on the expected payoff of the second-last innovator is

$$\frac{\partial V^e}{\partial \alpha} = \int_0^T \left[\frac{\partial L(s,T)}{\partial \alpha} f(s,T) + L(s,T) \frac{\partial f(s,T)}{\partial \alpha} \right] ds \tag{11}$$

The first term in the integrand of equation (11) shows the increase in the licensing fee from the last innovator, i.e., $\partial L(s,T)/\partial \alpha = v(1-e^{-r(T-s)})/r > 0$. On the other hand, the second term shows the decrease in the probability of the last innovation at each time *s*, making the net effect ambiguous. Similar to the case of patent life, we can find a specific parameter space, which makes the net effect on the expected payoff zero, i.e., $\partial V^e/\partial\alpha = 0$). In this case, the analysis of the current payoff is sufficient to examine the effect of a royalty rate. For other sets of parameters, however, the effect on the expected payoff is ambiguous depending on the duration of overhang.

5. DYNAMIC EFFECTS OF PATENT SYSTEM AND THE IMPLICATIONS OF FARMERS' RIGHTS

DYNAMIC INNOVATION BEHAVIOR

We numerically solved the general dynamic version of the model for chosen parameter values using the dynamic programming approach, as discussed above. We assume an infinite horizon,[17] and use a discrete approximation to the continuous Poisson process. For a given parameterization,[18] the incentive of an innovator—i.e., the hazard rate λ—is a monotonically increasing function of the number of periods for which the previous patent will remain valid and the patent life T.

As shown on the right side of Figure 4, longer patent lives mean higher hazard rates once the previous patent has expired. This also implies that the first innovator always benefits from longer patent life. Longer patent lives also yield higher hazard rates when the overhang of the previous patent is a large portion of its patent life T, as is illustrated on the left side of Figure 4.

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[17] The assumption of a constant flow return v to successful innovation in each period does modest violence to the interpretation of v as the value of fixed decrement in the cost of production.

[18] Unless otherwise specified, the following parameter values are used for the rest of figures: $r = 0.2$, $\theta = 1$, $\varepsilon = 0.8$, $v = 0.3$, $\alpha = 0.5$, and $T = 20$. The parameter ε, which indicates the responsiveness of innovation probability to R&D incentive, is an important factor in the following analysis. High ε implies that innovation is sensitive to R&D investment, and the role of expected payoff is more prominent for high ε.

