Managing the Pace of Technological Change: The Case of GMOs

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Abstract:

The management of the pace of technological change within biotechnology is considered within the model of creative destruction developed by Aghion and Howitt (1998). We discuss modern techniques of genetic modification as the capacity to choose the "step size" of innovation in biotechnology industries. It is demonstrated that the socially optimal step size of innovation depends on the prevailing beliefs concerning the responsiveness or adaptation of a biological system to technological interventions. Patent-based mechanisms do not motivate private firms to take into consideration biological responses to technological change, and so do not target the social optima in this context. The case of GMOs is indicative of the important differences between technological change in various sectors, and the importance of modifying intellectual property right mechanisms to account for these differences.

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1. Introduction

In 2003 the United States (US) lodged a complaint against the European Union (EU) within the World Trade Organisation, alleging that the EU was illegally discriminating against the importation of US products containing genetically modified organisms (GMOs).[1] The essence of the complaint by the US was that there was no scientific basis for distinguishing between the impacts of genetically modified organisms and those of other more traditional forms of agricultural innovations. Despite the absence of demonstrable effects on human health or the environment, there is a pronounced difference of opinion on the importance of the introduction of GMOs into the environment. Approximately two-thirds of the US public believes that biotechnologies in agriculture should be encouraged, while approximately two-thirds of the EU public believes the opposite (Priest 2000). Why are there such divergent views on this new technology? Is this a case of modern-day Luddite-ism or is there some distinguishing characteristic of the biotechnological sphere that renders this area more amenable to disagreement than other areas?

Biotechnology has a number of characteristics that distinguish it from other areas of technological progress and that raise important technology-specific policy issues. For example, the distinction between basic and applied research in many biotechnological areas is particularly amorphous (Carraro and Siniscalco 2003), imitation costs tend to be comparatively low (Grabowski 2002), and its products are particularly prone to suffer from market and government failures (Kremer 2000). We argue in this paper that one key distinguishing characteristic of the biotechnological realm is the capacity of the biological environment to respond directly to human innovation (Munro 1997). One example is the observed phenomenon of resistance to applied innovations[2] (Goeschl and Swanson 2003, Munro 1997, Mangel 1985). The adaptation of biota (pests and pathogens) to widely-used pharmaceuticals and plant varieties is a "fact of life", and it implies that the widespread use of

[1] Genetically modified organisms (GMOs) are biological organisms created by non-natural forms of human intervention.

[2] Plant breeders' R&D efforts are increasingly addressed to the ongoing problems of pest adaptation and resistance. 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). The advent of GMOs enables several new strategies within this biological contest. First, it is possible to incorporate traits that render the plant more tolerant of other interventions, such as the application of chemicals and other pesticides (e.g. "Roundup Ready soybeans"). Second, it is possible to incorporate traits that render the plant toxic to its usual pests and pathogens (e.g. Bt Cotton) – inbuilt pesticides. Third, it is also possible to incorporate traits that are so novel that they render the plant unrecognisable or distasteful to its usual pests or pathogens. Each of these strategies is capable of advancing technology within the contested environment, but the overall impact of each depends on the aggregate impact of intervention and environmental response (Swanson 2002).

any biotechnology must necessarily imply a biological response that will mitigate its initial effectiveness (Weitzmann 2000).[3]

The presence of such adaptive responses makes biotechnology an area of technology where many of the preconceived notions of progress do not apply. In such a context, it is no longer accurate to conceive of progress as the steady advancement upwards along a technological "ladder" (Goeschl and Swanson 2003).[4] If the widespread use of a technological advance must necessarily imply the increasing rate of arrival of problems, then prior progress is always subject to future loss. In a departure from 'ladder theories' of growth (Grossman and Helpman 1991), it may therefore be more accurate to think of the biotechnology sector as a race that requires the innovator to advance not on a ladder, but rather up the "down" escalator. Success in this type of race must then be measured relative to actual progress up the escalator, not just steps taken by the innovator along the escalator.

How should the idea of genetic modification be considered within this 'escalator' paradigm? We believe that it should be thought of as the ability to choose the size of the technological step taken within this contest. Prior to the advent of modern biotechnological means of genetic modification, the range of possibilities for technological advance in the life sciences was circumscribed by the range of genetic resources that were available to interbreed within a given species.[5] Biotechnologies have relaxed this constraint by enabling the crossing of these lines between species, thus engineering organisms that could not have normally been generated by a process of crossing and interbreeding. In the limit, the GMOs so produced can cross virtually any amount of genetic distance and represent the combination of virtually any resources within the gene pool. It is this enhanced genetic distance that best describes the enhanced "step size" of technological change. In economic terms the biological production set formerly can be thought of as a set of rays representing distinct genetic resource combinations enabled via standard reproduction (i.e. species), while now the entire set of convex combinations along the biological production surface are now available (Weitzman 1998). We conceptualise the difference between choosing the next point on this much larger production surface (as opposed to the next point along a given ray of production) as representing the larger steps afforded by biotechnology. In this sense, the steps are larger in

[3] Well-established laws of evolution exist to describe this type of pathogen response, driven by the *scale* of application of a new technology within a biological environment (Hofbauer and Sigmund 1988).

[4] In other R&D industries, the solutions generated can last forever. This quality of "durability" gives rise to the essentially cumulative nature of technological progress in other sectors and is captured in the concept of a "quality ladder" (Grossman and Helpman 1991).

[5] Reproductive isolation is the usual definition of an individual "species" and, in the past, the aggregate gene pool (generating all living organisms) was seen as segregated down the lines of individual species, with genes unable to cross these predetermined lines.

terms of both economics (affording a much larger production set from which to choose) and genetics (enabling much greater genetic distances to be bridged).

