On Biology and Technology: The Economics of Managing Biotechnologies

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Summary

This paper considers those sectors of the economy that operate under the same regimes of rewarding private innovators as others, but differ in that they face recurring problems of resistance, as occur in the pharmaceutical and agricultural industries. This recurrence originates in the natural processes of selection and evolution among humanity's biological competitors. The paper examines the capacity for decentralised patent-based incentive mechanisms to result in socially optimal outcomes in these sectors under scale- and speed-dependent evolution of pathogens. It demonstrates that there is a fundamental incompatibility between the dynamics of the patent system and the dynamics of the resistance problem under both types of evolution. Under scale-dependent evolution, the externalities within a patent-based system indicate that decentralised mechanisms will result in systematic underinvestment in R&D that decreases further with an increasing severity of the resistance problem. Under speed-dependent evolution, a patent-based system will fail to target socially optimal innovation size. The overall conclusion is that patent-based incentive mechanisms are incapable of sustaining society against a background of increasing resistance problems. The paper concludes with appropriate policy implications of these results.

Keywords: Biotechnology, R&D, Patents

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1. Introduction

Human interventions within the biological world produce natural responses that automatically erode the effectiveness of the initial intervention. This effect is seen in the phenomenon of antibiotic resistance in the health context, or in the phenomenon of pest resistance in the agricultural context. These responses from nature are predictable and automatic because, when we choose to make a biological resource more prevalent than it would otherwise be, we are simultaneously selecting higher rates of prevalence for the pests and pathogens that prey upon that resource. These pests and pathogens will prosper by reason of our choices, and erode any gains from the initial intervention, unless we are able to intervene once again in a way that will restore the original gain. Thus, by intervening within the biological world, we are committing ourselves to a continuing race of innovation against nature.

Sustaining production in the face of these contests of biological innovation is the essence of the task that society assigns to the biotechnological industries. The biotechnology industries do so by generating and putting in place solutions to these recurring problems. Just like in any other R&D intensive industry, it operates under an innovation reward system based on patents in order to provide incentives for innovation. However, in other R&D industries, solutions generated last forever since there is no endogenous response to the innovative activity that renders previous innovations physically obsolete. This quality of "durability" that solutions in other sectors have gives rise to the essentially cumulative nature of technological progress in those sectors and is captured in macroeconomic models in terms of a "quality ladder" (Grossman and Helpman 1991). In the presence of evolving pests and pathogens, solutions are transient and temporary tools in a perpetual race that – metaphorically – appears much more like a treadmill than a ladder. The fundamental question is then whether a patent system designed for the world of durable solutions is an appropriate system of rewarding private firms for innovations that will not last. The analytical framework that we use to address this question builds on the model of "creative destruction" devised by Aghion and Howitt (1992). Their model considers the dynamics occurring within an industry that is motivated by the pursuit of patent-based rents from innovation. This "industrial" race of innovation takes place between industrial competitors, in which success is measured by the displacement of a rival's innovation with one's own. We introduce a second, namely "biological", race in which innovations are displaced by the successful evolution of pathogens. Thus our paper examines the intersection between two distinct races of innovation, one biological and one industrial. We examine the interaction between the dynamics of the problems of biological resistance and the dynamics of the policies based on patent-based incentive mechanisms. The principal enquiry pursued here concerns the use of decentralised incentive systems to motivate the pursuit of these objectives.

As indicated above, the Aghion and Howitt framework enables the investigation of the impact of atent-based incentive systems on the biotechnology industry. Under patent-based R&D systems, firms compete for patents that provide revenue streams until such time as another innovation renders that patent obsolete. In the biotechnology industry these patents will be displaced by a competitive firm's creation or a competitive pathogen's adaptation. How will firms operating under a patent system respond to the challenge implied by these biological contests? Are patents adequate for targeting the achievement of the gains sought by society? The distinction between the social objectives regarding biotechnology and the patent-based incentives to pursue them is the focus of this enquiry.

We commence in section 2 with a description of the intersection of the systems of dynamics represented by biological problems and patent-based incentives. In section 3 we develop our analytical framework, a model of the biotechnology industry and of the dynamics resulting from

human intervention. In section 4, we define the social objective with regard to the biotechnology sector. Sections 5 through 7 focus on scale-dependent adaptation of pathogens. We first derive the social optimality conditions for investment in biotechnology (section 5), then the patent-based incentive mechanism for motivating the biotechnology sector (section 6) before identifying the failures of a patent-driven system under scale-dependent selection by contrasting the social and private optima (section 7). Sections 8 through 10 follow the same structure in the context of speed-dependent selection in pathogen populations, deriving the social optimum (section 8) and then firm-level choice (section 9) in order to highlight the shortcomings of the patent system under this selection process (section 10). In section 11 we discuss some policy implications of the demonstrated inadequacy of the incentives for investment in biotechnology under patent systems and conclude in section 12.

2. Resistance Problems and R&D Policies: The Intersection of Dynamic Systems

In this section we describe the dynamic system that evolutionary biologists use to characterise the realm within which biotechnology operates, and how this system intersects with the dynamics inherent within a patent-based incentive system for innovation. Here biotechnology will refer to the use of biological resources as inputs into the research and development for the development of solutions to biological problems within the context of evolutionary processes. Biological problems are perceived by evolutionary biologists as zero-sum games between competing predators. Thus an infestation or infection simply represents the appropriation of a larger share of the available surplus by a competing organism. The evolutionary process is the combined result of the processes of selection, adaptation and reproduction. Thus the application of a particular pesticide or pharmaceutical to a pest population simply selects disproportionately those in the population which are resistant to it, resulting in disproportionate reproduction by those resistant, and consequently in the observed adaptation of resistance over time.

The biotechnology industries engage in an ongoing contest to solve these biological problems against the background of these evolutionary processes. For example, the pharmaceutical industry deals with such problems in its research into antibiotics, where it attempts to halt the progress of pathogens successfully reproducing themselves within the human population. After application of an antibiotic, the industry must then deal with the consequences of selection and adaptation, when the pathogen population begins to demonstrate resistance to the antibiotic (Laxminarayan and Brown 2001). The agricultural industry deals with such problems in its research into new plant varieties, when it attempts to produce new varieties in order to replace those registering declining yields. The commercially obsolete plant variety, as host to an increasingly successful pest population, is one that is registering the same problem that is preying on the human population in the pharmaceutical context. Again, the introduction of the new plant variety induces the responses of the pest population by reason of selection and adaptation, and the new variety begins its decline (Evans 1993; Scheffer 1997).

This indicates that one unusual characteristic of these sorts of problems is their refusal to go away (Munro 1997). When a solution has been ascertained and applied within the biological world, the nature of the biological world is such that it will commence immediately to erode the usefulness of that application. For empirical examples of this, see table 1 at the back. Adaptation of biota (pests and pathogens) to widely-used pharmaceuticals and plants is a “fact of life”, and it implies that the widespread use of any biotechnology must necessarily imply its own eventual demise

(Weitzmann 1999, Anderson and May 1991). This type of pathogen response is driven by scale of application and conforms to well-described laws (Hofbauer and Sigmund 1988).

A second type of pathogen response has received increasing attention in the recent past in the context of the release of genetically modified organisms. Here the driving factor is the speed at which new technologies are developed and applied. The impact of the speed of innovation on pathogen evolution is more speculative and various linkages have been suggested. One possibility discussed in the literature is that increasing the pace at which technology proceeds simply increases the speed of response by pathogen populations because innovations imply selection among competing pathogen populations (Stenseth and Maynard Smith 1984) or competing genes (Frank 2000). Widespread and rapid rates of innovation by biotechnologists therefore imply widespread and rapid rates of innovation by the pathogens as well. Biologists refer to these as Red Queen Contests, in which it is necessary to innovate more and more rapidly merely to maintain parity within the contest (Maynard Smith 1976). Another possibility is that increased pace of technology slows down the response from the pathogen population as it will take longer for successful survival strategies to emerge at the population level. This implies an opposite effect of the speed of innovation. Against the background of scale- and speed-dependent responses, the meaning of technological progress is much less straightforward. If the widespread use of a technological advance must necessarily imply the increasing rate of arrival of problems, then what is to be the measure of success? Think of the biotechnology sector as engaged in a race by the innovator up the "down" escalator. Then success in the race must be measured relative to actual progress up the escalator, not just steps taken by the innovator. Imagine as well that the escalator belt runs freely, so that quicker or larger steps by the innovator simply results in bringing the stairs down more quickly. Given that individual attempts at progress result in both discrete moves forward and an increasing pace of the background contest, the full impact of an innovation must be discerned by its aggregate impact across time. It is possible that small initial advances might ultimately aggregate into large net losses.

In sum, the biotechnology sector is presented here as that area of human enterprise dedicated to the maintenance of the stability of the "biological production sector", against this background of competing organisms continually evolving to introduce new biological problems. It pursues this objective by making investments that either a) slow the rate of arrival of biological problems; and/or b) increase the rate of arrival of solutions to such problems. One of the primary functions of the biotechnology sector is to determine the optimal amount of resources devoted to the diverse biological resources that are necessary to achieve these objects (Goeschl and Swanson 2002, forthcoming). The biotechnology sector is the manager of society's research and development efforts in order to make progress in the contest of biological innovation through the appropriate management of biological resources.

Having described the role of the biotechnology sector as that of generating innovations within the biological contest, we turn briefly to the role of the *industrial contest* that motivates the biotechnology industry to generate these innovations. The biotechnology sector is motivated by the pursuit of limited-term monopolies from the conferment of patents upon its innovations. In accordance with patent law, monopolies of a specified duration are allowed for useful innovations of a specified magnitude, i.e. representing a certain minimum level of advance. In focusing on patent-based mechanisms for motivating decentralised R&D, this paper is related to the literature on contests of innovation well known from the theory of industrial organization (Tirole 1988). The specific framework adopted here is the model of a sector engaged within a process of *creative destruction* (Aghion and Howitt 1992). Creative destruction is of course Schumpeter's term for the process by which firms innovate against a background of competitive innovation within the industry. In this scenario an innovation secures an advance for the firm, but only until

such time that another firm within the industry secures an innovation that destroys the usefulness of the first. Hence a patent-based incentive mechanism provides the capacity to capture a stream of rents from an innovation, but also provides the prospect that that stream of rents may be truncated by reason of a competitor's innovation.

With regard to the industrial contest, the one significant modification that we apply within this framework is to incorporate the possibility of another overlaid process of ongoing obsolescence deriving from forces within the biological, as opposed to the industrial, world. The stream of rents from an innovation may be truncated by reason of a competitive innovation originating in either contest, biological or industrial. We term the impacts of the biological contest on the industrial innovation contest a process of *adaptive destruction*. Against this background of creative and adaptive destruction, the biotechnology firm must compete to innovate in order to remain within the industry. Hence, it is the intersection of the dynamic systems represented by biological problems and patent-based policies that generate the ultimate incentives that motivate the biotechnology industry. How these unusual dynamics produce outcomes, and how these outcomes relate to the ultimate objectives society holds for the sector are the subjects of this paper. In the next section we set out the basics of a biotechnology sector, its role in addressing biological problems and the contest of biological innovation within which it operates.