Figure 4 Hazard-rate functions under alternative patent lives

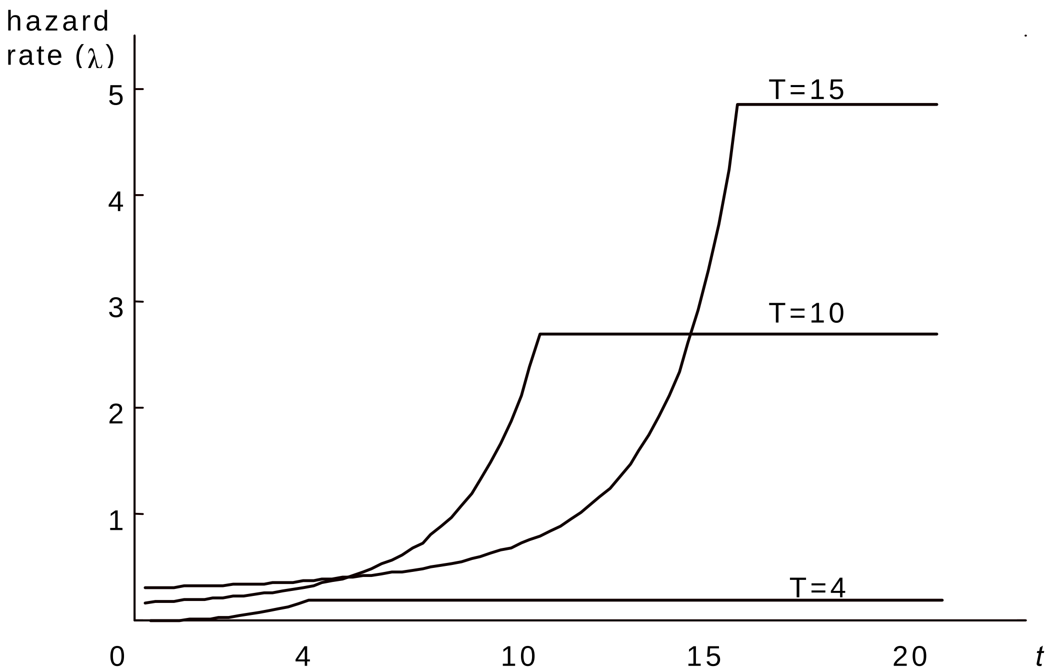
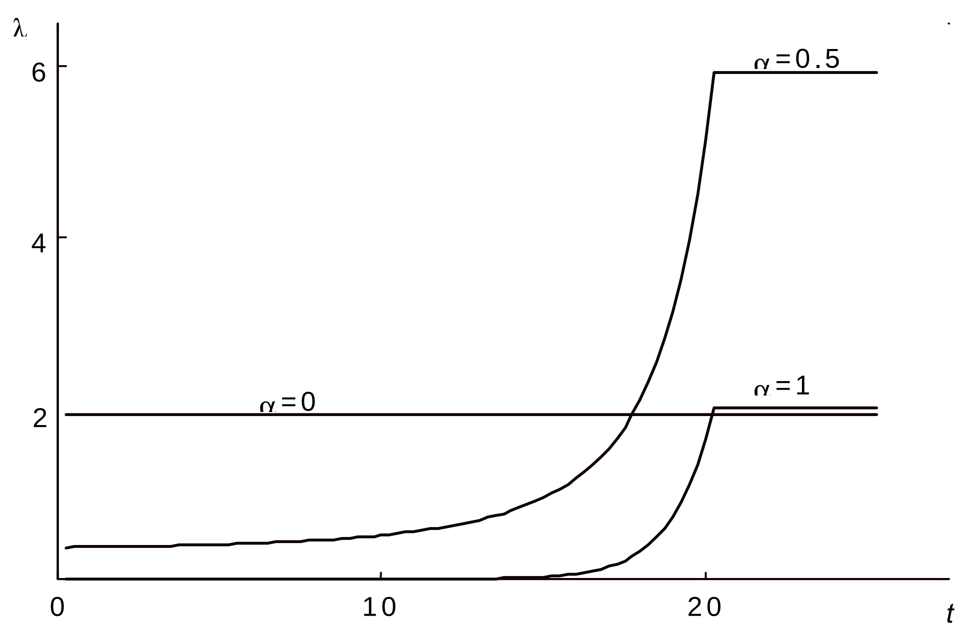


Figure 5 Hazard-rate functions under alternative royalty rates



For moderate overhang, however, a shorter patent life can actually induce a higher hazard rate, as is seen in the comparison of the curve for $T = 10$ relative to the curve for T=15, evaluated around ten years from the previous innovation. The prospect of deliverance from overhang encourages increased competition for the next innovation (even though a royalty must be paid if a discovery is made before the previous patent expires) as the time of expiration of the previous patent draws close. When the prospect is very distant, the effect of extending one's own patent life dominates the effect of an extension of the date when the previous patent will expire.

When the patent life is fairly short (say $T = 4$), longer patent life (say, to $T = 10$) increases the hazard rate everywhere, shown in Figure 4. For a short patent life, the timing t^*, defined in equation (8), is likely to be larger than T, and patent life has a positive effect on the hazard rate everywhere.

The hazard rate is also a highly nonlinear function of the royalty rate α. In Figure 5, the hazard rate is constant when there is no licensing agreements ($\alpha = 0$), which corresponds to the case of existing models without licensing agreements (e.g., Horowitz and Lai 1996). When the royalty rate α rises from zero, the hazard rate falls if overhang is large, and rises if it is small or zero. But the effects are certainly not monotonic.