What are the impacts of "step size" on the background contest? Imagine that the escalator belt runs freely, so that larger leaps up the escalator ("two stairs at a time") simply result in bringing the stairs down more quickly. Given that individual attempts at progress result in both discrete moves forward and also an increased pace of the background contest, then 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. The biotechnology industry is not only in charge of generating solutions to problems, it is also implicitly in control of the background biological contest of innovation from which the problems derive. Rates of innovation, as well as the "step size" of innovation, are important decision variables in this management problem.

Does society provide the correct incentive mechanism for biotechnology firms to both innovate and to manage this background contest of innovation? Just as in any other R&D intensive industry, this industry operates within a patent-based system of incentives for innovation. One fundamental question is then whether the *patent system* has been formulated to provide incentives for pursuing R&D that considers both the rate of innovation and this background contest of innovation. These are the questions that we address here: What is the socially optimal "step size" of technological change to pursue within a biological environment? Will the biotechnology industries (motivated by patent-based incentives) manage both innovation and the background contest of innovation? And, finally, are there reasons within this context to explain why reasonable persons would reach very different conclusions regarding these questions?

We find that the socially optimal pace of technology (i.e. the optimal "step size" of the innovation) depends crucially on the beliefs concerning the prospects for success within a biological setting. At this point in time, there is no way to determine *a priori* which set of beliefs will ultimately prevail, and so very different conclusions regarding optimal policies are possible. In addition, we find that, irrespective of the beliefs applied, the patent system does not provide adequate incentives to motivate industries to consider the importance of managing the pace of technological change. In sum, society must develop other forms of incentive mechanisms to manage the introduction of new biotechnologies, such as GMOs.

The paper proceeds as follows. In section 2 we lay out the model of a biotechnology sector based on the model of creative destruction by Aghion and Howitt (1992; 1998). In section 3

we describe the unusual character of the R&D sector in biotechnology, contributing t o both the level and trajectory of future growth. In section 4 we set out the various plausible conjectures that might apply to the nature of the biological response to biotechnological interventions, and then explore the implications of these various beliefs for the socially optimal step-size of innovation. In section 5 we analyse the patent-based incentives to select the step-size of innovation, and contrast these with those existing under social optimum. In section 6 we conclude.

2. A Model of a Biotechnology Sector Producing GMOs

In this section we set out the basics of our approach to modelling the role of a biotechnology sector that produces GMOs for use in agricultural production. (Goeschl and Swanson 2001, 2002; 2003a) The approach builds on the model of creative destruction developed by Aghion and Howitt (1998), extended to include the impact of biological responses to human innovations. 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 by conducting R&D to provide a flow of innovations to sustain society in the contest of biological innovation. In between the research and production sectors, there is an intermediate goods sector that has the role of embodying the information developed in the research sector for application within the production sector.

Within this context the base R&D sector is the biotechnology sector working within the agricultural industry, and the intermediate goods are the genetically modified organisms (GMOs) within by which the innovations are transferred from R&D to production. The R&D sector identifies useful information (in the form of useful traits or characteristics generated by specific genetic code), and it then incorporates this useful information within the intermediate good (resulting in the GMO). The intermediate good is then used in the final production sector to generate consumer goods.

We will think of GMOs as representing "technological leaps" in terms of both the initial intervention and the ensuing adaptation. The GMO is conceived of as a novel form of strategy that is inherently more successful in production by reason of the amount of technological change it represents and, since the frequency of innovation is assumed to be unaffected, the overall pace of progress is increased by the move to GMO-based techniques.[6]

[6] It would be straightforward to incorporate other assumptions about the affects of biotechnologies on the rates of innovation as well, but we choose to focus on the biological response side of the problem to

Then the only issue concerns the response of the biological environment to the GMO, and the aggregate impact of initial intervention and ultimate response.

2.1 Modelling the Different Sectors within the Biotechnology Industry

Assume that there is a single consumption good (y) 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 that 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.

2.1.1 Final Good Production Sector

Final good production relies on only two inputs: the intermediate good (GMO 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 $F_{xx}<0$ 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.

2.1.2 Intermediate Good Production 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

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illustrate the importance that beliefs about biological response hold for the optimal pace of technology. Innovation is discussed briefly in section 4.3 below.

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. 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.[7]

2.1.3 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. In this model therefore, 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.

[7] One interesting development in the biotech industry is the advent of information appropriation strategies that are inbuilt within the final good, so-called genetic use restriction technologies. We have discussed the impacts of these developments separately. (Goeschl and Swanson 2001, 2002; Swanson 2002)

2.2 Technological Progress – 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 characterised 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.

2.2.1 Modelling the Innovation Process

It is assumed that the timing of innovations flowing from the biotechnology sector follows a Poisson process denoted by $ø$. The frequency of innovations within this process is determined in part by the level of investment in research and development (R&D) and in part by the impact of the step pursued. 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 $øi(v,\gamma)$ per time period where $i(v,\gamma)$, $i(0)=0$, $i_v>0$, $i_\gamma > 0$, $i_{\gamma\gamma} < 0$, is an innovation production function.

The impact of an innovation consists of a discrete shift in the level of productivity in the final sector, A_t. Assume initially that the size of shift is exogenously fixed at magnitude $\gamma>1$ such that $A_{I+1}=A_I\,\gamma$ with the index I denoting the current level of technology in use in final goods production. We will discuss the implications of relaxing the assumption of a fixed step size later.