3. A Model of a Biotechnology Sector

In this section we set out the basics of our approach to modelling a biotechnology sector. In this model we are looking at the role of the underlying research and development (R&D) sector that sustains the production sector. The biotechnology sector performs this task, explicitly, by conducting R&D to provide a flow of necessary innovations to sustain society in the contest of biological innovation. Implicitly it is determining the level of investment into R&D, including the level of investment of biological resources, and consequently the relative sizes of the production and reserve sectors. In between the research and production sectors, there is an intermediate goods sector whose sole role is to embody the information developed in the research sector for application within the production sector.

In order to render the discussion concrete, we will fix it within the agricultural sector. Within this context the base R&D sector is the plant breeding sector of the agricultural industry, and the intermediate goods are the registered seeds and high-yielding plant varieties (HYVs) within which innovations are embodied.[2] The only consumer good resulting from this industry is the agricultural output ultimately produced by the application of the intermediate good (HYVs) to the lands retained within the production sector.

Plant breeders' R&D efforts are increasingly addressed to the ongoing problems of pest adaptation and resistance.[3] Pests and disease now account for average annual crop losses of 28.9%, increasing with each year of the use of a given plant variety. (Oerke et. al. 1994; Evans 1993; Scheffer 1997). Plant breeders also engage individually in a contest of innovation against one another. Together these contests limit the commercially useful life of any newly introduced HYV to between 3 and 7 years. Hence the biotechnology sector underlying agriculture must continually innovate in order to address the problem of depreciation occurring within the production sector. Agricultural production takes place within an ongoing biological contest against continually adapting pests and pathogens. In this contest the plant breeding sector acts as society's innovator and thus determines society's ability to sustain production within this biological contest. As adaptation to existing HYVs occurs, the plant breeding sector must develop

new varieties of plants sufficiently innovative to thwart the advance of the prevailing population of pests and pathogens. Of course, if it succeeds, its success merely selects another strain of pests and pathogens for disproportionate evolutionary success, and the contest begins anew.

3.1 Modelling the Role of a Biotechnology Sector

Assume that there is a single consumption good that is generated by a three-tiered production system. The final goods sector consists only of production but it is sustained and stabilised by decisions made in the underlying R&D sector. The R&D sector generates innovations which are embodied in intermediate goods that are then inputs into the production of the final consumption goods. Think of the plant breeding sector at the base (the R&D sector) of the crop production industry, with the seed producers in the middle (the intermediate good sector) and agricultural production in the third tier (the final good sector). All value within the system derives from consumption of the final good, but that level of consumption is sustained by advances within the R&D sector.

3.1.1 Final Goods Sector

Final good production relies on only two inputs: the intermediate good (seeds) and the natural resource (land). Production of the final good occurs under the conditions of a fixed proportions production function, such that a fixed amount (β) of the intermediate input (x) is combined with each unit of the natural resources input (L). The proportion of the natural resources factor (L) allocated to final good production is termed *d*.

The final goods sector has a production function of the form

$$y_t = A_t F(x_t) \qquad (1)$$

with $F(0)=0$, $F_x>0$ and $F_{xx}<0$ [6] defining a concave production function in C^3. The productivity parameter A_t is determined by the level of technology being employed in the final goods sector at time t, and x is the amount of the intermediate good being used in that sector. This function is well-defined since, due to the fixed proportions in production, a choice of x uniquely determines the optimal allocation of L to this sector, d.

3.1.2 Intermediate Goods Sector

The intermediate good sector provides the link between the production sector and the underlying R&D sector. It does so through the production of an intermediate good that embodies the information produced within the latter, while being an essential input into the former. The actual production of the intermediate good exhibits the same type of production function as before. Here a unit increase in the amount of L allocated to intermediate good production will generate an increase in the production of the intermediate good x proportional to the factor z. The proportion of L allocated to intermediate good production will be termed g. Given these assumptions about the two production functions, the following identity will hold:

$$x_t = \frac{d_t}{\beta} = \frac{g_t}{z} \qquad (2)$$

Therefore, a given level of production of the intermediate input x is always associated with a specific allocation of the essential input L to production, as well as its allocation between intermediate and final good production.[7] The Leontievian structure of production in both the intermediate and the final sector can be justified by reference to the actual practice in the agricultural industry where there is an optimal fixed input of seed per hectare. It also helps abstract from the substitutability between production factors that would otherwise cloud the analysis.

This sector is important in this model only in that it affords the biotechnologist the capacity to capture the value of its innovations. Intermediate goods (here, seeds) are patented products that encapsulate the information generated within the underlying R&D process. Without the intermediate good, the production of information in the R&D sector would go unrewarded. We will return to the role of the intermediate market good as an incentive mechanism in section 5 below.

3.1.3 The R&D Sector

The R&D sector of the biotechnology industry produces disembodied technological innovations through the combination of human and natural resources. These innovations are then fed into the intermediate good sector for embodiment, and ultimate use in the production sector. The biotechnology industry must attract investment to this stabilisation function. Within this model we will be looking at a single factor of production used within both R&D and production sectors, viz. the supply of biological resources. A supply of biological resources is necessary for R&D in order to generate innovations. Likewise, biological resources are also required for production to occur in the production sector. The biotechnology sector's ability to attract investment will determine the relative allocation of these essential resources between the two functions, production or R&D.

Figure 1 gives a depiction of the biotechnology sector and its role in this production system. Here the biotechnology sector performs R&D and uses the essential natural resource as an input into its research activities. Innovations result in new technology that is embodied within patented products in the intermediate sector; the intermediate good also requires a small allocation of the essential input for production. Finally, the intermediate good is then used in the final goods production sector in combination with the essential natural resource in order to produce the goods that are marketed to consumers.

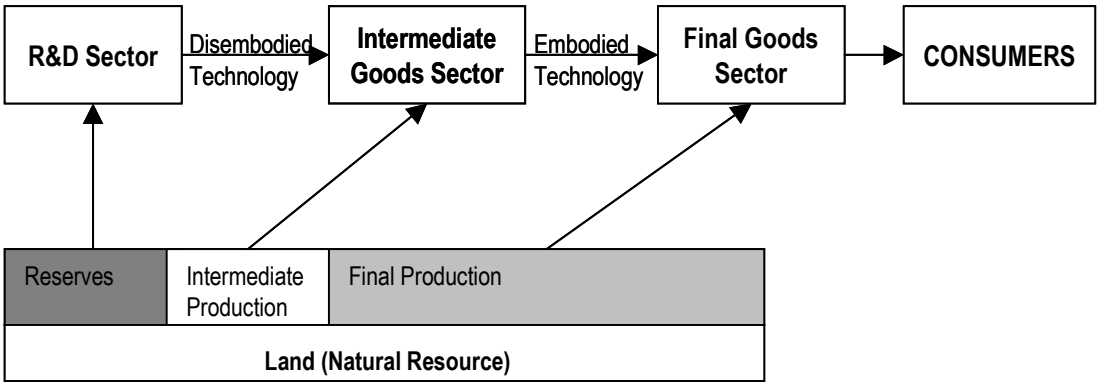


Figure 1: The biotech sector within a three-tiered production system

Here we will define “Land” as the underlying factor that determines how biological resources will be allocated between production and R&D. Land provides agricultural production when allocated to the production sector, while providing diverse plant genetic resources when dedicated to non-production (the “reserve sector”). The problems of interest to us involve the manner in which the biotechnology sector will determine the optimal allocation of the natural resource (land) between production and R&D. A part of this problem concerns the capacity of patent-based systems for providing optimal incentives for the attraction of investments into the biotechnology sector. Before we turn to these issues, it will be necessary to define the dynamic structure of the model.

3.2 Dynamics - Innovation and Adaptation

We have previously described the dynamics of the biological contest, where innovations induce adaptations. Here we specify this contest within the step-climbing context that we used to describe it earlier. An innovation represents a step upwards, while an adaptation is standardised as a step backwards. The current stage of technology is then a single parameter that captures the history of the competition to date as the net of the number of such steps, forwards and backwards.

3.2.1 Innovation and Creative Destruction

It is assumed that the timing of innovations flowing from the biotechnology sector follows a Poisson process denoted by $\varnothing$. The frequency of innovations within this process is determined in part by the level of investment in research and development (R&D). A distinguishing characteristic of biotechnology industries is that they depend in part on supplies of biological resources for undertaking the R&D process, and this is the factor of production on which we focus. Specifically, it is assumed that the frequency of innovation increases with the proportion (v) of the essential input (L) allocated to R&D. Innovations hence arrive at a rate $\varnothing\, i(v)$ per time period where $i(v)$ $i(0)=0$, $i_v>0$, is an innovation production function.

The impact of an innovation consists of a discrete shift in the level of productivity in the final sector which we denoted in (1) by A_t. Although this assumption will be relaxed later, assume initially that the size of shift is exogenously fixed and that this shift is of magnitude $\gamma>1$ such that $A_{I+1}=A_I\cdot\gamma$.[8] The index I denotes the current level of technology in use in final goods production.

We will note for application in later sections that innovations also have a destructive facet to their characters within the industrial context. The occurrence of a “technological innovation” is an event that renders the currently prevailing technology within the industry obsolete, i.e. innovations in this model are "drastic".[9] Hence each act of creation is an act of destruction with regard to the usefulness of all previous innovations. Under a patent system, this is equivalent to stating that an “innovation” is defined to be only that amount of technological change sufficient to warrant patent protection. We will standardise innovation at this magnitude, in order to provide a standard measure of innovation with which to compare technological progress across various systems of organisation. Hence we will measure aggregate technological change as the sum of the number of discrete “steps” of innovation of the minimum length required to acquire a patent.

3.2.2 Innovation and Adaptive Destruction

As discussed above, the biotechnology sector has the unusual characteristic that the application of its innovations within the production sector results in an induced response in the form of

"biological innovations" by pathogens. In this paper, we consider both scale and speed-driven responses. These responses will then render the innovation obsolete, a process we termed "adaptive destruction". The impact of a biological innovation is to reduce the economic productivity of the final goods sector - by eliminating the gains that were generated by the adoption of the current technology. Previous models describing the process of scale-driven endogenised response have cast this mechanism in the equations of frequency-dependent selection arising out of the biological literature (Laxminarayan and Brown 2001, Munro 1997, Mangel 1985). Here we allow for a more general type of relationship between scale of technology application and speed of adaptation that also reflects the stochastic nature of the process. Analytically, we model the dynamic process of biological innovations forced by selection pressure as a Poisson process represented by λ.[10] In purely scale-dependent selection, the frequency of innovation increases with the use of the intermediate input that embodies the current technology in accordance with an induced evolution function $a(x)$, $a(0)=0$, $a_x>0$.[11] Hence, pathogens adapt to and overcome current technologies at a rate of $\lambda a(x)$.[12] In speed-dependent selection, the frequency of adaptations is also influenced by the step size of innovations. In this case, we write the induced evolution function as $a(x, \lambda)$ and the resultant rate of innovation as $\lambda a(x,\gamma)$. Possible functional relationships between step size γ and induced evolution are discussed later.

