13a

Do patent-style intellectual property rights on transgenic crops harm the environment?

Timo Goeschl[#]

Abstract

This paper examines the linkages between the system that society uses to incentivize R&D by private innovators in the area of crop improvement on the one hand and the environment on the other. This examination is an important addition to the technology-assessment exercise conducted in the context of transgenic crops since it focuses on the organization of the R&D process rather than on the outputs. The paper first demonstrates that design choices with respect to the system of rewards under which crop improvement is carried out determine important characteristics of R&D outputs. In particular, it shows that choosing a patent-style system of intellectual property rights (IPR) will impact on the rate, direction, pace and mode of technological change in the agricultural system. This is relevant in an environmental context because the R&D outputs thus generated interact with biological systems. Specific production and adoption characteristics of these outputs therefore matter in environmental terms. While the presence of these environmental impacts is a generic characteristic of carrying out crop R&D under patent-style IPRs, the extent of these deviations differs between conventional and transgenic crops and is determined by a number of biological, technological and legal key determinants. A comparison of the differences in these key determinants between conventional and transgenic crops shows that there are some areas in which there is no difference between conventional and transgenic crops, in particular with respect to the mode and direction of technological progress. In those areas where we find differences, the differential environmental impact of moving from conventional to transgenic crops is ambiguous.
Keywords: R&D; intellectual property rights; patents; transgenic crops; environmental impacts

Introduction

There is a sizeable and expanding literature that examines the direct effects of releasing genetically modified crops into the environment (for a survey, see Conner, Glare and Nap 2003). This literature concerns the possibility, probability and consequential environmental harm of such a release and forms an integral part of the process of technology assessment in agriculture. In this assessment process, the products of the societal research and development (R&D) process are thus to be subjected to due scrutiny.

[#] Department of Agricultural and Applied Economics, University of Wisconsin-Madison, Madison WI 53706, USA. E-mail: goeschl@aae.wisc.edu

The starting point for this paper is that the literature on the environmental impacts of transgenic crops may answer the question of the impact of specific R&D *outputs*, but not the more fundamental question of the impact of the R&D *process*. While the former is a question of how to manage a given technology, the latter is a question of how society should organize the biotechnological research process of which the specific technologies are an outcome. The organization of the R&D process that delivers crop improvements can be analysed from a number of perspectives such as sociology (Buttel 1999; Busch et al. 1991) and history (Ruttan 2001; Palladino 1996). For economists, an essential determinant of this organization is effected through the assignment of property rights to different actors at different stages of the R&D process (Swanson and Goeschl 2000). These property rights take the form of residual ownership over various inputs and outputs of the R&D process. The focus of this paper is a specific subset of property rights, namely those defined over the intangible asset of information that are the essential inputs and outputs of the crop improvement process. These property rights are commonly referred to as 'intellectual property rights' (IPR).

Why is the specific nature of IPR and structure of their ownership of relevance to the environment? There are two principal reasons. The first is that biotechnologies are endogenous in the sense that the organization of the biotechnological research process determines important aspects of their nature and shape. As we will show, organizing an R&D process under the specific reward system of IPR affects the volume and nature of the R&D outputs pursued. Since the R&D outputs at the centre of this paper are crop plants, these aspects are of direct environmental relevance. The ecological characteristics of crops determine their interaction with the biological environment of the agricultural system, while their production characteristics determine – at the margin – the returns to alternative uses of land and hence the relative allocation of intensive production, extensive production, and land outside agricultural usage. Systems of ownership over R&D outputs are therefore of direct environmental relevance. However, the organization of the R&D process in society determines ownership not only over R&D outputs, but also over the inputs into the R&D process. In the case of crops, one essential R&D input is genetic resources. These genetic resources need to enter into the R&D process on a continuous basis emanating from active agro-ecological system (Swanson 1999; Holden, Peacock and Williams 1993). The nature of how property rights are assigned over these R&D inputs is the second reason why society's choice of how to organize the R&D process has environmental relevance. In an abstract sense therefore, this paper examines the nature and impact of the linkages between the institutions that society chooses to incentivize agricultural R&D and the natural environment. The specific angle from which we will examine the environmental impacts will be land use patterns as the main determinant of environmental quality in agro-ecological systems.