For the (provisionally fixed) step size γ large enough, 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". 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. Initially, we will standardise the step size of innovation at this magnitude, in order to provide a standard measure of innovation with which to compare technological progress across various systems of organisation.

2.2.2 Modelling Adaptation – the Biological System’s Response

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. 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. Here we allow for a general type of relationship between the nature of technological change and the biological response, one that reflects the stochastic nature of the process.[8]

Analytically, we model the dynamic process of biological response mechanism induced by human intervention as a Poisson process.[9] This process has two components, the first being an exogenous component that gives rise to new pathogen types. This can be thought of as the rate of mutation in pathogen or the rate of gene transfer between pathogens, λ. The second is an endogenous component that can be thought of as a measure of how conducive the human-made conditions are for a mutant to become established in the pathogen population. The two parameters that determine the endogenous component in the model are the scale of uniform application of a technology, x, and the step size of human innovations, γ. The conduciveness function determined by the scale of application and the technological step size is denoted by $a(x,\gamma)$ and the resultant rate of successful adaptation or 'biological responsiveness' as $\lambda a(x,\gamma)$. Since a greater scale of uniform application is generally considered to be conducive for successful adaptation, it is reasonable to assume that $a_x(x,\gamma) > 0$ and $a_{xx}(x,\gamma) > 0$. Conjectures about the nature of the functional relationship with respect to step size γ are discussed later.

A "biological innovation" is normalised so that a single innovation eliminates the relative advantage of the prevailing technology. This results in a shift of γ^{-1} in productivity. Thus, $A_{D+1} = A_D \gamma^{-1}$ with D denoting the aggregate number of biological innovations. This implies that after a biological innovation has occurred, the economy reverts to the technology of the previous productivity level.

2.2.3 The Aggregate Impact of Technological Change – the Technological Stage of the Economy

The two processes of innovation and adaptation jointly determine the current state of productivity (A) within the final goods sector. Each technological innovation that occurs

[8] Previous models describing the process of scale-driven biological response have cast this mechanism in the equations of frequency-dependent selection arising out of the biological literature (Laxminarayan and Brown 2001, Munro 1997).

[9] 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).

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,

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

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.

3. 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. 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 available resources (here, land) will be allocated between the various sectors of the biotechnology 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 share of resources allocated to R&D, i.e. *v*. From (3) and (5) follows that $x=(1-v)/(\beta+z)$ such that $a(x)$ can be expressed as $a(v)$ with $a_v<0$. In order to incorporate the concepts of creative and adaptive destruction, 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:

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

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

We are now in a position to set out the social objective for a biotechnology sector. Expressions (1) – (7) can be re-arranged and aggregated to re-state the social objective of maximum production as follows (Goeschl and Swanson 2003):

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

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 implies the existence of a trade-off between investing 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 present value of social welfare from the allocation of this input between these sectors is.

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

where $F(\bullet)$ is $F[\beta^{-1}(1-v-g)]$ and $a_v<0$ from (5).[10] 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 resources to the production sector is denoted in the numerator, while the impact from allocation of resources 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 allocating increased resources (i.e. land) to final production. Moving resources instead toward the denominator increases those available for R&D, and increases the rate of innovation. The aggregate meaning of the denominator is a sort of "own discount rate of biotechnology" that is applied to determine the aggregate value of production given biological response to technological change. It is a composite of the social rate of time preference (r) reduced by the rate of technological innovation, $\phi\, i(v)$, and increased[19] by the rate of biological response $\lambda a(\gamma)$.

This denominator captures the expected aggregate 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 of agricultural production is very steep by reason of rapid technological change. Conversely, if the biotechnology sector is very unsuccessful, the biological response exceeds the rate of innovation, and the production system is unsustainable. The third possibility is that the biological response is equivalent to the technological intervention; then the biotechnology sector is in a closely-contested Red Queen race which provides little growth despite the existence of technological innovation.

Overall, the social object regarding the biotechnology sector is to allocate resources toward R&D in such a manner as to balance impacts of initial production and future growth (Goeschl and Swanson, 2003a,b). The problem of future growth requires further consideration, however, as the aggregate impact of biotechnological change depends on the net effect of the initial intervention and the ensuing biological response. We turn now to look at these issues.

[10] For a derivation, see Goeschl and Swanson 2003b.

4. Social Management of the Pace of Technological Change in Biotechnology

The management of technological change in biotechnology is important because the sum of the biological response to an intervention, in the aggregate, might outweigh the benefits derived from the initial intervention. The form of management required depends on the nature of the biological response that is anticipated. In this section we describe the range of possibilities concerning biological responsiveness, and the difference this makes for the optimal management of technological change.

4.1 Conjectures over the Impact of Intervention

To this point we have assumed that innovations were uniform in step size, being of the size required to acquire patent rights in the associated intermediate product. We now consider the implications of biotechnology enabling the choice of the step-size of technological change (γ).

Choosing a larger step size will generate a higher rate of technological progress (assuming that the rate of innovation remains the same) and – in accordance with (9) above – the only motivation for bounding step-size would be by reason of its indirect effects on either on the adaptation function, $\lambda a(v,\gamma)$, or the innovation function, $i\phi(v,\gamma)$. We look first at the adaptation function as the more interesting case for our analysis, and return to the innovation function in 4.3 below.

In our view, there are two main alternative conjectures concerning the responsiveness of biological systems to the pace of technological change, with two possibilities existing under each conjecture. All of these conjectures concern the rate of adaptation to new technologies exhibited by a biological system.[11]

Conjecture 1 (Biotechnological Optimism): $a_\gamma(v,\gamma)<0$ with:

1a) $a_{\gamma\gamma}<0$ *("potential winnability") ; or*

[11] We restrict ourselves to "nicely behaved" linkages, i.e. continuous and differentiable functions, although one could readily think of more complex linkages.