As indicated above, the rate and extent of adaptation depends on the rate and extent of uniform adoption of the innovation. Since we have assumed that innovations are "drastic", this means that a technological innovation displaces all other competitors from use throughout the final goods sector. Then the extent of use of the innovation will depend only on the relative size of the production sector (relative to the reserve sector). Thus, the only limitation on the use of the intermediate good (x) will be the extent of the reserve sector (v), and we can equivalently express the function determining the rate of biological innovation as a function of the size of the reserve sector. A "biological innovation" is normalised so that a single innovation eliminates the relative advantage of the current technology.[14] This results in a shift of γ^{-1} in productivity.[15] Thus, with D denoting the stage of biological innovations (i.e. depreciation), $A_{D+1}= A_D \cdot \gamma^{-1}$. This implies that after a biological innovation has occurred, the economy reverts to a technology of the previous productivity level.

3.2.3. The Net State of Technology

These two processes of innovation and adaptation jointly determine the current state of productivity (A) within the final goods sector. Each technological innovation that occurs represents a positive shift in sector productivity, while each biological innovation represent a negative shift. With s denoting the current technological stage given a history of innovations and adaptations, the productivity at stage s is then,[16]

$$A_s = A_0\gamma^s = A_0\gamma^{I-D} \qquad (3)$$

Equation (3) therefore describes the current state of technology in use in the final goods sector as a single parameter expressing the history or aggregate impact of the contests of creative and adaptive destruction. Progress in the production sector in the sense of absolute improvements in productivity occurs only to the extent that the number of technological innovations exceeds the number of biological ones.

4. The Social Objective for Biotechnology

We commence by assuming that society consists of a continuum of individuals of mass *1,* each with an intertemporal utility function linear in the consumption of final good y, of the type:

$$u(y) = \int_{\tau=0}^{\infty} e^{-r\tau} y d\tau \qquad (4)$$

In this representation of the problem the individuals concerned are giving no direct consideration to the costs of instability, uncertainty or risk. The individuals in this society value only the flow of consumption goods from the final production sector, with no inherent value given to the products of the R&D sector. This social objective creates a role for an intermediate goods sector, in which R&D outputs are embodied, and it makes clear that any increase in production will be considered equally valuable.[17] Hence the decision problem with which we are concerned is the optimal allocation of natural resources (land) in the pursuit of the objective of maximum production. The importance of sustainability within this objective will be inferred from the need to maintain production against the background of pathogen adaptation.

Noting that the total amount of land will be allocated between the various sectors of this industry, this implies the existence of the constraint (for $L=1$):

$$1 = v + d + g \qquad (5)$$

Equation (5) implies that the processes governing both creative and adaptive destruction can be rewritten as functions of the reserve size v only. From (3) and (5) follows that $x=(1-v)/(\beta+z)$ such that $a(x)$ can be expressed as $a(v)$ with $a_v<0$. We now need to incorporate the concepts of creative and adaptive destruction within the model. We use the probability distributions $\Pi(I,t)$ (the probability of I technological innovations by the time t) and $\Pi(D,t)$ (the probability of D biological innovations by the time t) defined as:

$$\prod(I,t) = \frac{1}{I!}[\phi i(v,\gamma)t]^I e^{-[\phi i]t} \qquad (6)$$

$$\prod(D,t) = \frac{1}{D!}[\lambda a(v,\gamma)t]^D e^{-[\lambda\alpha]t} \qquad (7)$$

We are now in a position to set out the social objective for a biotechnology sector. As shown in the appendix, we can combine the expressions (1) – (7) and aggregate to re-state the social objective of maximum production as follows:

$$\underset{v,\gamma}{Max} U = \int_{t=1}^{\infty} e^{-rt} \sum_{I=0}^{\infty} \sum_{D=0}^{\infty} [\Pi(I,t)\cdot\Pi(D,t)] A_s F(x) dt \qquad (8)$$

The societal objective is to maximise the social welfare function (8) by choosing the proportion (v) of the essential input (L) to be allocated to R&D, subject to the constraint (5) and under the assumption of innovation size being a choice variable by choosing γ. This objective contains the race of innovation within it. A_s represents the current state of technology, which is generated by the history of past innovations. The probability distributions indicate the current period's contest,

i.e. the number of innovations and adaptations occurring within that period. Production is the product of both the net state of technology generated by the race (represented by A_s) and the amount of land that is dedicated to production. Thus the re-stated objective intimates the trade-off between investing biological resources into production or into innovation.

We are able to see the explicit nature of the trade-offs involved by means of integrating equation (8) over real time and making use of (4); the appendix shows how to arrive at the following expression for the present value of social welfare from the allocation of this input between these sectors.

$$U = \frac{A_0 F(\bullet)}{r - [\phi i(v,\gamma) - \lambda a(v,\gamma)\gamma^{-1}](\gamma - 1)} \qquad (9)$$

where $F(\bullet)$ is $F[\beta^{-1}(1\text{-}v\text{-}g)]$ and $a_v<0$ from (5).

Equation (9) captures the differentiated roles of the production and R&D sectors in generating social welfare over time. The impact on output from the allocation of lands to the production sector is denoted in the numerator, while the impact from allocation of lands toward the R&D sector is captured in the denominator. In simplest terms, the choice of the size of the production sector determines the initial level of production, while allocations of resources to the R&D sector determine the growth path of production. The role of the biotechnology sector is then seen to be the determination of the trajectory of welfare generated within the production sector, by sustaining the sector in the biological contest.

The numerator exhibits a straightforward impact from increased land in production in that reducing v benefits the output in the final sector. The denominator gives a sort of "own discount rate of biodiversity" that has to be applied to determine the value of the perpetuity that is the flow of final sector output over the infinite time horizon. It is a composite of the social rate of time preference (r) reduced[18] by the rate of technological innovation, $\phi i(v)$, and increased[19] by the rate of biological innovation $\lambda a(v)$.

This own discount rate captures the expected impact of the contest of innovation between the biotechnology sector and the biological world. There are really three cases. If the sector is successful in maintaining innovation rates significantly in excess of adaptations, then the own discount rate may approach zero, implying a substantial multiplier on initial production levels. This is the case where the growth trajectory is very steep. Conversely, if the biotechnology sector is very unsuccessful, the number of adaptations will follow closely the number of innovations and the growth trajectory will be flat. In the extreme, the production system is unsustainable with adaptations exceeding innovations. Finally, there is the situation in which the biotechnology sector is in a closely-contested Red Queen race, in which it attempts to make advances against the background of a system always responding to depreciate those gains.

From equation (9) a number of policy-relevant propositions result. We first examine the limiting cases of allocating land to the reserve sector in terms of their implications for welfare.

PROPOSITION 1: If all land is converted to use in the final production sector, social welfare converges to zero.

PROOF: Total conversion of land into intensive use implies that the share of land allocated to the final sector, *x*, is one. From *x=1* follows that all reserve lands are converted such that *v=0*. Taking the limit of equation (9) with respect to $v \to 0$, we get

$$\lim_{v\to 0} U = \lim_{v\to 0} \frac{A_0 F[\bullet]}{r - [\phi i(0) - \lambda a(0)\gamma^{-1}](\gamma - 1)} = 0$$

An allocation that does not result in a positive size for reserves implies an intrinsic discount rate of infinity. The intuition is that the expected rate of biological adaptation rises to infinity in such a setting, implying practically immediate obsolescence of production technologies and no generation of further innovations.

PROPOSITION 2: As the reserve sector expands to the total available land, social welfare converges to zero.

PROOF: Taking the limit of equation (9) with respect to $v \to 1$, we get

$$\lim_{v\to 1} U = \lim_{v\to 1} \frac{A_0 F[0]}{r - [\phi i(1) - \lambda a(1)\gamma^{-1}](\gamma - 1)} = 0$$

An allocation that does not allocate land to productive use denies consumptive utility to society and hence results in no welfare creation in the economy. Land in intensive use is therefore necessary to generate instantaneous returns to land assets.

Propositions 1 and 2 together suggest that the optimal solution to the allocation problem entails putting some amount of land into productive use while balancing the dynamic problems arising in this area through a reserve sector. We believe that, in the long run, this is the correct way in which to view the role of the biotechnology sector. It is the sector responsible for attaining and maintaining small amounts of relative advantage within a contest of biological adaptation.

5. The Optimal Allocation of Resources to the Biotechnology Sector under scale dependent selection

What is the optimal allocation of resources (i.e. land) to the biotechnology sector? Solving (9) for the optimal level of *v*, we get the following expression for the socially optimal level of investment in the biotechnology sector.

PROPOSITION 3: The allocation of resources to the biotech sector is socially optimal where the gross marginal loss in production (including intermediate production) through additional land in reserves equals the net present value of the net increase in productivity in the final goods sector generated by the reserve sector.

PROOF**:** Maximizing equation (9) with respect to reserve size *v* results in the following optimality condition:

$$\frac{F_v(\bullet)}{\beta + z} = \frac{[\phi i_v(v) - \lambda a_v(v)\gamma^{-1}]F(\bullet)}{r - [\phi i(v) - \lambda a(v)\gamma^{-1}]} \qquad (10)$$

at the optimum with $F(\bullet) = F[\beta^{-1}(1-v-g)]$.[21] The RHS of equation (10) is the cost of moving the last unit of land out of productive use into the reserve sector and thus measures the loss in production. The LHS is the benefit of adding a unit of land to the reserve sector in terms of productivity increases. Note that the net present value of productivity increases in the final goods sector referred to in proposition 3 is determined by the marginal increase in the rate of arrival of innovations and the marginal reduction in the rate of biological innovation that result from expanding the reserve sector and – as a result – reducing the final sector.[22]

The own discount rate applied is -as discussed below - the composite rate used by the social planner which takes into account the rates of technological and biological innovation.[23] In short, the trade-off is between an initially increased level of production versus a perpetual increase in the rate of growth. To see this, consider equation (9). This expression defines an expected expansion path for final output in the economy along the path $\left[\phi i(v^*) - \lambda a(v^*)\gamma^{-1}\right]\ln\gamma$. This path is unambiguously increasing in R&D investments (v). Any small advantage acquired in the current period's contest of innovation may be warranted by reason of the change in path that it implies.