To illustrate the environmental relevance of the organization of the R&D process, Figure 1 below gives a simple schematic representation of the R&D process and its linkage with land-use patterns. Essential informational inputs relevant for the biotechnological R&D process are generated in biodiverse systems that we will repeatedly refer to as 'reserves' to emphasize their conservation function. These systems are rich in genetic resources and are generally found in non-converted areas or areas of low-intensity production. The main form through which informational inputs arise in biodiverse systems is through the interaction of a diverse set of genetic resources with specific ecological conditions that vary through time and that generate information about currently successful ecological strategies such as resistance to a current pest that is used

to produce more productive R&D outputs such as a virus-resistant crop variety (Swanson 1999). The information so produced is used in the R&D process to enhance existing cultivars. These cultivars form the output of the R&D process and are then applied in intensive production systems. The relationship between R&D inputs and outputs is therefore characterized by both complementarity and competition: in the R&D process, there is a reliance of new cultivars on available genetic resources while, in terms of land use, genetic resources and new cultivars compete for land resources. The challenge is to design and assign property rights over these inputs and outputs in a way that leads the R&D process to effect the correct land-use structure. The question regarding the environmental impact of intellectual property rights on crops can then be framed as one regarding the impact of assigning such rights over R&D outputs on key characteristics of biodiverse and intensive systems (such as relative size), and this is the angle from which we will approach the question in this paper.

The paper has two parts. The first examines to what extent IPR – as the preferred incentive regime for agricultural R&D – are a causal factor in inducing land-use patterns that deviate from what would be first-best from society's point of view. The conclusions of this first part are generic rather than technology-specific, and highlight the welfare loss relative to a putative (i.e. non-existent) first-best system. They point to quite fundamental questions about the adequacy of a conventional IPR system in managing biotechnologies that are fully developed elsewhere (Goeschl and Swanson 2003c).

The second part analyses to what extent the trend towards genetic modification as the preferred technology in agricultural R&D exacerbates or reduces the deviation from the optimum. In examining the second question, it is important to declare the baseline against which the comparison is made, and for this purpose the most appropriate choice must be conventional forms of breeding. The analysis shows that the net environmental impact of a trend from conventional towards transgenic crops is ambiguous since it is determined by complex interactions between technological, biological and economic parameters pulling in different directions.

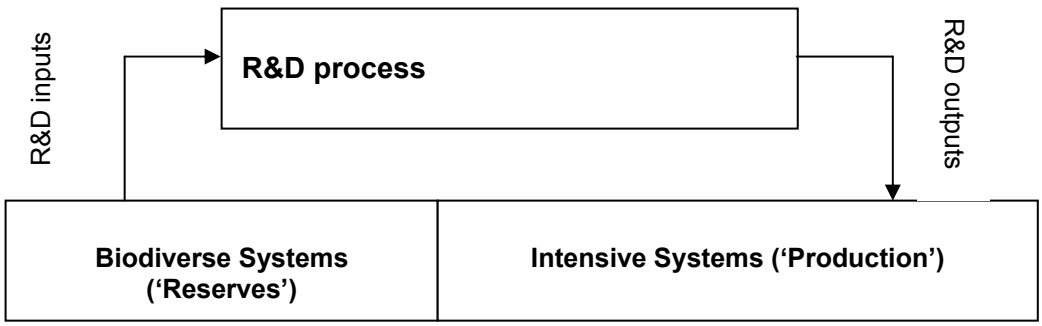

Figure 1. Schematic view of R&D process in land-use terms

To develop the argument, this paper first describes the relationship between intellectual property rights and the organization of the agricultural R&D process, and how IPR impact on the various dimensions of technological progress such as rate, pace, direction and mode. In the next section, the paper summarizes the results of some recent work that sheds light on how an R&D process conducted under IPR impacts on the environment. The following section then examines how a shift from

traditional to transgenic forms of plant breeding modifies these impacts. The last section concludes.