1b) $a_{\gamma\gamma}>0$ *("positive but diminishing returns to change in pace").*

This conjecture spells out the first of two 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 the observation that unusual amounts of change are something to which pathogens have not had to adapt, thus diminishing the probability that pathogens are able to adapt readily to unusual amounts of change. If $a(v,\gamma)=0$ for some very large γ, then the race against pathogens can be ultimately "won" by a sufficiently radical innovation. This would occur if the amount of technological change that occurred was so drastic as to present the pest or pathogen with an environment within which none of the existing population could survive. Then the pest or pathogen would become extinct, and adaptation would no longer remain a possibility. (O'Shea and Ulph 2002)

If extinction of pathogens does not occur, then increased innovation size merely serves to delay the biological response as an increasing ($a_{\gamma\gamma}(v,\gamma)<0$) or decreasing ($a_{\gamma\gamma}(v,\gamma)>0$) function of innovation size. Under these conjectures the pace of change is something to which biological systems are always able to respond, but the pace of change dulls the response rate. This might occur, for example, if the increasing amount of technological change resulted in severely diminished populations of surviving pathogens, and then (assuming logistic growth in pathogen populations) severely restricted levels of pathogen populations would imply the passage of time before the population with the resistant trait was restored to its pre-existing levels.

These then constitute the "optimistic belief system" concerning biological systems and their responsiveness to the pace of technological change. Under these beliefs, the effect of enhanced rates of technological change is an increasingly severe cull of the population of pathogens, resulting in reduced population levels that require the passage of time to return to prior levels. Under the most optimistic beliefs, it is possible to cull the population so severely as to reduce it beneath the critical mass required for its continued survival. Then the pace of technological change is capable of winning the biological contest with finality.

Conjecture 2 (Biotechnological Pessimism): $a_{\gamma}(v,\gamma)>0$, with:

2a) $a_{\gamma\gamma} < 0$ *("negative but diminishing returns to pace of change"); or*

2b) $a\gamma\gamma>0$ *("Red Queen Race")*

This conjecture lists the other two possibilities regarding the potential biological system's response to technological change. These conjectures represent the alternate "pessimistic" belief system regarding the overall impact of intervention within the biological world. The positive impact on the adaptation function indicates a belief in the conjecture that an increase in innovation size will trigger an accelerated response from pathogens. There are reasons within evolutionary theory that would support this conjecture. One explanation would be that greater step size in innovations favours the more rapidly adapting pathogens within the pathogen population that would otherwise be mitigated by more slowly evolving pathogens within the population. This would occur if the enhanced rate of technological change was viewed as a rapidly changing environment, within which only the most adaptable of pathogens was capable of survival. Then the effect of the enhanced pace of technological change is only to select that portion of the pathogen population that is capable of survival in the presence of rapid change. Essentially, this belief introduces a second level of selection pressure into the model, namely one that selects among pathogens at the level of the absolute speed of adaptation.

Again, two variations of this conjecture 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 is accelerating, i.e. $a_{\gamma\gamma}(v,\gamma)>0$. The first possibility represents the belief that the change in technology introduces the new level of selection, but that technology then is able to compete effectively at this level as well (i.e. it is possible to outrace the pathogens if the pace of technological change is increased sufficiently). In this case the belief system indicates that it is important to recognise that technologies can induce responses in the rate of adaptation, and so R&D investments must address this possibility as well.

The other possibility is far more pessimistic. It states that, if the technology introduces the contest at this level, then the biological response must continue to outpace the capacity of technology to maintain parity with it. This is the nature of a "Red Queen Race" in which it is necessary to innovate more and more rapidly merely to maintain parity with the biological competition.[12] This belief then indicates that intervention within the biological world has the character of a new "arms race": once introduced it provides a new dimension for costly competition without any prospect of ultimate gain.

The four cases discussed above set out the four possible belief systems regarding the relationship between human intervention and biological system response, ranging from the

most optimistic to the most pessimistic. In the ensuing section, we map these beliefs into the social decision concerning the optimal pace of technological progress. Following that we look at the extent to which patent-based incentive mechanisms motivate choices consonant with these various beliefs.

4.2 The Socially Optimal Pace of Technological Change

What is the optimal pace of technological change, given these alternative conjectures concerning the response of the biological system to the step-size of innovation? The social planner will choose to maximise expression (9) by choosing the correct innovation size, γ.[13] From equation (9) it is clear that the optimal size, γ^*, will be such that it maximises the following expression

$$\left[\phi i(v,\gamma) - \lambda a(v,\gamma)\gamma^{-1}\right](\gamma - 1) \qquad (10)$$

Differentiating equation (10) with respect to γ to arrive at the socially optimal pace of technological change (in terms of step size):

$$\gamma^* \;:\; \phi\left[\left[\; i(\bullet) + i_\gamma(\bullet)\;\right](\gamma^* - 1)\right] = \lambda\left[a_\gamma(\bullet)\frac{\gamma^* - 1}{\gamma^*} + a(\bullet)\gamma^{*-2}\right] \qquad (11)$$

The LHS of equation (11) is the marginal change in the rate of innovation with respect to innovation step-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 effect, consisting of $\lambda a_\gamma(\bullet)(\gamma-1)\gamma^{-1}$, is the effect of a greater size of innovation on the speed of response by pathogens. This effect depends on the sign of $a_\gamma(\bullet)$, which is the term through which the alternative conjectures concerning biological response will enter.