Biotechnology here is seen to be an industry that determines the relative weights that society will give to the goals of production versus stabilisation within the biological sector. In order to do so, it implicitly determines the relative allocations of resources to the "production" and "diversity" sectors that are required to implement those goals. As in Weitzman (2000), the threat of unsustainability of this industry may be viewed as the choice of any path that might lead ultimately towards zero production. More generally, the problem of optimal biotechnology investment may be seen to be any decision that places the sector on a path with inadequate rates of innovation.

Propositions 3 determines the socially optimal solution to the problem of choosing a development path in the presence of pathogen adaptations in the final sector that occur in response to the scale of application. In reality, decision-makers in biotechnological companies choose this path based on the incentives prevailing in the industry in a decentralised fashion. These incentives and their impact on industry choices are the subject of the following section.

6. Firm Decision Making under scale-dependent selection

A decentralised R&D industry requires substantial policy intervention to be operable. This is because the benefits generated from investments in R&D are usually inappropriable or very inexactly appropriable, and this leads to suboptimal levels of investment in R&D (Arrow 1962). One policy response to this problem is the creation of a regime of monopoly rights in the marketing of intermediate goods that embody some of this information, e.g. *patent rights*. As those in other sectors of the economy, innovations in the biotechnology industry are rewarded using the same regime of patents. Here, we examine the incentives created by a patent system for investment in biotechnological innovations, initially under the assumption that the size of innovations is fixed. The question is: How will a private biotechnology firm within an industry of the type described above respond to the incentives to invest in R&D? To answer this question, we explore how an individual firm in pursuit of a patent in the intermediate good sector will approach the same decision faced by the social planner in the previous section, i.e. the allocation of an essential input between the R&D and production sectors.

6.1. Patent-based Profits in the Intermediate Good Market

The initial question concerns the magnitude of the rewards to be obtained through innovation. What is the level of the profits obtainable by the patent holder in the intermediate goods sector? Firms in possession of a patent have the capacity to choose the optimal level of output for the intermediate good embodying the patented technology. As we are assuming a perfectly competitive final goods sector, the optimal amount of good *x* produced is the level of output that maximises revenues minus the cost of producing the intermediate good on land g*(x),* where land commands the price *p* per unit.

$$x_s^* = \arg\max[A_s F_x(x)x - p(x)gx] \qquad (11)$$

In the context of an industry with an effective monopsony over the use of the essential input, the price of that factor may be endogenised.[24] Then the monopolist would take into consideration the effect of its intermediate output decision on the demand for land generated by the final and intermediate goods sector and thus on the price of land. With the price of land *p* a function of *x*, then

$$x^* = -\frac{F_x(x)}{F_{xx}(x)} \qquad (12)$$

This means that monopolistic profits in the technological state *s,* π_s, would be:

$$\pi_s = -A_s \cdot \frac{[F_x(x_s^*)]^2}{F_{xx}(x_s^*)} \cdot \left(1 - \frac{z}{\beta}\right) \qquad (13)$$

6.2. Private Firm's Investment in R&D

What are the investment incentives for firms in pursuit of these monopoly rents? Assume that there are *n* firms in this sector of the economy of which one will be holding a patent for the current technology. It is known that the balancing condition for investment is that at the margin the expected profits generated by investment in R&D must equal the opportunity cost of capital (Kamien and Schwartz 1982). Hence, taking into account the expected obsolescence of technological innovations (by reason of the processes of both creative and adaptive destruction), each firm that is not currently producing the intermediate good faces the R&D balancing condition that

$$rV_{I+1} = \pi_{I+1} - (n-1)\phi i(v_{I+1})V_{I+1} - \lambda a(x_{I+1})V_{I+1} \qquad (14)$$

This condition states that the expected return on the next innovation (the RHS) has to equal the opportunity cost of capital on the LHS. The expected return consists of the monopolistic profits from selling the intermediate good embodying the innovation to the final goods sector in the future technological stage **minus** the expected impact from obsolescence of the technology due to technological innovations made by one of the *(n-1)* competitors **minus** the expected impact from obsolescence of the technology due to biological innovation. Note that we assume that technologies of the previous technological stage are supplied competitively, implying a zero-

profit condition on technologies of earlier vintage. Rearranging (14) and making use of (3), we get the net present value of a single technological innovation

$$V_{I+1} = \frac{\pi_{I+1}}{r + (n-1)\phi i(v_{I+1}) + \lambda a(d_{I+1})} \qquad (15)$$

In this expression the numerator represents the monopolistic profits generated by the innovation and the denominator represents the own rate of discount for private investments in innovative activities. This is a composite rate made up of the opportunity cost of capital, the rate of obsolescence due to (others') technological innovation and the rate of obsolescence due to biological innovation. In sum, the private firm only values the monopoly rents that may be acquired from a technological innovation, and it discounts any future stream of such rents with regard to the expectation of any future technological and biological innovation.

6.3. Firm Decision Making Regarding Investment in R&D

We now wish to derive the private firm analogue to equation (10) above – the private incentives for investment in reserves for purposes of R&D. Land will be allocated by the patent holder in order to equalise returns in both the final goods sector and in R&D.

$$p = A_s \frac{F_x(\bullet)}{\beta} = \phi i(v_s) V_{I+1} \qquad (16)$$

where $F(\bullet)$ *is* $F[\beta^{-1}(1-(n-1)v-g)]$. This condition (16) provides the intertemporal link between technological stages.[26]

Combining (4) with (15) and (16) and solving for the steady state and using (5) to simplify, we derive the optimality condition for the private firm's allocation of land to the reserve sector in the steady state of a decentralised economy.

PROPOSITION 4**:** The allocation of resources to the biotech sector is optimal for a private firm where the marginal loss in final production through additional land in reserves equals the private net present value of the gross marginal increase in monopolistic rents in the final goods sector generated by the reserve sector.

PROOF**:** Differentiating equation (16) with respect to reserve size, we arrive at the following optimality condition.

$$\frac{F_v(\bullet)}{\beta} = \phi i_v(v) \cdot \frac{\gamma \frac{[F_c(\bullet)]^2}{-F_{vv}(\bullet)}}{r + (n-1)\phi i(v) + \lambda a((n-1)v, \gamma} \qquad (17)$$

As in (10), the LHS of (17) shows the marginal value of land allocated to production, although in the present case of private allocation the demand for land in the intermediate sector is neglected. The RHS the marginal value of land allocated to reserve status.[27] The marginal value of lands as reserves is equal to the expected value of monopoly rents accruing to the successful innovator by reason of the allocation of an additional unit of land to R&D, discounted at the private firm rate

that includes not only the opportunity cost of capital but also the anticipated effects of patent obsolescence (deriving from either the processes of creative or adaptive destruction).

Sections 5 and 6 present the socially optimal and the privately optimal incentives for investment in R&D in the biotechnology industry. It is immediately clear that the social and private optimality conditions contained in equations (10) and (17) are not identical. A full analysis of the differences is presented in (Goeschl and Swanson 2002, forthcoming). In the following section, we explore one implication of the differences in the optimality criteria of industry and society that represents a key failure of the patent system to align industry choice with the social optimum.

7. Failures of the Patent-Based Incentives for R&D under scale-dependent response

Now that we have derived the alternative decision making rules for social and patent-based decision making regarding resistance problems, it is possible to compare how these alternative decision making systems respond to the fundamental determinants of resistance problems. These are fully discussed in (Goeschl and Swanson 2002, forthcoming). What is of interest here is the performance of the patent system of rewarding innovations with respect to the fundamental problem in biotechnology, namely the recurrence of problems through endogenous adaptation. The following proposition demonstrates that this performance is problematic.

PROPOSITION 5: Under the criterion of social optimum, an increased rate of adaptation requires increased allocation of resources to R&D. Under a patent regime, an increased rate of adaptation leads to reduced allocation of resources to R&D by industry.

PROOF: Proposition 5 can be easily proved through the comparative statics of equations (10) and (17). Taking the partial derivatives of (10) with respect to the variables specified, we see that the socially optimal amount of investment in biotechnology increases with (i) a decrease in the discount rate r, (ii) an increase in the magnitude of the impact of an innovation γ, (iii) an increase in the arrival rate of technological innovations ϕ and (iv) – critically - an increase in the arrival rate of biological innovations λ.[28] Conversely, the optimal level of investment by the individual biotechnology firm responding to patent-based incentives increases with (i) a decrease in the discount rate r, (ii) an increase in the magnitude of the impact of an innovations γ, (iii) an increase in the arrival rate of technological innovations ϕ, and (iv) – again critically - a decrease in the arrival rate of biological innovations λ.

The comparative statics show – unsurprisingly - that a higher discount rate leads to a lower present value of the benefits of innovation and hence of the inputs that generate these innovations both for industry and for society as a whole. Likewise for society, if the step size of technological innovation increases, innovation becomes relatively more profitable, which leads to increased investment in reserves. For industry, increased step size means that monopoly rents are likely to accrue over longer time periods, thus raising the benefits associated with R&D, although the impact is less straightforward since competitors also gain from this increase which affects expected monopoly rents in an adverse manner.[29]

An increase in the arrival rate of innovations improves the profitability of the R&D sector. This shifts allocation of reserves towards the R&D sector as the sacrifice in current consumption is outweighed by the gains from a higher growth trajectory. With respect to discount rate, innovation size and rate of technological innovation, the direction of response of industry and

society to changes in the parameters is essentially the same, even though they will differ in terms of magnitude (Goeschl and Swanson 2002). However, the response of society and industry to an increase in the rate of response from pathogen, an indicator of the severity of the problem of recurrence, is opposite. Investment in R&D is society's instrument for responding to biological innovations, and so the marginal benefits from R&D will increase as the rate of biological innovation increases.[30] From industry's perspective, when biological innovations are more frequent, then patents become obsolete more quickly, thus providing reduced incentives for investments. Increasing rates of adaptation imply reduced time horizons for product usefulness, and hence a truncated flow of future benefits. The industry will see reduced incentives to investing in the solution of problems, if the expected life of that solution is reduced, and so a patent-based system is ill-suited to the problem of adaptive pathogen response and recurrence .

How serious is this problem? That is, what is it that would cause the rates of biological innovation to increase? The fundamental nature of adaptation problems is such that an increasing rate of biological innovation is a given, as it results from any attempts by society to make progress. Society pursues growth in production through either increased allocations of biological resources to the production sector, or via increased rates of innovation. Either approach results in increased rates of biological innovation. Increased areas of land dedicated to production result in increased prospects for any given biological innovation taking hold. Increasing numbers of technological innovations increase the number of different pathogens that are implicitly selected by society for possible trial. For this reason biotechnological processes are usually modelled as a form of "arms race": an increasing rate of response from the competitor is induced by any attempt to gain an advantage.