IPR and the R&D process in plant breeding

Intellectual property rights

In order to examine the relationship between IPR and the R&D process, some background in the economics of property rights in general is required. Economists understand their paramount function in the economy to consist of directing economic activities and the allocation of goods and services. They do so by assigning ownership in certain assets in the economy to individual economic agents. These rights are usually assigned through a legislative process that is coupled with a judicial process in which disputes over rights can be settled. Ownership of property rights, thus secured, is generally regarded as "the most common and effective institution for providing people with incentives to create, maintain, and improve assets" (Milgrom and Roberts 1992, p. 288).

Property rights can be defined over both tangible and intangible assets. Arguably the most important type of property rights over intangible assets are intellectual property rights. This regime is often used to allocate ownership in industries that are focused on the production of useful information through a process of R&D. When R&D is a significant part of the production process within an industry, it is not always possible to obtain a reasonable rate of return on the product without an extended right of control over its subsequent use and marketing. This is because the end result of the R&D process is an idea, and this idea is then embodied in the products in which it is sold, and potentially lost on first sale. The software industry is a typical example: a computer program that balances a bank statement is first an idea, and then a specific list of computer instructions created to effect that idea. If there is no exclusive right to control the subsequent marketing of the good (or close facsimiles thereof), then the first purchaser of that good would have the right to produce competitive products without expending all of the R&D resources required to produce it initially. The first sale of the computer code would enable the purchaser to make a similar program and set up in competition with the first. This is problematic if the first seller invested years in the construction of the program while the second only invested the few minutes (and dollars) required to copy it. In industries in which a substantial amount of the value produced is attributable to the information it contains (generated through R&D), there would be no incentive to invest in this R&D in the absence of the capacity to control the marketing of its goods even after their transfer to others. Intellectual property-right regimes are analysed by economists as incentive mechanisms which give extended rights of control over the marketing of certain goods in order to provide incentives for the information-generating investments (R&D) that resulted in them, notably the right to exclude others from their use (Arrow 1962; Swanson 1995).

There is a great variety of rights denominated 'intellectual property': trade marks, copyrights, patents, plant variety rights etc., which differ in the strength of the right to exclude. The most important thing that all of these rights have in common is that they allow the holder to control some of the uses of the good subject to these rights *even after the good has left the rightholder's possession*. Thus, a person with a copyright on a book is able to sell the book but retains the exclusive right to copy it. A person with a patent on a machine is able to sell the machine while retaining the exclusive right to manufacture it. A person with a registered plant variety certificate is able to sell that plant while retaining the exclusive right to reproduce it for re-sale.

The function of this extended right of control is to vest the holder with an exclusive marketing right in the particular good, usually for a limited period of years. This allows the holder to obtain a reasonable rate of return on the book, machine, plant variety or other good that is subject to the recognized right. Note that this rate of return is only available to the extent to which users recognize and enforce this right after the good has already left the possession of the rightholder. To the extent that the other users are willing to purchase from prior purchasers, the rightholder's exclusive marketing right will be of little value. There is a substantial increase in the rate of return afforded by allowing rightholders to control the uses of their rights outside of their possession. Various studies have substantiated the investment-stimulating effect the introduction of IPR regimes has had on R&D intensive industries, in particular plant breeding (for a survey, see Fuglie et al. 1996). In the following section, we examine how IPR are assigned in the R&D process that generates crop improvements.

The vertical industry of plant breeding

In Figure 1, the R&D process appears as a 'black box' into which R&D inputs enter and from which R&D outputs leave. Here we 'open' this 'box' to understand the various actors involved in the various stages of the R&D process and how IPR are assigned along this vertical chain. Swanson and Goeschl (2000) present a schematic view of the agricultural R&D process that highlights the vertical structure of the biotechnological R&D industry and is reproduced in figure 2.