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[12] 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…."

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

PROPOSITION 1 (Aghion and Howitt 1998): In the absence of biological adaptations, there exists a unique socially optimal innovation step-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 a biological response to technological change, the RHS of equation (11) 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 under the various conjectures concerning potential biological response.

How do biological responses 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, $\lambda a(\bullet)\ \gamma^{-2}$. This is because adaptations work a cost to all technological change, meaning that *ceteris paribus* an enhanced rate of technological change has less of an impact than in the absence of a biological response.

However, this assumes that technological change cannot provide for the biological response mechanism, and this will depend on the conjectures applied concerning the interaction between technological intervention and biological response. The first-order effect can be dominated by second-order effects working through the conjectures regarding the biological response to technological change, a_γ. This means that for a_γ negative and sufficiently large (in absolute terms), innovation size under adaptation might exceed that under no adaptation (i.e. $\gamma^*>\gamma_B$), implying that technological change might be able to "build in" the capacity of the biological system to respond. This capacity to anticipate and manage biological responses depends of course on the beliefs applied to the implied contest of innovation.

[13] 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.

The conjectures in the previous section describe the range of possible belief systems concerning the capacity of technology to manage the response of the biological system.[14] Depending on the extant beliefs concerning the plausible biological response, the following four cases for the optimal step-size result:

PROPOSITION 2.1: ("Winnability") If RHS>LHS for all $\gamma \geq 1$, then $\gamma^* \to \infty$.

PROOF: Assume RHS>LHS for all $\gamma \geq 1$, then the expression (10) 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 $a_{\gamma\gamma} < 0$, *i.e.* conjecture 1a (*Winnability conjectures*) must apply.

PROPOSITION 2.2: ("Red Queen Race") If RHS<LHS for all $\gamma \geq 1$, then $\gamma^* < 1$.

PROOF: Assume RHS<LHS for all $\gamma \geq 1$, then expression (10) is continuously decreasing in γ and is therefore maximised for γ<1. For RHS<LHS to arise, necessary conditions are that $a_\gamma > 0$ and $a_{\gamma\gamma} > 0$, i.e. conjecture 2b (*Red Queen Race conjectures*) must apply.

PROPOSITION 2.3: If RHS=LHS for some $\gamma \geq 1$ and $a(\bullet) < - a_\gamma(\bullet)\gamma^*(\gamma^*-1)$, then $\infty > \gamma^* > \gamma_B$.

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 (11), 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 2.3 follows. A sufficient condition for Proposition 2.3 to hold is $a_\gamma < 0$, $a_{\gamma\gamma} > 0$ *(Positive but Diminishing Returns to Pace of Technology Conjectures).*

PROPOSITION 2.4: If RHS=LHS for some $\gamma \geq 1$ and $a(\bullet) > - a_\gamma(\bullet)\gamma^*(\gamma^*-1)$, then $1 < \gamma^* < \gamma_B$.

PROOF: This is the converse of the proof for proposition 2.3. A sufficient condition for Proposition 2.4 to hold is $a_\gamma > 0$, $a_{\gamma\gamma} < 0$ *(Negative but Diminishing Returns to Pace of Technology Conjectures)* although this proposition may hold under a wide range of fairly general conditions (see discussion below).

Figure 1 graphically characterizes the optimal choice of innovation size established under propositions 2.1 to 2.4. The benchmark step-size γ_B is situated where the function denoting the LHS of expression (11), graphed using a solid line, intersects with the *x*-axis. γ_B represents the optimal step-size for innovation in the absence of any anticipated biological response.

Where a biological response is anticipated, then the optimal step-size will be indicated by the intersection of the biological response function contained in the RHS of expression (11) with

[14] Since $\gamma < 1$ implies a decreasing growth path over time, we only consider equilibria for $\gamma \geq 1$.

the LHS of the same expression. The two other lines in the centre of the figure illustrate such intersections: the intersection marking γ_1^* is indicative of an anticipated negative response from the biological system while the intersection marking γ_2^* represents a more positive response anticipated from the system. We will now discuss each of the four alternative conjectures, and their implications for optimal technological change, in more detail.

Figure 1: Socially optimal innovation step-size under various conjectures

[figure 1]

Commencing with the lowermost line in Figure 1, this is the graph of the biological response function illustrating Proposition 2.1 regarding the implications of the conjectures concerning potential "winnability". This is the case where an increasing innovation step-size delays the pathogen response at ever increasing rate; then maximum innovation size should be targeted as there are essentially increasing returns to size-driven productivity growth (i.e. there is no intersection with the benchmark function). The possibility of "winnability" exists when adaptations cease above a certain innovation size. This is the demonstration of the most optimistic of beliefs regarding the potential implications of technological intervention.

The starkest contrast with these beliefs may be garnered by looking to the uppermost line in Figure 1. This line graphs the biological response function in the case where increasing innovation size accelerates pathogen response at an ever-increasing rate as set out in Proposition 2.2 above. Here the beliefs indicate that any step-size of biological intervention will generate selection pressures for increasing rates of adaptation, and increasing rates of technological change merely translate into even greater rates of adaptation. These represent conjectures based on the belief in "Red Queen Races" of biological innovation: any attempt to win the contest will merely enhance the pace of the contest instead. The optimal step-size goes to zero, since any form of intervention merely raises the contest to a new level of costliness without any attendant benefits.

These two cases provide the two polar perspectives on the capacity of technological change to generate progress in contests of biological innovation. Those who are pure biotechnological optimists will believe that "change is for the good", and even more change is even better. Those who are pure biotechnological pessimists will believe that "you can't fool with Mother Nature", and that any intervention is ultimately to ill effect.