IPR systems are very poor mechanisms for providing incentives in such contests of innovation. The induced response from nature implies an expectation that any innovation's lifespan will be short, and this reduces the incentives to invest in innovation from the outset. If, for some reason, society does make an initial attempt to achieve growth in production in the biological sphere, the IPR system provides an increasingly diminishing incentive to attempt to remain within the contest of innovation that results. Just as society becomes reliant on the biotechnology sector to address the resulting problems, the biotechnology sector becomes increasingly less motivated to pursue those problems. Innovation and adaptation do not only depend in the scale of innovation, but also on the second component determining the absolute rate of productivity development, namely the size of innovations. We now explore the implications of generalizing the results in this direction.

8. Socially optimal choices under speed-dependent selection

As the preceding analysis has shown, the fact that the processes of innovation and adaptation depend on the scale of application has significant implications for the optimal allocation of land to production and stabilisation. In this section, we generalise the previous results by considering linkages between the innovation and adaptation processes. These linkages introduce a selection mechanism into the model that depends on the speed of technological progress. This speed is captured in the step size of productivity increases between two sequential technological stages. The presence of these linkages is at present speculative and their nature likely to be complex as speed-dependent selection is ultimately associated with multi-population models with competition for resources (Hofbauer and Sigmund 1988). However their potential presence and general nature has significant ramifications for the optimal design of an IPR system to generate such innovations as the following analysis shows.

8.1. Technological expectations

In the following section, we explore the implications of both the innovation and the adaptation function being dependent not only on the reserve size (and by implication on the size of technology application), v, but also on the size of the technological innovation, γ. Remember that so far, this shift parameter was determined exogenously. Removing this condition means on the one hand that innovators can choose the size of the innovation and on the other that the response of pathogens may itself vary with the innovation size.

Analytically then, we can describe the innovation function as $i\phi(v,\gamma)$ and the adaptation function as $\lambda a(v,\gamma)$. We look primarily at the adaptation function as the more interesting case.

ASSUMPTION 1: The function $a(v,\gamma)$ depends on the long-run magnitude of γ in a stationary equilibrium.

This assumption is in keeping with the focus on stationary equilibria and simplifies the analysis. We discuss what violating assumption 1 might imply at a later point.

We now make two possible, but mutually exclusive assumptions about possible linkages between innovation size and rate of response. We restrict ourselves to "nicely behaved" linkages, i.e. continuous and differentiable functions. although one could readily think of more complex linkages.

ASSUMPTION 2: $a_\gamma(v,\gamma)<0$.

This assumption spells out the first of two basic possibilities, namely that the response rate of pathogens will decrease *ceteris paribus* as the size of innovations increases. This formulation can be justified by reference to pathogens having to face unfamiliar types of ecological conditions, thus diminishing the probability that pathogens find a solution rapidly. If the race against pathogens can be ultimately won by a sufficiently radical innovation, then $a_{\gamma\gamma}(v,\gamma)<0$ and $a(v,\gamma)=0$ for some very large γ. If not, increased innovation size merely serves to delay that response as an increasing ($a_{\gamma\gamma}(v,\gamma)<0$) or decreasing ($a_{\gamma\gamma}(v,\gamma)>0$) function of innovation size.

ASSUMPTION 3: $a_\gamma(v,\gamma)>0$.

The second possible linkage between innovation size and rate of adaptation is one where an increase in innovation size triggers an accelerated response from pathogens. One explanation would be that greater step size in innovations favours more rapidly adapting pathogens within the pathogen population that would otherwise be held in check by more slowly evolving competitors. This introduces a second level of selection pressure into the model, namely one that selects among pathogens at the level of absolute speed of adaptation. Again, two variations of this linkage can be distinguished, one where the effect of this additional selection process decreases with increasing size of innovation, i.e. $a_{\gamma\gamma}(v,\gamma)<0$, and one where this effect as accelerating, i.e. $a_{\gamma\gamma}(v,\gamma)>0$.

The four cases discussed above lay out possibilities regarding the linkage between rate of adaptation in pathogens and innovation size. With respect to the innovation function, the conventional assumption is that - all other things equal - the probability of an innovation is a decreasing function of target size, i.e. $i_\gamma(v,\gamma)<0$ and $i_{\gamma\gamma}(v,\gamma)<0$. We discuss a possible variation of this assumption in biotechnology at a later point.

8.2. Social value of innovations under speed-dependent response

What are the implications of innovation size being a choice parameter on the social value of innovations? The first point to note is that innovation size will now be chosen such that it maximises the net present value of the biotechnological sector. The social planner will choose to maximise expression (9) by choosing the correct innovation size, γ. From equation (9) it is clear that the optimal size, γ^*, will be such that it maximises the following expression

$$\left[\phi i(v,\gamma) - \lambda a(v,\gamma)\gamma^{-1}\right](\gamma - 1) \qquad (18)$$

Differentiating equation (18) with respect to γ to arrive at γ^*, we get

$$\phi\left[i(\bullet) + i_v(\bullet)\left(\gamma^* - 1\right)\right] = \lambda\left[a_\gamma(\bullet)\frac{\gamma^* - 1}{\gamma^*} + a(\bullet)\gamma^{*-2}\right] \qquad (19)$$

as the solution to the optimal choice problem. The LHS of equation (19) is the marginal change in the rate of innovation with respect to innovation size, which consists of the positive effect of a greater size of innovation on the absolute rate of progress and of the negative effect of greater innovation size on the probability of arrival. The RHS is the marginal change in the rate of adaptation-driven productivity losses. This consists of two effects: The first is the positive effect of greater size of innovation on the absolute rate of productivity loss in the final sector, $\lambda a(\bullet)\gamma^2$. The second is the effect of a greater size of innovation on the speed of response by pathogens, $\lambda a_\gamma(\bullet)(\gamma-1)\gamma^1$. The direction of this effect depends on the sign of $a_\gamma(\bullet)$ depends on whether assumption 2 or 3 holds and it is through this second effect that the assumptions enter.

It will be convenient to define a benchmark size of innovations for comparison. We take as a benchmark the optimal size of innovations in the absence of biological adaptations.

PROPOSITION 6 (Aghion and Howitt 1998): In the absence of adaptations, there exists a unique socially optimal innovation size γ_B such that $\phi[i(\bullet)+i_\gamma(\bullet)(\gamma_B-1)=0$

PROOF: See Aghion and Howitt (1998).

In the absence of adaptations, the LHS of equation (19) is zero. Since the innovation function is concave in the size of innovations under conventional assumptions, a unique solution for the optimality $\phi[i(\bullet)+i_\gamma(\bullet)(\gamma_B-1)=0$ can be shown to exist. This optimum is our benchmark value of innovation size, γ_B, against which we will compare the optima in the presence of adaptation.

How do adaptations affect optimal innovation size? The general tendency in the presence of adaptations is to depress the optimal size of innovations such that $\gamma^*<\gamma_B$. The reason for this lies in the first-order effect of innovation size on the absolute rate of productivity loss, $\lambda a(\bullet)\ \gamma^2$. However, this first-order effect can be dominated by second-order effects working through the marginal impact on the response time, a_γ. This means that for a_γ sufficiently small, innovation size under adaptation exceed that under no adaptation, or that $\gamma^*>\gamma_B$. Since $\gamma<1$ implies a decreasing growth path over time, we only consider equilibria for $\gamma\geq 1$. The following four cases result:

PROPOSITION 7.1: If RHS>LHS for all $\gamma \geq 1$, then $\gamma^* \to \infty$.

PROOF: Assume RHS>LHS for all $\gamma \geq 1$, then the expression (18) is continuously increasing in γ and is therefore maximised for $\gamma \to \infty$. For RHS>LHS to arise, necessary conditions are that $a_\gamma < 0$ and $a_{\gamma\gamma}(\gamma) < 0$.

PROPOSITION 7.2: If RHS<LHS for all $\gamma \geq 1$, then $\gamma^* < 1$.

PROOF: Assume RHS<LHS for all $\gamma \geq 1$, then expression (18) is continuously decreasing in γ and is therefore maximised for $\gamma < 1$. For RHS<LHS to arise, necessary conditions are that $a_\gamma > 0$ and $a_{\gamma\gamma} > 0$.

PROPOSITION 7.3: If RHS=LHS for some $\gamma \geq 1$ and $a(\bullet) < - a_\gamma(\bullet)\gamma^*(\gamma^*-1)$, then $\gamma^* > \gamma_B$.

PROOF: If RHS=0, then $\gamma^* = \gamma_B$. If RHS<0, we know from the concavity of the LHS that for an innovation size to solve equation (19), it needs to be greater than γ_B, hence $\gamma^* > \gamma_B$. For RHS<0, $a(\bullet)\gamma^2 + a_\gamma(\bullet)\gamma^1(\gamma^*-1) < 0$ has to hold and proposition 7.3 follows. A necessary condition for Proposition 7.3 to hold is $a_\gamma < 0$.

PROPOSITION 7.4: If RHS=LHS for some $\gamma \geq 1$ and $a(\bullet) > - a_\gamma(\bullet)\gamma^*(\gamma^*-1)$, then $\gamma^* < \gamma_B$.

PROOF: This is the converse of the proof for proposition 7.3.

Figure 1 graphically characterizes the optimal choice of innovation size established under propositions 7.1 to 7.4. The benchmark size γ_B is situated where the function *I* denoting the LHS of expression (19) intersects with the *x*-axis. This is the optimal innovation size in the absence of adaptation, setting the marginal impact of innovation size on the absolute rate of productivity growth equal to zero.

Start with the graph illustrating proposition 7.1: This is the case of increasing innovation size delaying pathogen response at ever greater rate. In this case, maximum innovation size should be targeted as there are essentially increasing returns to size-driven productivity growth. As discussed in section 8.1., one realistic variant of this scenario is the assumption of "winnability" in that adaptation will cease above a certain innovation size, thus resulting effectively in a backstop technology. Then this finite innovation size should optimally be targeted.

Figure 1: Socially optimal innovation size under various assumptions about speed-dependent selection

Graph P7.2 demonstrates the case of increasing innovation size accelerating pathogen response at ever greater rate due to the response rate being convex in γ. Here even small steps are assumed to trigger significant increases in the rate of adaptation in pathogen. Here the optimal steady-state strategy is to cease productivity-enhancing R&D due to the net present loss resulting from subsequent pathogen responses.

In case of graph P7.3, pathogen rate of response is negatively related to innovation size, although not at a sufficiently increasing rate (for a comparison, see graph P7.1). Here the derivative of adaptation rate with respect to innovation size, $a_\gamma(\bullet)$, is sufficiently small (or large in absolute

terms) to outweigh the first order effect of increased innovation size, but does not get small enough to prevent an equilibrium size. This implies increasing the optimal size of innovation to be targeted in the R&D process to γ_2*, which lies above the benchmark value due to the additional dynamic benefits that arise out of delaying pathogen innovation.