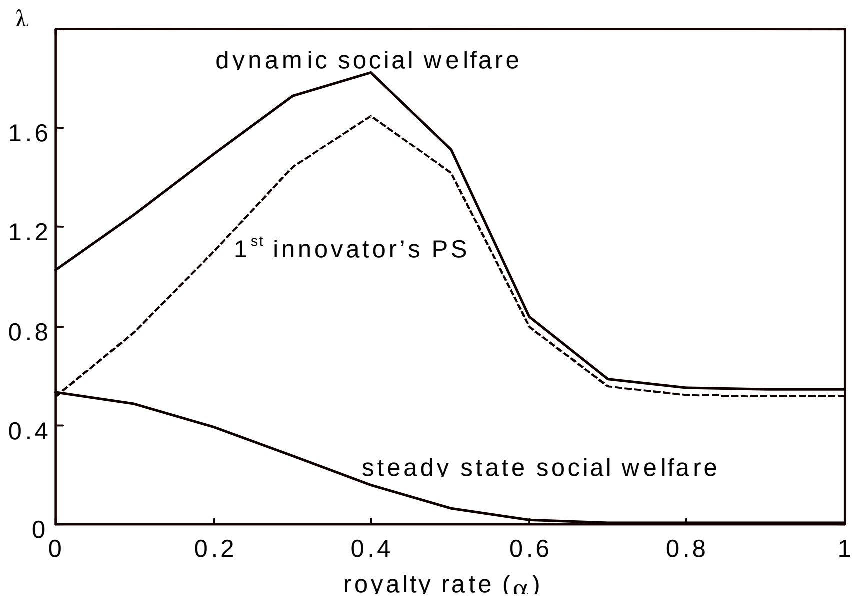
If the royalty rate is confiscatory (i.e., α is close to one), follow-on innovation is severely discouraged, reducing the incentives for current research and the overall rate of innovation. The first innovator's rate of innovation is decreased even when there is no overhang from a previous patent—i.e., the hazard rate with $\alpha = 1$ after 20 years is less than that with $\alpha = 0.5$ on the right side of Figure 5. For a very high royalty rate, the expected payoff of the first innovator is greatly reduced since the subsequent innovations, if any, occur slowly. So the first innovator is not better off by charging an excessively high royalty rate because the expected payoff is large when there are many subsequent innovations within the patent life, and this is achieved through a royalty rate that is less than confiscatory.

IMPLICATIONS FOR SOCIAL WELFARE

What does this behavior of innovation intensity as represented by the hazard rate imply for the welfare effects of the introduction of patents and licensing? In a situation in which access to genetic resources was previously free, the comparative-statics approach on welfare effects can be totally misleading. An increase in the royalty rate from zero reduces steady-state social welfare, as Figure 6 shows. The negative welfare effect of a higher royalty via patent overhang dominates the positive effect of increased revenue from subsequent patents, as noted by O'Donoghue (1996), for a simple, steady-state model. This result can be established analytically in our model for the special case where patent life is infinite (see appendix).

In contrast to the steady-state results, dynamic social welfare (in the partial equilibrium sense of the sum of the present values of consumer and producer surpluses) actually increases as the royalty increases in the case illustrated. From society's viewpoint, the speed-up of the first innovation, encouraged by the prospect of license fees, dominates the later negative effect of the lower steady-state innovation rate. The first innovator will, if he or she has the bargaining power, choose a royalty rate around 0.4 (Figure 6) to maximize the present value of producer surplus, which in this case constitutes the maximum of the dynamic social welfare.

Figure 6 Social welfare under alternative royalty rates



For the combination of parameter values, longer patent life always increases dynamic social welfare. Were patent life shortened, the social gain would be lower, but consumers would be major beneficiaries at sufficiently low patent life.[19] As the patent life increases, expected consumer surplus is more discounted and the producer surplus takes the larger portion of the social welfare.

EFFECTS OF A TAX ON BEHALF OF FARMERS' RIGHTS

The financing of a fund for farmers' rights, confirmed at the Convention on Biological Diversity in 1992, has been hampered due to lack of legal enforcement. Though the details on the implementation of farmers' rights are vague, one suggested proposal for financing the fund is to levy taxes on commercial seeds. Though this scheme is often criticized on the grounds that it would be the farmers themselves who would finally finance the fund, it certainly is one feasible mechanism through which the fund could be established.