The intermediate cases correspond to situations where expectations differ, but do not diverge so spectacularly. In the case of the second bottommost line in Figure 1, the biological response function is depicted as positively related to innovation size, although not at a sufficiently increasing rate to justify pure technological optimism. Here the derivative of adaptation rate with respect to innovation size, $a_\gamma(\bullet)$, is sufficiently large (in absolute terms) to outweigh the first order effect of increased innovation size, but does not large enough to prevent an equilibrium size. This implies increasing the optimal size of innovation to γ_2*, which lies above the benchmark value due to the additional benefits that arise out of delaying pathogen innovation.

As explained above, due to the first-order effect of innovation size on the rate of net productivity growth in the presence of adaptations, the existence of a biological response indicates that the optimal step-size within the biological context will generally lie below the benchmark value (γ_B). This general result can arise under all of the various specifications (beliefs) concerning the nature of the adaptation function, so long as the impact of technological change on the response function does not outweigh the first order impact of the existence of a biological response. The remaining line in Figure 1 illustrates the case of Proposition 2.4. This case results in an optimal size (γ_1*) that is smaller than that chosen in the absence of adaptation (γ_B) as the consequence of a dynamic penalty on a greater step size.

We conclude from this analysis that the optimal pace of technological change in the biological context will differ from that which exists in other contexts. The nature of that change will depend on the nature of the anticipated biological response to changes in the pace of technology, and the differences can be very stark. A set of beliefs that are technologically optimistic will indicate that the optimal pace of technology is unbounded, and therefore any feasible magnitude of technological advance should be pursued. A set of beliefs that are technologically pessimistic will indicate that the optimal pace of technological change is zero (as all technological contests within the biological context are ultimately of the wasteful nature of arms races), and so paths toward new technologies should never be pursued.

Both sets of beliefs are scientifically plausible, and so the range for disagreement within this context is potentially vast.[15] The underlying reason for this difference is that interventions

[15] There is no scientific consensus concerning the biological response to GMOs. One possibility discussed in the literature is that an increasing pace of technological change may simply increase the speed of response by pathogen populations (Maynard Smith 1976) or competing genes (Frank 2000). Biologists refer to such contests of innovation as "Red Queen Contests", those in which it is necessary to innovate more and more rapidly merely to maintain parity within the contest (Maynard Smith 1976). Another possibility discussed is that an increased pace of technological change might slow the rate of response from the pathogen population, or possibly eliminate the

within the biological world do not necessarily constitute one-off and reversible attempts at advance up a "quality ladder", but instead potentially resemble the engagement of society within a new and ongoing "contest of innovation". The latter has few of the attributes of the ladder. The issue is whether this background contest will ultimately erode away any gains achievable through the initial intervention. Depending on one's perspective on the nature of the biological world, it is possible for the full range of step-sizes to be plausible choices.

4.3 Impact of Step-Size on the Costs of Technological Innovations

To this point we have considered only the impact of step-size on biological adaptation. A final consideration in this analysis concerns the innovation function and its responsiveness to step-size. The standard assumption in the R&D literature is that the probability of innovation is declining in innovation step-size, indicating an increasing marginal cost of innovation size. This might not necessarily be the case in this context. Biotechnologies such as GMOs are unusual in that their introduction may enable a large number of innovations to occur at a relatively constant marginal cost. Biotechnologies, as the combination of material across much greater genetic distances, offer a one-time increase in the size of the choice set from which a large number of useful innovations may then be generated. One way to think about the impact of biotechnology is then as both an increase in step-size as well as an increase in the productivity of the R&D process (i.e. a shifting out of the innovation function).[16] Formally then, this implies a technological shift resulting in an innovation function $i'(v,\gamma)$ such that $i'(v,\gamma) > i(v,\gamma)$ and $i_\gamma'(v,\gamma) > i_\gamma(v,\gamma)$ for any γ.

PROPOSITION 3: If $i'(v,\gamma) > i(v,\gamma)$ and $i_\gamma'(v,\gamma) > i_\gamma(v,\gamma)$ for any γ, the positive root γ'^* of equation (11) for $i'(v,\gamma)$, if it exists, will be such that $\gamma'^* > \gamma^*$ where γ'^* denotes the positive root of equation (11) for $i(v,\gamma)$.

PROOF: If $i'(v,\gamma) > i(v,\gamma)$ and $i_\gamma'(v,\gamma) > i_\gamma(v,\gamma)$ for any γ, the LHS of equation (11) will unambiguously increase for the enhanced innovation function $i'(v,\gamma)$. For any given functional form on the RHS of expression (11), this implies that the $\gamma'^* > 0$ required to solve (11) will lie to the right of γ^*.

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population altogether (the so-called prospect of "winnability"). Depending on the view taken, differences in expectations concerning the biological response to the pace of biotechnological change will indicate that very different sorts of optimal policies.

[16] Even though other constraints (such as information processing capacity) ensure that increasing marginal costs will set in at some point. (Weitzman 1998)

Proposition 3 simply states the obvious implication of an increase in the absolute and marginal productivity of the innovation process on the optimal innovation size, viz. to increase it. This can be seen in figure 2 as a simple outward shift of the innovation function and the resultant movement to the right of the optimal step-size of innovation size.