At its base, effective characteristics for new plant varieties develop naturally through the process of 'natural selection': only those which are able to survive existing threats (pests and environmental changes) remain and reproduce. Since the set of threats is constantly changing, the natural environment continuously produces new information on the characteristics that are relatively fit under current conditions. The maintenance of a relatively greater diversity of genetic resources and the dedication of greater amounts of lands to the retention of that diversity are the investment choices that determine the amount of information flowing out of this stage of the industry on the nature of the plants that work effectively in the prevailing environments.

The next stage of the industry consists of the individuals who observe the natural process of selection and aid in the dissemination of its information. 'Traditional farmers' have themselves survived by means of a process of observing this naturally produced information and the disproportionate use and transport of those plant characteristics which have aided survivability. They invest in the production of this information both by means of their land-use decisions (as mentioned above) and by dedicating their time and resources to the observation and discriminatory use of those genetic resources which are revealed by nature to be of greater fitness. Their choices each year result in the capture of some of the flow of information on what was successful in the environment prevailing in the current year. This information also accumulates as a 'stock': traditional plant varieties (landraces) encapsulate the accumulated history of the information that nature has generated and that farmers have observed and used disproportionately (Swanson 1999).

At the end of this process, the 'plant-breeding industry' has collected the set of varieties that farmers have created over millennia and hence the stock of naturally-produced information that is encapsulated within them. By investing in laboratory equipment and scientists, the breeding process becomes focused on the use of this set of information for the preparation of the best possible variety for current environmental conditions. The modern plant breeder has then used its investments to create a variety

that is an amalgam of some subset of the traditional varieties. We now proceed to characterize the current structure of assignment of IPR across this vertical industry.