Imagine a fixed amount of tax assessment on the *first* successful innovator in a previously open access system in plant genetic resources. If the tax is levied when the innovation for the first patent is made, the present value of this fixed tax for farmers' rights is highest under the royalty rate chosen by the first innovator—say 0.4 in Figure 7—in spite of a fixed amount of tax. The reason is that a positive royalty encourages a higher initial hazard rate for the first innovation, and so the delay before payment of the tax is lower, so its present value rises. In Figure 7, the tax assessment, which maximizes its present value of the tax revenue, occurs when $\alpha = 0.4$. This size is identical to the present value of initial royalty revenue when the rate is chosen by the first innovator to optimize his or her income from subsequent royalties, given patent life T.

Thus, optimization of the tax for farmers' rights in this model reduces the dynamic social welfare by setting the first innovation effort at its steady-state level. Without the initial boost in innovation induced by a new patent regime, the rate of search is initially lower, cost reductions are delayed, and social welfare declines. In this parameterization, much of the loss is borne by the effort of the suppliers of research in the form of a reduction in expected first-period producer surplus. For other parameterizations, the details of incidence could be substantially different.

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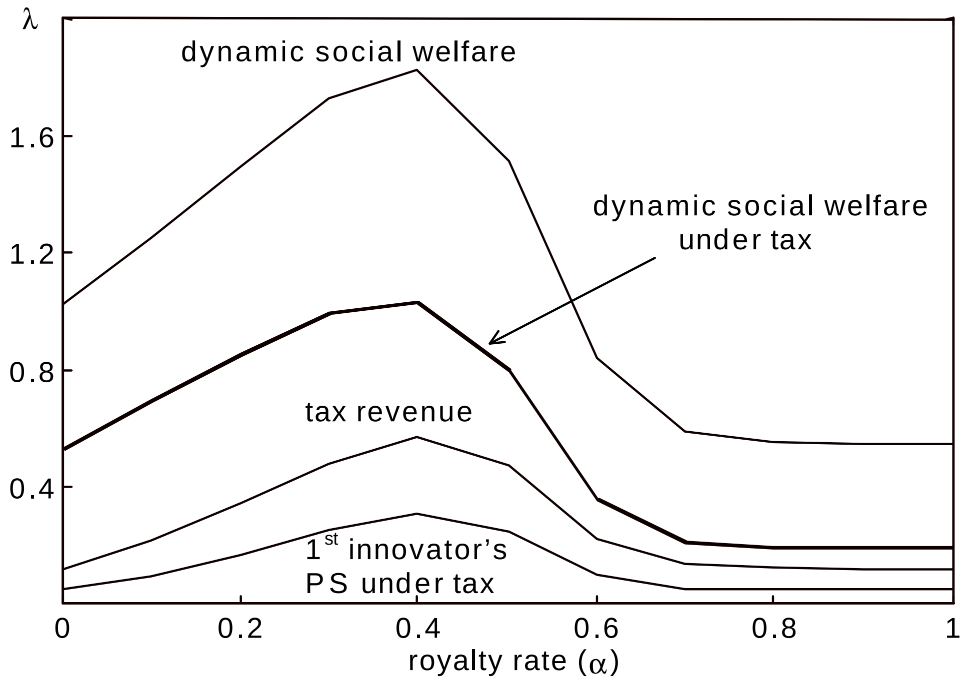
[19] In this model, consumers gain only after a patent expires, so shorter patent lives are more attractive up to the point where the incentive to innovate becomes too small.

Figure 7 Fixed tax on the first innovator: Dynamic effects



6. CONCLUSION

Rapid changes are occurring throughout the world in property rights protection, especially with respect to agricultural genetic resources and biotechnology. With the initiation or strengthening of property rights in genetic resources, innovators have the opportunity to use high-yield breeding material developed by public investment from a foundation of farmers' varieties and wild varieties to develop new, even higher-yield varieties that can be exploited like other private intellectual property.

In exploiting this dynamic property opportunity, private breeders maximize their profits by initiating a chain of licensing payments that can reduce subsequent yield increases relative to the open-access case. Nevertheless, the high dynamic incentive associated with the privatization of genetic innovations can increase dynamic social welfare if it dominates the discounted effect of subsequent permanent slowdown in innovation. Existing studies that focus on the steady-state innovation will provide a misleading policy option, and the balance of the incentives between the first innovator and the subsequent innovator should be carefully taken into account in the design of patent policy.