Insert Figure 2

If this assumption is correct, then the advent of biotechnology is important for both enabling the choice of step size and also for enhancing the productivity of innovation. Both have important first-order effects in the determination of the overall pace of technological change. However, the innovation effect is important as it positively impacts the background contest of innovation, while the step-size effect can have either positive or negative effects (as we have seen). Hence the impact of biotechnology through its effect on innovation is unambiguously positive. For example, it may lead to a positive step-size of innovation even under Red Queen conjectures (see Figure 2). So, a second factor to consider concerning the social welfare effects of biotechnologies is the characterisation of the technological change that they involve: to the extent that the enhanced pace of technological change derives from an enhanced scale of innovations (rather than their rate of arrival), the greater is the possibility that management is required.

5. Biotechnology Industry Choices Under Patent-based Incentives

We have demonstrated that the choice of the socially optimal step-size of innovation is the outcome of the combined effect of step size on both the scale and the pace of the background contest. Will R&D firms operating under patent-based incentives be motivated to consider both in their innovation decision making? 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 (12) below, adapted from Aghion and Howitt (1998). Allowing for a linkage between innovation size and innovation and adaptation function, equation (12) provides that the present value of innovation I+1 as a function of the profits from that innovation (π) summed over an infinite time horizon in accordance with the "own discount rate of the biotechnology sector" (discussed in section 3 above)[17]:

[17] The only alteration to the own discount rate of biotechnology is the presence of the factor (n-1) representative of the number of firms in pursuit of the next innovation.

$$V_{I+1} = \frac{\pi_{I+1}}{r + (n-1)\phi i(v_{I+1}, \gamma_{I+1}) + \lambda a(v_{I+1,} \gamma_{I+1})} \qquad (12)$$

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 which there is no expected biological response function, i.e. $a(.) = 0$. The value of the next innovation V_{I+1} equals γV_I and the expected net benefits from R&D for each of the $(n-1)$ firms given the current value of a patent V_I and given R&D investment v_s is

$$B_{I+1} = \phi i(v_s, \gamma)\gamma V_I - A_s \frac{F'(\bullet)}{\beta} v_s \qquad (13)$$

Note that under the stationary equilibrium assumption the firm can take the following-period profits as given. The private biotech firm's profit-maximizing choice of innovation size γ_P is then:

$$\gamma_p \ : \ i(v,\gamma) + \gamma i_\gamma(v,\gamma) = 0 \qquad (14)$$

Comparing expression (14) with the social optimum in equation (11) gives rise to proposition 4.

PROPOSITION 4: (Aghion and Howitt, 1998): In the absence of an anticipated biological response, the privately optimal innovation size γ_P is smaller than the socially optimal size γ_B.

PROOF: See (Aghion and Howitt, 1998).

The intuition for the result is that by the concavity of the innovation function $i(v,\gamma)$, the solution to the LHS of equation (11) lies on the decreasing part of the function $\gamma i(v,\gamma)$ and thus to the right of the solution to equation (14). This implies under-investment by the private industry into the step-size of innovation.

How does patent-motivated choice change when we introduce the anticipated biological response to intervention?

PROPOSITION 5: Industry choice is invariant to the existence of biological response.

PROOF: In the stationary equilibrium, any firm in the industry will take V_{I+1} as given. Since the adaptation function does not enter into the optimality condition in expression (13), the optimal choice of γ is determined by expression (14) 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. In short, the individual firm engaged within a patent race does not recognise the effects of its own actions on the rate of adaptation.

Comparing firm-level choice captured in (13) and (14) with the social optimum defined by expression (11), the shortcomings of a patent-driven system under speed-dependent response become apparent. In the presence of a biological response function, there are four possible cases to consider, depending on the beliefs that may inhere under Conjectures 1 and 2. These four cases give rise to four propositions on the divergence of patent-based incentives from the social optima existing under these various conjectures.

PROPOSITION 6.1: ("Winnability") If the socially optimal step-size is infinite (i.e. $\gamma^* \to \infty$), private firms will target *insufficient* innovation step size.
PROOF: Equation (14) defines a finite optimum for γ_P under conventional assumptions about $i(v,\gamma)$. From this follows that $\gamma_P < \gamma^*$.

PROPOSITION 6.2: ("Red Queen Race") If the socially optimal step-size is zero (i.e. $\gamma^* < 1$), then firms will target *excessive* innovation step 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 (14) must therefore hold for $\gamma_P > 1 > \gamma^*$.

PROPOSITION 6.3: ("Positive but Diminishing Returns to Pace of Technology") If the socially optimal step size is greater under biological response than in its absence (i.e. $\gamma^* > \gamma_B$), then firms will target *insufficient* innovation size.
PROOF: From Proposition 6, $\gamma_P < \gamma_B$ and by transitivity $\gamma_P < \gamma^*$.

PROPOSITION 6.4: ("Negative but Diminishing Returns to Pace of Technology") If the socially optimal step size is reduced under biological response than in its absence $\gamma^* < \gamma_B$, then firms will target an innovation step size that is either:

a) *insufficient* if $a_\gamma(v_P, \gamma_P) < C$;

b) socially optimal if $a_\gamma(v_P,\gamma_P)=C$; or

c) *excessive* 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 differences between the socially optimal step size and that occurring under private choice highlight the failure of a patent driven system to target the socially optimal innovation step-size in the context of the biotechnology industry.[18] The existence of a biological response function indicates that the management of the pace of technological change requires careful consideration, the nature of that management depending on the beliefs that prevail concerning the underlying biological contest of innovation.[19] [20] It is clear from Propositions 6.1-6.4 that the patent-based system of management does not target the socially optimal step-size of innovation in general. In short, the use of the patent system as a mechanism to motivate the management of the pace of technological progress clearly is inadequate within the biotechnological realm.