As explained before, because of the first-order effect of innovation size on the rate of net productivity growth in the presence of adaptations, under many specifications a finite size of innovations γ* will be optimal that is below the benchmark value γ_B. This general result can arise under both positive and negative gradients of the adaptation function with respect to innovation size. Graph P7.4 illustrates the case of a positive gradient that follows proposition 7.4 Here response time decreases with innovation size, but at a decreasing rate. This results in an optimal size γ_1* that is smaller than that chosen in the absence of adaptation γ_B as there is a dynamic penalty on a greater step size.

We conclude from the analysis of the linkage between innovation size and rate of adaptation that the optimal size of innovations in the presence of adaptation will differ from the optimal size in its absence (the benchmark value). Whether the size is above or below the benchmark critically depends on the assumptions about the adaptation function. In general, the optimal innovation size will tend to be below the benchmark value, highlighting the negative impact of biological adaptations on the optimal growth path of the final sector. However, if pathogens react negatively to size of innovations, an innovation size greater than the benchmark is optimal. If evolutionary response is highly sensitive to innovation size (cases 7.1 and 7.2), the possibility of zero and infinite steady-state target size being optimal clearly exists.

A final consideration in this analysis concerns the conventional assumptions about the innovation function and its dependence on innovation size. These are that probability of innovation decreases in innovation size at an increasing marginal cost. Although realistic, in the domain of biotechnology another assumption may need to be considered, namely that of the probability of innovation being invariant to the size of the innovation.[32] Biotechnology nowadays affords the possibility of exchanging useful genetic information across species boundaries at essentially the same cost as within. If the "size" of the innovation is measured on the basis of a biological metric such as the genetic distance between two crops and correlates with productivity impacts, then biotechnology may be able to evade the decreasing marginal returns usually expected in innovation. In that case, $\iota_{\gamma}(v,\gamma)=0$ is a distinct possibility and the function I in figure 1 is bounded away from the x-axis. In the absence of adaptations, this implies the optimal innovation size converging to positive infinity. When adaptation is present, it reduces the analysis of optimal size to two extreme cases. In the first, the optimal innovation size would remain infinitely large even in the presence of adaptation. This holds for all specifications developed in graphs P7.1, P.7.3 and P.7.4. However, a non-concave innovation function does not alter the conclusions reached under proposition 7.2. Despite the increasing returns to investment into innovation size, the optimal steady-state innovation size remains below one. This is the second case.

In the following section we contrast the sensitivity of the optimal social choice of innovation size with the response of private industry to the link between innovation size and adaptation.

9. Firm Decision Making under speed-dependent response

As before, we consider innovation and adaptation functions to depend on innovation size γ, although here the context is that of a patent-driven industry rather than that of society. The

starting point in this analysis is the net present value of an innovation expressed in equation (15), previously developed for the case of scale-dependent selection. Allowing for a linkage between innovation size and innovation and adaptation function, we can re-express equation (15) as:

$$V_{I+1} = \frac{\pi_{I+1}}{r + (n-1)\phi i(v_{I+1}, \gamma_{I+1}) + \lambda a(v_{I+1,} \gamma_{I+1})} \qquad (20)$$

As in the previous analysis, we only consider stationary equilibria with positive growth and follow the conventional assumptions about $i(v, \gamma)$. Again, we define as a benchmark the case in the absence of adaptation. Here the firm takes the following-period profits as given and the individually optimal amount of investment fulfils the condition in equation (16) modified for the endogenous choice of innovation size such that

$$p = A_s \frac{F'(\bullet)}{\beta} = \phi i(v_s, \gamma)\gamma V_I \qquad (21)$$

The profit-maximizing choice of innovation size γ_P is such that

$$i(v, \gamma) + \gamma i_\gamma(v, \gamma) = 0 \qquad (22)$$

Comparing expression (22) with the social optimum in equation (19) gives rise to proposition (6).

PROPOSITION 8 (Aghion and Howitt, 1998): In the absence of adaptation, the privately optimal innovation size γ_P smaller than the socially optimal size γ_B.

PROOF: See (Aghion and Howitt, 1998).

The intuition is that by concavity of the innovation function $i(v, \gamma)$, the solution to the LHS of equation (19) lies on the decreasing part of the function $\gamma i(v, \gamma)$ and thus to the right of the solution to equation (22). This implies in the absence of adaptation under-investment into the step size of productivity growth. How does industry choice change when we introduce speed-dependent selection?

PROPOSITION 9: Industry choice is invariant to speed-dependent response.

PROOF: If assumption 1 holds (i.e. if the adaptive response is determined by stationary value of γ), then any firm in the industry will take V_{I+1} as given.[33] Since the adaptation function does not enter into the optimality condition in expression (21), the optimal choice of γ is determined by expression (22) alone. Hence firm-level choice is invariant to the linkage between innovation size and rate of adaptation. The functional dependence of the adaptation function on the step-size of innovation arises only at the aggregate level of the industry through the effective discount rate on patent rents.

Comparing firm-level choice captured in (21) and (22) with the social optimum defined by expression (19), the shortcomings of a patent-driven system under speed-dependent response become apparent.

10. Failures of the Patent-Based Incentives for R&D under speed-dependent pathogen response

The failures of patent-based R&D incentives under speed-dependent response arise out of its inability to influence the targeting of innovation size by firms in line with the linkage between step size and the rate of pathogen response. They can be made explicit by contrasting private choice with the social optima defined by expression (19) and the resultant range of socially optimal choices for innovation size that are laid out in propositions 7.1 to 7.4.

Since firm-level choice is invariant to the presence of speed-dependent pathogen response, the prevailing size of innovation targeted by firms will be γ_P as derived in expression (22) and will be smaller than γ_B, the benchmark size of the social optimum (proposition 8). Since γ^* will differ from γ_B in the presence of speed-dependent adaptation, the following statements can be made about the relationship between the private optimum γ_P and the social optimum γ^*:

PROPOSITION 10.1: If $\gamma^* \rightarrow \infty$, then firms will target insufficient innovation size.

PROOF: Equation (22) defines a finite optimum for γ_P under conventional assumptions about $i(v,\gamma)$. From this follows that $\gamma_P < \gamma^*$.

PROPOSITION 10.2: If $\gamma^* < 1$, then firms will target excessive innovation size.

PROOF: Any "discovery" with a productivity effect $\gamma < 1$ is productivity decreasing since it would imply a technological state $A_{t+1} = \gamma A_t < A_t$. In a competitive market, demand for such a "discovery" is obviously nil. The solution to equation (22) must therefore hold for $\gamma_P > 1 > \gamma^*$.

PROPOSITION 10.3: If $\gamma^* > \gamma_B$, then firms will target insufficient innovation size.

PROOF: From proposition 8, $\gamma_P < \gamma_B$ and by transitivity $\gamma_P < \gamma^*$.

PROPOSITION 10.4: If $\gamma^* < \gamma_B$, then firms will target an innovation size that is either too small if $a_\gamma(v_P, \gamma_P) < C$, socially optimal if $a_\gamma(v_P, \gamma_P) = C$ or too great if $a_\gamma(v_P, \gamma_P) > C$ with $C = -i_\gamma(v_P, \gamma_P)\left[\phi/\lambda + i(v_P, \gamma_P) + i_\gamma(v_P, \gamma_P) i(v_P, \gamma_P)^{-2}\right]$

PROOF: Since both $\gamma_P < \gamma_B$ and $\gamma^* < \gamma_B$, the relation between γ_P and γ^* depends on the specifics of the functional form of the innovation and adaptation functions. The private optimum can either exceed the social one if $a_\gamma(v_P, \gamma_P)$ is sufficiently large (i.e. if the change with which the adaptation rate increases with innovation size is greater than the critical value C) or lie below it if $a_\gamma(v_P, \gamma_P)$ below the critical value. With minuscule probability, it coincides with the social optimum.

The ambiguity in proposition 10.4 arises because both optima lie to the right of the benchmark size. However, they do so for entirely different reasons: The social optimum because it internalises the additional effect on adaptation; the private optimum because the individual firm does not compete against its own patents and thus receives the total impact of innovation (γ) in terms of monopolistic rents rather than the social rewards of the technological differential (γ_1).

The differences between social optimum and private choice highlight the failure of a patent driven system to bring about optimal innovation size. This failure also exists in the absence of

speed-dependent selection among pathogens (see proposition 8). There it has been suggested to modify the patent system in order to align social and private optima. In the cases discussed in propositions 10.3 and 10.4 a similar approach may be called for (see below). However, if the linkage between innovation size and rate of adaptation is rather extreme such as in propositions 10.1 and 10.2, the patent system is woefully inadequate by principle. This is the case both under the most optimistic form of linkage (delay of response or the "magic bullet") and the most pessimistic (something akin to an "arms race"). In these cases, entirely novel mechanisms of rewarding innovation against humanity's biological competitors have to be devised. Moreover, this is also the case if biotechnology could escape the conventional assumptions about decreasing returns to innovation as a function of innovation size.

11. Policy implications

11.1 Modifications

Where boundary solutions are socially optimal (such as in propositions 10.1 and 10.2), alternative innovation reward systems to patents are required. Where intermediate optima result (such as in propositions 10.3 and 10.4), modifications to the patent systems could be envisaged. Possible modifications in the absence of adaptations are discussed in (Aghion and Howitt 1998). Here, we only highlight some ideas about modifications to the patent system in biotechnology.

Where the crux of the failure of the patent system lies in the imperfect appropriability of rents generated by innovations, modifications of patent length and patent breadth can have considerable effects (O'Donoghue, Scotchmer and Thisse 1995). Where adaptations are present, there are two reasons for rent truncation, namely technological obsolescence due to pathogen evolution and commercial obsolescence due to competitors' innovations. Interestingly, this means that at any given point there may be a number of innovations present that although commercially obsolete, are still technologically adequate. Patents in these innovations still have a net present value to the extent that they may return to commercial viability if a competitor's product has become technologically obsolete (Goeschl and Swanson 2001). However, the since the duration of a patent is defined in calendar time, the value of these patents is elapsing continuously, even though no monopolistic rent extraction is taking place. It is merely an option on such rents if the circumstances allow the product to return to commercial viability. One possible modification in this context would then be to define patent length on the basis of commercial life rather than calendar time, which could be approximated through cumulative output.

Another instrument works through the definition of "patentable innovations", i.e. the minimum size of an innovation that is required to be considered 'useful'.[34] The rationale is that in order for a temporary monopoly to be granted to an innovator, the resultant welfare loss can only be tolerated for innovations of at least a certain size. This rationale is also valid in the context of biotechnological innovations. Under the conditions that give rise to proposition 10.4 however, if private innovation size is excessive, a lowering of the standard of novelty can be appropriate as long as the overall social welfare effect of this measure is not negative. On the other hand, this contrasts with the possibility arising by virtue of adaptations in pathogens that innovation size may too great (see proposition 10.3), implying the need for a maximum size of innovations allowed. The policy question is then to establish the conditions under which the two requirements have both to be implemented and under which they conflict. This goes beyond the scope of this paper.