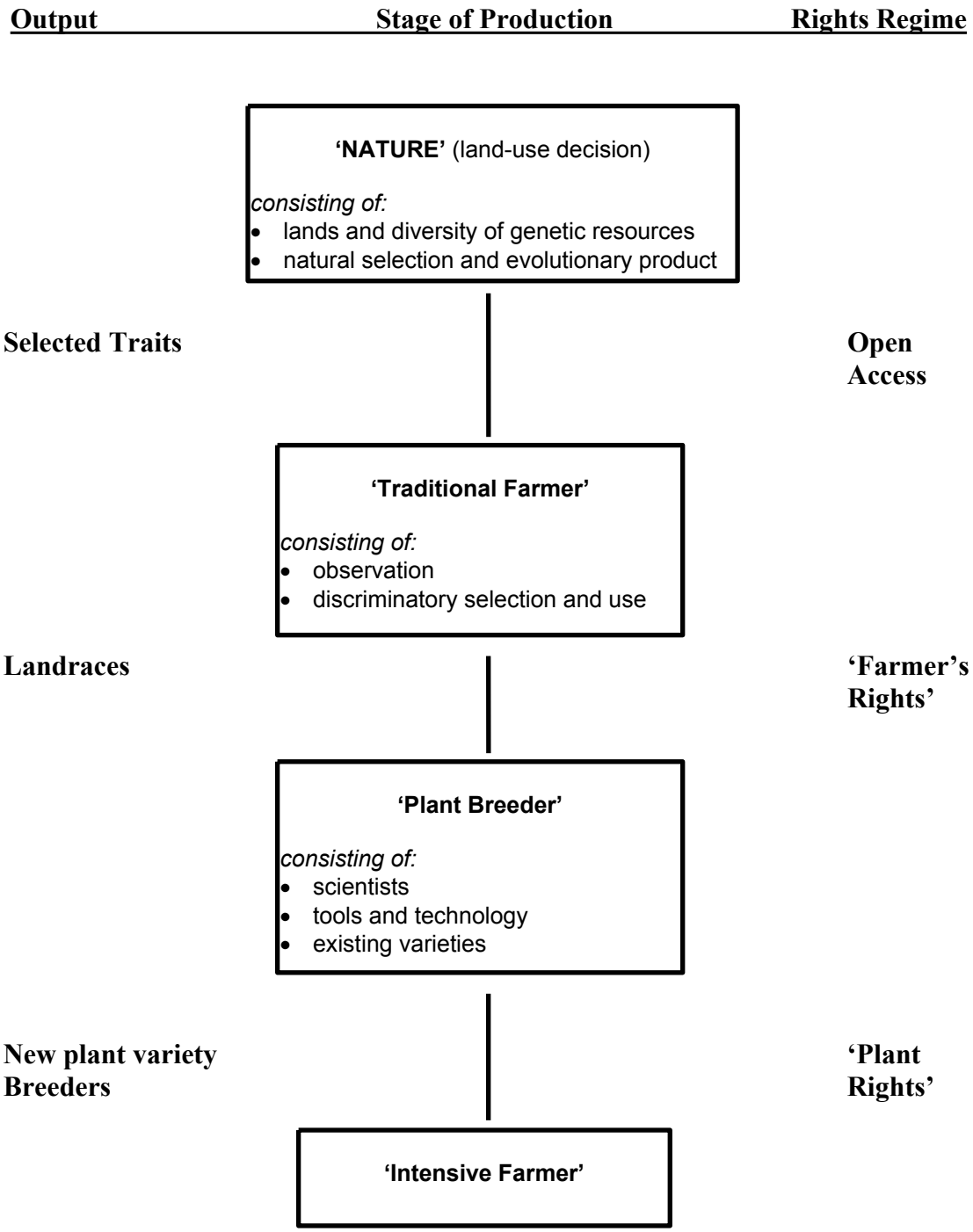

Figure 2. The R&D process of plant breeding (source: Swanson and Goeschl 2000)

Intellectual property rights in crop R&D

One important characteristic of the vertical industry of plant breeding is that it involves the flow of information between several stages of the R&D process. Between each stage, information is exchanged in a particular form between different agents: land-use decisions of landowners allow the appropriation of information about successful ecological strategies by any observer. Farmers engaged in extensive production generate

sets of information embodied in landraces. These are subsequently used by plant breeders to incorporate value-adding traits into cultivars. Finally, farmers use the information embodied in new cultivars in the final production process. From an economic point of view, the question is how to ensure that the exchange of information along this vertical industry is carried out efficiently by adequately distributing rents to the different agents across the various R&D stages (Swanson and Goeschl 2000).

IPR can be thought of as the institution created to enable the voluntary exchange of information to occur efficiently just in the same way as property rights in general enable the exchange of conventional goods from agent to agent. What IPR govern the exchange of information along the sequence of R&D stages in plant breeding? Swanson and Goeschl (2000) provide a detailed analysis of the IPR structure. Their key observation is that IPR in the crop R&D process are instituted in an asymmetric fashion. Only one stage of the industry is invested with IPR, namely the retail end of the vertical industry where R&D outputs are marketed. Even though there are some recent policy initiatives to create so called 'farmers' rights' and there are some nascent national IPR systems governing biodiversity (for example in the Philippines), so far prior stages of the R&D process, in particular those involved in producing R&D inputs, do not benefit from a formally instituted and enforceable system of IPR protection.

Asymmetry in property-rights allocation along a vertical industry is not in itself an indicator of inefficient institutional design as Coase (1952) has demonstrated. In the presence of transaction costs, however, the nature of the asymmetry is of critical importance for the overall efficiency of the choice of institutions. Here we merely note the presence of this asymmetry and refer the reader to Swanson and Goeschl (2000) for a full discussion of whether the implicit differentiation of property-rights protection to different forms of land use are a potential source of inefficiency.