6. Conclusion

Technological progress means different things in different settings. In some areas of human enterprise and endeavour, it is of the nature of a ladder. Steps may be taken forwards and backwards on a surface that is relatively well-known, simple and solid. Then the idea of a *direction* for progress is clear-cut ("upwards") and the metric for evaluating it is a given

[18] The ambiguity in proposition 7.4 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}).

[19] This failure also exists in the absence of speed-dependent selection among pathogens (see proposition 4). There it has been suggested to modify the patent system in order to align social and private optima (Aghion and Howitt 1998).

[20] Moreover, this is also the case if biotechnology could escape the conventional assumptions about decreasing returns to innovation as a function of innovation size (see section 4.3)

("how many steps"). Motivating individuals and enterprises in this direction is also a relatively simple matter, as the number, size, and frequency of steps all move in the same direction.

This is not necessarily the case within the context of the biological industries, or life sciences. These industries work within an area of experience in which the target is itself in motion. Rather than being of the nature of a ladder, it is more like the previously-mentioned race up the down escalator, and one in which the choices about steps (number, size, frequency) determine in part the motion of the background contest (i.e. the direction and the speed of the escalator itself). In this context, the individuals and enterprises concerned are indirectly in control of both the race and the nature of the contest itself. Motivating these individuals to pursue the social optimum is much more complex, when the nature of technological progress is so much more complex.

The first issue concerns the ascertainment of the social optimum in the context of such complicated contests. We have found that the nature of the optimum depends crucially on the prevailing system of beliefs about the fundamental relationship between human society and the biological world. Is it the case that "you can't fool with Mother Nature", or can biotechnology harness the life sciences just as the knowledge of physics harnessed the atom? That is, is there something fundamentally different about the biological world that will resist restructuring, or will the building blocks of biology (genes) be amenable to becoming part of the human toolkit? Depending upon one's beliefs concerning these fundamental questions, the socially optimal pace of biotechnological progress can be either zero, or infinite.

We find that there are four distinguishable sets of beliefs concerning the capacity of biological systems to respond to human intervention, and at least three very different social optima resulting from these belief systems. Science has not yet disqualified any of these potential belief systems, and there is little consensus concerning any one of them. As mentioned at the outset, this has resulted in public opinion moving in very different directions in different parts of the world. The outcome of this divergence in beliefs is the wide range of policies extant in the area of biotechnology, and the fundamental disagreements between different jurisdictions concerning which should apply.

None of this would matter if we could trust this contest of innovation to our innovators. However, and irrespective of the quality of human ingenuity, we can only do so to the extent that our incentive systems require innovators to focus on the correct objective. How well does the patent system motivate the private biotechnology industry to consider both

innovation and the background contest of innovation? We have shown that patent-based firms are concerned only with the achievement of the next innovation, and not at all with the impact on the pace or direction of the contest itself. Depending on the relative importance of the background biological contest, this omission may entirely misdirect the biotechnology industry.

In conclusion, the problem of GMOs is a case in which the received thinking about technological progress and patent mechanisms is indeed brought into question. The divergence in beliefs between the believers in the Red Queen and the believers in winnability explains much of the conflict over policy options in this area. More fundamentally, the GMO case study makes clear once again that the patent mechanism is a very crude instrument for managing all of the various facets of technological change. (Goeschl and Swanson, 2003)

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Figure 1: Optimal innovation size under various assumptions regarding the adaptation process

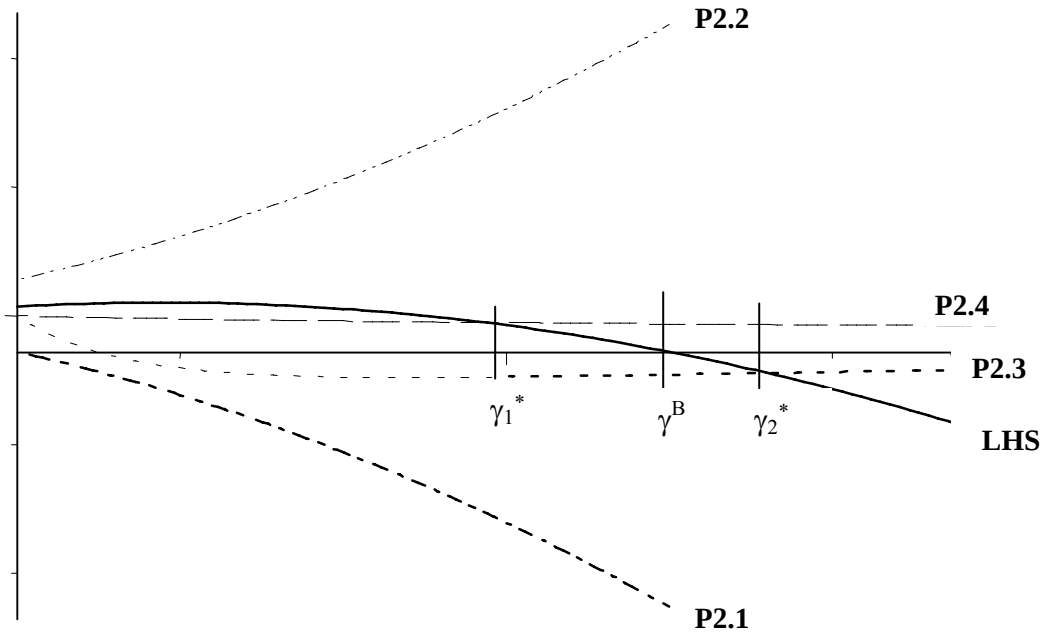

Figure 2: Increase in optimal innovation size implied by increased R&D productivity