11.2 Alternatives

Whereas in the previous cases, the patent system required adjustment, in the cases established under propositions 10.1 and 10.2 the patent system is an entirely inappropriate instrument for generating the optimal amount of R&D. In the case of proposition 10.2, innovation should be discouraged by withholding rewards to innovators. Even a steady-state that generates innovations of the minimum size required on efficiency grounds for a patent system incurs significant dynamic losses and is therefore not socially desirable. In the case of proposition 10.1 the patent system fails to translate the welfare gains from winning the innovation-adaptation race into appropriate incentives for innovation at the firm level. This result is well known from the literature on optimal incentives for antibiotics (Goeschl and Swanson 2000), vaccinations (Geoffard and Philipson 1997) and new pesticides (Goeschl and Swanson 2001). One response with desirable characteristics is to create a prize for successful innovation in order to solve the problem of inappropriate rent capture by the innovator (Kremer 2000a, 2000b, 1998).

12. Conclusion

Summarizing the socially optimal management of biotechnological research, there are two areas that require regulatory scrutiny. The first area is the amount of investment in biotechnological innovations in the light of scale-dependent response by pathogens. The second area is the step size of new innovations pursued by in the biotechnological domain in the light of a size-dependent response by pathogens.

We examined the performance of a patent-driven industry in addressing these two areas of concern. The conclusions are that a patent-based system fails in the first area because it induces firms to engage in a cyclical pursuit of innovations rather than in a process of growth through innovations. In the second area, the requirement of a minimum innovation size in a standard patent system aligns social and private decisions only under highly restrictive conditions. Modifications to enhance the appropriable share of rents from innovations are required as a matter of course. Moreover, in the most serious manifestations of recurrent problems, alternative R&D reward systems are required to manage the innovation process. In light of the performance in both areas of concern, therefore, the application of a patent-based system of rewarding innovations to a sector where recurrence of technological problems is an ineradicable feature is arguably not the first-best option. Where the problem of recurrence is most severe, i.e. where pathogens have a high exogenous adaptation rate and respond with a significantly increased rate of adaptation to increases in innovation size, the failures of a patent system are most serious. This shows that the relationship between pests, plagues, and patents is an inherently problematic one.

References

Aghion, P., Howitt, P. (1998): *Endogenous Growth Theory*. Cambridge, M.A.: MIT Press

Aghion, P. Howitt, P. (1992): A Model of Growth through Creative Destruction. *Econometrica* **60**: 323-51

Anderson, R.M. and R.M. May (1991): Infectious Diseases of Humans. Dynamics and Control. Oxford Science Publications. Oxford: Oxford University Press

Arrow, K. (1962): Economic Welfare and the Allocation of Resources for Invention. In R. Nelson (ed.): *The Rate and Direction of Inventive Activity*. Cambridge M.A.: Harvard University Press

Barrett, S. (1992): Economic Growth and Environmental Preservation, *Journal of Environmental Economics and Management* **23**: 289-300

Brown, G. and J. Swierzbinski (1988): Optimal Genetic Resources in the Context of Asymmetric Public Goods", in: Smith,V.K (ed): Environmental Resources and Applied Welfare Economics, RFF:Washington, 293-312.

Evans, L.T. (1993): *Crop Evolution, Adaptation and Yield*. Cambridge: Cambridge University Press

Evenson, R., Gollin, D. (1991): Priority Setting for Genetic Improvement Research. Los Banos, Laguna, Philippines: International Rice Research Institute

Evenson. R. (1998) Plant Breeding: A Case of Induced Innovation. in Evenson, R., Gollin, D., Santaniello, V. (eds). (1998): *Agricultural Values of Genetic Resources*. CABI:London, ch.1

Frank, S.A. (2000): Polymorphism of attack and defense. *Trends in Ecology and Evolution* 15:167-171

Frank, S.A. (1994): Recognition and polymorphism in host-parasite genetics, *Philosophical Transactions of the Royal Society, London, Series B* **346**, 191-197

Goeschl, T., Swanson, T. (2002): The Social Value of Biodiversity for R&D. *Environmental and Resource Economics*, forthcoming.

Goeschl, T., Swanson, T. (2001): Lost Horizons: The Inappropriateness of the Patent System to Solve

Recurrent Problems of Resistance in Antibiotics. Paper presented at American Economic Association meeting. New Orleans, Jan. 2001.

Goeschl, T., Swanson, T. (1998): *Optimal Management of Agricultural Biodiversity: Genetic Resources, Gene Banks and Land Use*. Paper presented at the World Congress of Environmental and Resource Economists, Venice, Italy, June 1998

Gollin, D., M. Smale, and B, Skovmand (1998): *Optimal Search in Ex situ Collections of Wheat Genetic Resources*. Economics Working Paper No. 98-03. Mexico City: CIMMYT

Grossman, G., Helpman, E. (1991): Quality Ladders in the Theory of Growth. *Review of Economic Studies* 58(1), 43-61.

Heisey, P.W., Brennan, J.P. (1991): An Analytical Model of Farmers' Demand for Replacement Seed. *American Journal of Agricultural Economics* **73**(4): 1044-52.

Heisey, P. W. (ed.) (1990): *Accelerating the Transfer of Wheat Breeding Gains to Farmers: A Study of the Dynamics of Varietal Replacement in Pakistan*. CIMMYT Research Report No. 1, Mexico, D.F.: CIMMYT

Kamien,M. and Schwarz,N. (1982): *Market Structure and Innovation*. Cambridge: Cambridge University Press.

Kiyosawa, Shigehisa (1989): Breakdown of Blast Resistance in Rice in Relation to General Strategies of Resistance Gene Deployment to Prolong Effectiveness of Disease Resistance in Plants; in: Leonard, K.; Fry, W. (eds.): *Plant Disease Epidemiology. Vol.2. Genetics, Resistance, and Management*. New York: McGraw-Hill, pp.251-283

Kremer, M. (1998): Patent Buyouts: A Mechanism for Encouraging Innovation. *Quarterly Journal of Economics* 113(4), 1137-67.

Kremer, M (2000): Creating Markets for New Vaccines Part I: Rationale. NBER Working Paper W7716

Kremer, M (2000): Creating Markets for New Vaccines Part II: Design Issues. NBER Working Paper W7717

Laxminarayan, R. and Brown, G. (2001): Economics of Antibiotics Resistance: A Theory of Optimal Use. *Journal of Environmental Economics and Management*, forthcoming.

Mason,R. and Swanson,T. (forthcoming), "The Costs of Uncoordinated Regulation", *European Economic Review*.

May, R.M. and R. Anderson (1983): Epidemiology and Genetics in the Coevolution of Parasites and Hosts, *Proceedings of the Royal Society London B* 219, 281-313.

Maynard Smith, J. (1976): A comment on the Red Queen. *The American Naturalist* 110, 325-330.

Munro, A. (1997): Economics and Evolution. *Environmental and Resource Economics* **9**: 429-229

O'Donoghue, T. Scotchmer, S., Thisse, J.F. (1995): Patent Breadth, Patent Length and the Pace of Technological Progress. Department of Economics Working Paper 45-252, University of California – Berkeley.

Oerke, , E-C., Dehne, H-W., Schönbeck, F., Weber, A. (1994): *Crop Production and Crop Protection. Estimated losses in major food and cash crops*. Amsterdam: Elsevier

Scheffer, R. (1997): *The nature of disease in plants*. Cambridge University Press

Schumpeter, J.A. (1942): *Capitalism, Socialism and Democracy*. New York: Harper and Bros.

Simpson, R.D., Sedjo, R.A. (1996): *Valuation of Biodiversity for Use in New Product Research in a Model of Sequential Search*. Discussion Paper 96-27 (July 1996), Resources for the Future, Washington D.C.

Simpson, R.D., Sedjo, R.A., Reid, J.W. (1996): Valuing Biodiversity for Use in Pharmaceutical Research. *Journal of Political Economy* **104**(1): 163-185

Stenseth, N.C. and J. Maynard Smith (1984): Coevolution in Ecosystems: Red Queen Evolution or Stasis?, *Evolution* 38(4), 870-880

Swanson T., Luxmoore, R. (1998): Industrial Reliance on Biodiversity, WCMC:Cambridge.

Tirole, J. (1988): *The Theory of Industrial Organization*. Cambridge: MIT Press.

Weitzman, M. (2000): Economic Profitability versus Ecological Entropy. *Quarterly Journal of Economics* 115(1), 237-263.

Zadoks, J. and R. Schein (1979): *Epidemiology and Plant Disease Management.* Oxford: Oxford University Press

Table 1: Characteristic time for the appearance of resistance in some specific biological systems (from Anderson and May 1991)

Species	Control Agent	Time to resistance	
		Generations[a]	Years
Avian coccidia			
Eimeria tenella	Buquinolate	**6 (<6)**	**1**
	Glycarbylamide	**11 (9)**	**<1**
	Nitrofurazone	**12 (5)**	**7**
	Clopidol	**20 (9)**	**6**
	Robenicline	**22 (16)**	**10**
	Nicarbazin	**35 (17)**	**27**
Gut nematodes in sheep			
Haemonchus contortus	Thiabendazole	**3**	**<1**
	Cambendazole	**(4)**	**<1**
Ticks on sheep			
Boophilus microplus	DDT	**32**	**4**
	HCH-dieldrin	**2**	**<1**
	sodium arsenite		**40**
Black flies (Japan)			
Simulium aokii	DDT+Lindane		**6**
Simulium damnosum	DDT		**5**
Anopheline mosquitoes (different localities)			
Anopheles sacharovi	DDT		**4-6**
	Dieldrin		**8**
An. maculipennis	DDT		**5**
An. stephansi	DDT		**7**
	Dieldrin		**5**
An. culicifacies	DDT		**8-12**
An. annuaris	DDT		**3-4**
An. Sundaicus	DDT		**3**
	Dieldrin		**1-3**
An. quadrimaculatus	DDT		**2-7**
	Dieldrin		**2-7**

[a] The figures give the number of generations before a majority (>50 per cent) of the individuals in the population are resistance to the control agent. In brackets are the number of generations before resistance is first observed (usually >5 per cent of individuals resistant).