The providers of the original genetic resources are naturally anxious to claim part of the windfall from the privatization of the chain of innovation initiated by those resources. But if they achieve their compensation by taxing current innovators, the dynamic social benefits of privatization are reduced, even though the longer innovation rate might be unaffected. It is likely that alternative means of compensation could be found that are more efficient. These general effects of policy changes relating to patent rights should be of interest to those concerned with innovative incentives in other areas in which progress is cumulative.

Our conclusion is based on a very simple dynamic model, and several extensions are possible. First, other market structures such as monopoly or oligopoly may be instructive, considering the current trend of merger in the biotechnology and plant breeding industry. And, instead of a compulsory royalty rate, an assumption of an efficient bargaining on the royalty rate among successive innovators is another extension of our model (O'Donoghue et al. 1998). If the bargaining among innovators is allowed, the optimal royalty rate of a steady-state innovator depends on the overhang period from the previous patent. Though patent scope is implicitly included as the size of the royalty rate α in our model, we can also explicitly include the patent scope as the probability of next innovation. If the scope is narrow, the subsequent innovation is likely to be outside the current innovation, so effectively, from the current innovator's viewpoint, there is no following innovation.

APPENDIX 1
THE EFFECT OF LICENSING WHEN PATENT LIFE IS INFINITE

When patent life is infinite, an innovator's decision problem at each time *t* is the same—i.e., he or she gets (1 – α) of the constant payoff at every time. Unlike other cases where the hazard rate depends on the timing of the innovation, the case of an infinite patent life gives a constant hazard rate, enabling us to derive analytical solutions. Given that the first innovation has been found at time 0, the expected payoff from the next innovation by time τ is

$$\alpha v\int_0^\tau n\lambda\, e^{-(n\lambda+r)\tau_1}d\tau_1 = v\alpha\left(\frac{n\lambda}{n\lambda+r}\right)(1-e^{-(n\lambda+r)\tau})$$

The expected payoff to the first innovator from the next subsequent innovation by time τ, at time 0, is

$$\alpha^2 v\int_0^\tau n\lambda\, e^{-(n\lambda+r)\tau_1}\int_{\tau_1}^\tau n\lambda\, e^{-(n\lambda+r)\tau_2}d\tau_2\,d\tau_1 = v\alpha^2\left(\frac{n\lambda}{n\lambda+r}\right)^2\frac{(1-e^{-(n\lambda+r)\tau})^2}{2!}$$

The total expected present value of the payoff of the first innovator, including the transfers from subsequent innovations, as well as the payoff from his or her current innovation, is the infinite summation.

$$v\left[1+\alpha D(1-e^{-(n\lambda+r)\tau})+\frac{\left(\alpha D(1-e^{-(n\lambda+r)\tau})\right)^2}{2!}+\dots\right] = ve^{\alpha D(1-e^{-(n\lambda+r)\tau})}$$

where $D = n\lambda/(n\lambda+r)$. If the first innovation is subservient to a previous infinite patent, we get the expected present value of the payoff of the steady-state innovator.

$$V=\int_0^\infty (1-\alpha)ve^{\alpha D(1-e^{-(n\lambda+r)\tau})}e^{-r\tau}\,d\tau \qquad \text{(A1)}$$

If we differentiate (A1) with respect to α, we get the following.

$$\frac{\partial V}{\partial \alpha} = v\int_0^{\infty}\left[e^{\alpha D(1-e^{-(n\lambda+r)\tau})-r\tau}\left((1-\alpha)\alpha D(1-e^{-(n\lambda+r)\tau})-1\right)\right]d\tau$$

Since $(1-\alpha)\alpha D(1-e^{-(n\lambda+r)\tau}) < 1$, the sign of equation (A1) is if $n\lambda > 0$. Thus, under an infinite patent life, licensing ($\alpha > 0$) reduces the incentive for innovators in the steady state because the current innovation is always subservient to a previous innovation.

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