Appendix: Derivation of equation (9)

Derivation of equation (9)

From (1) and setting $A_0\, F(x) = 1$, we can rewrite the utility function as

$$U = \int_{t=0}^{\infty} e^{-rt} \sum_{s=-\infty}^{+\infty} \Pi(s,t)\gamma^s dt \qquad \text{(i)}$$

with $s = I - D$ (ii)
with the histories of I and D are generated by the processes described in (6) and (7)

$$\Pi(I,t) = \frac{1}{I!}[\phi i(v)t]^I e^{-[\phi i]t} \qquad (6)$$

$$\Pi(D,t) = \frac{1}{D!}[\lambda a(v)t]^D e^{-[\lambda a]t} \qquad (7)$$

such that

$$\Pi(s,t) = \Pr(\text{I innov. have occurred by time t} \mid \text{D adapt. have occured by time t}) \quad \text{(iii)}$$

Then,

$$U = \int_{t=0}^{\infty} e^{-rt} \sum_{I=0}^{\infty} \sum_{D=0}^{\infty} \frac{1}{I!}(\phi it)^I e^{-\beta it} \cdot \frac{1}{D!}(\lambda at)^D e^{-\lambda at} \cdot \gamma^{I-D} dt \qquad \text{(iv)}$$

which is

$$U = \int_{t=0}^{\infty} e^{-rt} \sum_{I=0}^{\infty} \sum_{D=0}^{\infty} \frac{(\gamma\phi it)^I}{I!} e^{-\phi it} \cdot \frac{\left(\frac{1}{\gamma}\lambda at\right)^D}{D!} e^{-\lambda at} dt \qquad \text{(v)}$$

Making use of the infinite series of the factorial and the exponential function, we can rewrite (v) as

$$U = \int_{t=0}^{\infty} e^{-rt-\phi it-\lambda at} \cdot e^{\gamma\phi it} \cdot e^{\frac{\lambda a}{\gamma}t} dt = \frac{1}{r - \phi i(\gamma - 1) + \lambda a \frac{\gamma - 1}{\gamma}} \qquad \text{(vi)}$$

The denominator of equation (vi) gives then the effective discount rate applied to the output function. Reformulating (vi) for some arbitrary $A_0\, F(x)$, we arrive at equation (9).

1 The term originates from Lewis Carroll's 'Alice in Wonderland' where the Red Queen proclaims to Alice that "around here, we must run faster and faster, merely to stand still…."

2 It is possible to claim "Plant Breeders Rights" in new plant varieties under the so-called UPOV convention and/or patent rights in genetically modified seeds and animal varieties.

3 A recent survey found that plant breeders cited pest resistance as the primary focus of their activities. (Swanson and Luxmoore 1998)

4 The literature on seed replacement cycles in agriculture documents a cycle of 3 to 7 years between introductions of new pest resistant plant varieties on commercially meaningful scales. (Heisey 1990, Heisey and Brennan 1991).

5 In the context of agriculture this only implies a proportional increase in the amount of high yielding seed x required with an increase in the amount of intensively cultivated land d.

6 Throughout the text, we follow the convention that derivatives with respect to a variable are indicated by a corresponding subscript.

7 This is a close approximation to reality within the seed industry where there is a crop-specific, but nevertheless linear relationship between the land used in seed production and the land sown using this seed. The relative size of b and z is in the order of 100:0.1 to 100:5 depending on the crop (Pioneer Seed, personal communications).

8 The "significance" of a technological innovation is a legal requirement for the acquisition of property rights in the innovation. As this is an issue that we will introduce in section 4, we will normalise the magnitude of any technological innovation to be equivalent to the magnitude (γ) required for the acquisition of a private property right in that innovation.

9 The industrial organisation literature defines innovations as "drastic" if the technological advantage conferred by the innovation is of such a magnitude that the innovating firm captures the entire market when setting the monopoly price. Non-drastic innovations force the innovating firm to sell below the monopoly price (Tirole 1988).

10 This assumption follows the standard literature in crop epidemiology where the emergence of virulence is assumed to follow a Poisson process (cf. Zadoks and Schein 1979, Kiyosawa 1986).

11 This assumption is consistent with both the theory of selection (since those pests with a matching gene for x have a relative advantage that increases with the use of x) and the empirical observation that the widespread use of HYVs is associated with reduced periods of commercial viability.

12 We can re-write this as $\lambda a(d)$ making use of equation (3) where λ is a parameter which measures successful mutation or recombination of the pathogen population and $a, a'<0$ measures the adaptive response rate of biological competitors relative to size of intensive agriculture once a successful mutation has occurred.

13 For an analysis of the situation in which adaptation may be dampened by the simultaneous use of many different production methods, see Goeschl and Swanson (2000b).

14 Modellers of the dynamics of evolutionary games view resistance as the accumulation of "matching genes" within the pest population, where such matches enable the pest to prey on the host. A biological innovation in this context would consist of a change from a paucity to the relative prevalence of such a matching gene throughout the current pest population.

15 This assumption represents a uniform metric of a continuous process of depreciation. The unit of analysis is fixed within the technological sector (by the requirement that a patentable innovation be significant).

16 It is important to notice a subtlety here in that the discrete nature of the Poisson process introduces two "time scales" into the system. One is natural time, denoted by t, while s denotes the productivity stage of the economy.

17 One benefit of choosing this functional form for this problem is that it implies no bias in favour of intergenerational transfers of utility. (see Barrett 1992 for a discussion in the context of biodiversity).

18 This reduces the own discount rate since new technologies shift the production set outwards and relax the budget constraint.

19 In this instance the innate growth capacity of the biological resource – pests and pathogens – detracts from available consumption, and so increases the own discount rate.

20 This is essentially the case of potential collapse investigated by Weitzman (2000).

21 A stationary solution to the problem is to be expected on account of the linearity of the objective function.

22 Recall that $a'<0$.

23 The result is discussed in more detail in comparison to the private market solution in section 5.7.

24 This assumption is not essential to the argument, but simplifies the analysis. It is also not an unrealistic assumption in the context of agricultural lands, where it is highly likely that there is a single most productive use of most arable lands and a single monopolist of the intermediate goods (HYVs) requisite for that use.

25 In other papers, the issue of strategic shelving of patents in situations where technologies degrade over time is taken up (Goeschl and Swanson 2000, Mason and Swanson 2000).

26 There is a subtlety in (14), (15) and (16): Since $s=I-D$, the pay-off from delivering the next innovation depends on the history of biological adaptations which have occurred since the last technological innovation. Strictly peaking, the NPV of the next technological innovation, V_{I+1} , is the expected value of monopoly rents based on a probability distribution over s. This is because the flow of profits p is directly affected by the current level of productivity A_s. which is a joint outcome of both technological and biological processes. The present value thus decreases if pathogen adaptations have occurred. But if the price of land is allowed to change within technological stages, then the fact that marginal productivity will decreases at exactly the same moment at which a biological adaptation occurs means that the

relationship between land prices and private R&D is unaffected by pathogen adaptation since the real cost of R&D (measured in terms of the cost of land) does not change.

27 Since the LHS is increasing in v and the RHS is decreasing in v for $F''' = 0$ (sufficient condition), the equilibrium will be unique assuming this restriction on F'''.

28 The effect of the rate of biological innovation requires a qualification in that it holds only as long as the discount rate exceeds the net marginal productivity of land for innovations, i.e. for $r > (\gamma - 1)\left[\phi(i(v) - \frac{i'(v)}{a'(v)} + \lambda(1 - a(v))\gamma^{-1}\right]$.

If this condition does not hold, it would mean that land in R&D is the most competitive opportunity to generate welfare available in the economy. We would therefore generally expect this condition to hold.

29 In fact, there are two effects at work, one as mentioned above, the other decreasing the expected value of innovations. But
the latter is only a second-order effect which is dominated by the first as the partial derivatives show.

30 The only qualification on this result is that if the reserve sector has a higher intrinsic growth rate than all other sectors in the economy that have impact on consumption, then a higher arrival rate of biological innovations frees up resources to be put to final goods production.

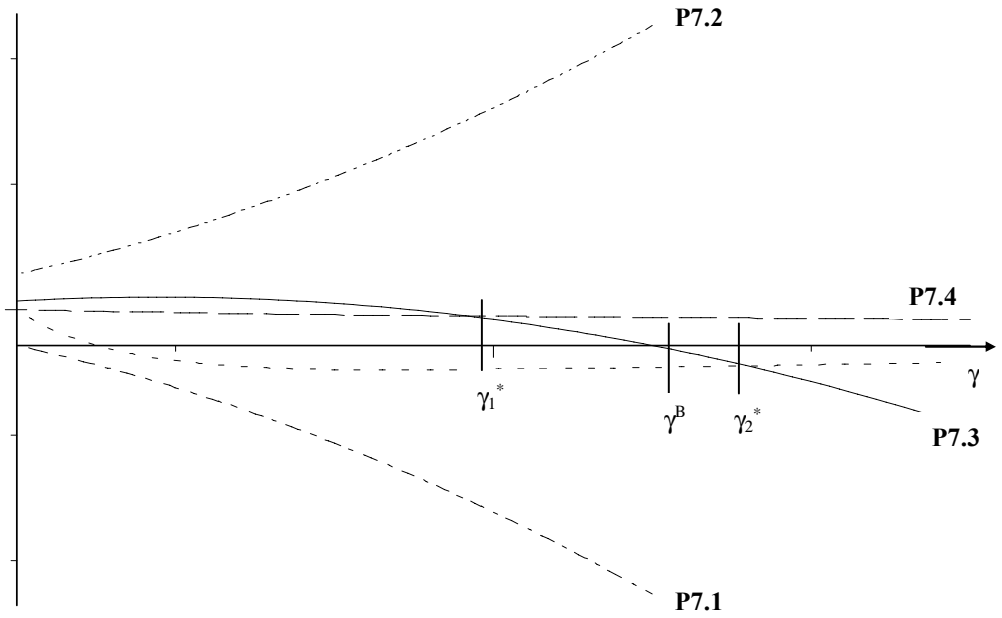
31 The second condition is the limit case. If it does not hold, it either implies the pursuit of innovations of very large size or of infinitely large innovations by society (or firms on its behalf) if there is no optimal point. See the further discussion,

32 A convex relationship between likelihood of innovation and innovation size is not very realistic as it would suggest the greater innovations would be relatively cheaper. This is therefore not explored here.

33 If assumption 1 does not hold, e.g. because the rate of response is determined by the last innovation, then an interdependence between the value of the patent and the choice of innovation size arises. This will lead to a partial internalization of the innovation size effect by the innovating firm. In the case of $a'(.) < 0$, this would lead to a decrease in the target size. In the opposite case, such as winnability, the effect is ambiguous: The first-order effect, effectively lengthening the patent duration, would encourage an increase in patent size. The second-order effect in the case of winnability is the positive effect of eradication of pathogens on the expected returns on patents for all competitors, thus shortening the length of the patent duration due to increased R&D activitity and the resulting higher rate of creative destruction in the industry.

34 Apart from usefulness, novelty and non-obviousness are the other two criteria required for being granted a patent.

Figure 1:



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