Impact of an intellectual property-rights regime: the nature of R&D

To complete our analysis of IPR and crop R&D, we need to examine in greater detail the impact the use of an IPR at the retail end of the vertical industry has on the R&D activity at this stage. This IPR hands the plant breeder the right to exclude others for a specific time period from the use of the information embodied in the cultivar either for the purpose of further R&D (unless allowed through a so-called 'plant breeders' exemption) or for the purpose of use in final production (unless allowed through a so-called 'farmer's privilege'). The intended consequence of IPR is to allow the creation of a temporary monopoly for the innovator and to reward the innovative step through the collection of monopoly rents.

What does the presence of such a reward system for plant breeders imply in terms of R&D pursued? Even though there is an extensive literature on the effects of IPR on R&D in general (e.g. Jaffe and Trajtenberg 2002; Merges and Nelson 1990; Nordhaus 1969), in order to answer this question in the context of crops, it is necessary to consider a fundamental distinction between the agricultural industry and other sectors (Goeschl and Swanson 2003c). This is caused by the fact that agricultural innovations such as new cultivars are threatened with obsolescence not only on account of better innovations entering the market, but also on account of pathogens present in the agricultural system adapting to new cultivars and causing a breakdown of their resistance. The significance of the pathogen problem in crop improvement can be gleaned from the observation that traits conferring virus (40%) and insect resistance (37%) account for 77 percent of the area sown with genetically modified crops (Nap et al. 2003). Pathogen evolution and consequential crop loss is therefore a major challenge to agricultural R&D (Oerke et al. 1994). How do firms operating under a patent system respond to the challenge implied

by the simultaneous presence of two contests, a commercial one against other firms and a technological one against biological competitors?

We have developed the analysis of the impact of IPR in life-science R&D in a number of papers (Goeschl and Swanson 2002; 2003a; 2003c; 2003b). Lack of space permits little more than a summary of the four key conclusions from these papers to the extent that they reflect on the environmental impacts of organizing the R&D process under patent-style IPR. These key conclusions concern the rate of R&D, the direction of technological change, the pace of technological change, and the mode of technological change in the agro-environmental system.

Impact 1: IPR as determinant of the rate of technological change

The socially optimal scale of investment in R&D in the biotechnology sector balances the increased benefits from increased innovation (from increased R&D) and from reduced adaptation (from reduced scale of production using the current technology) against the cost of foregone production. Private firms invest in R&D in order to increase the output of private innovation (Goeschl and Swanson 2003a). Private R&D therefore decreases with the severity of the adaptation problem while the socially optimal amount of R&D increases.

Impact 2: IPR as determinant of the direction of technological change

The social optimum implies investment in technologies that decrease the rate of biological adaptation. A typical example is R&D into the optimal design and scale of ecological buffer zones (such as refuge areas). Analytical results indicate that IPR-incentivized firms have little incentive to invest in R&D for the purpose of reducing the rate of adaptations since the benefits of investing in mitigation technologies dissipate across the industry (Goeschl and Swanson 2003c).

Impact 3: IPR as determinant of the pace of technological change

Biological systems respond to variations in the 'step size' of innovations, even though the direction and extent of this response is not very well understood so far. While society will vary the size of innovations and hence the pace of technological change in accordance with the response of the biological system to the size of innovations, industry choice of the pace of technological change will be invariant to the nature of biological response (Goeschl and Swanson 2003b).

Impact 4: IPR as determinant of the mode of technological change

While society would prefer a cumulative adoption of new technologies, private industry operating under an IPR regime prefers sequential adoption of new technologies. The IPR-incentivized firm does not consider the positive impacts of its R&D with regard to a) the social gains that would be received by reason of its own innovations that occur within an existing patent's life; b) the social gains that would be received by reason of reduced levels of adaptations from the introduction of an additional technology by itself or another firm (reducing the scale of application of other technologies) (Goeschl and Swanson 2002).

These four key conclusions highlight that the application of patent-style IPR to incentivize research and development in crop improvement generates a number of deviations from what economists refer to as the 'social optimum'. In part, the presence of such deviations is not surprising. It is well known that patents are strictly second-best instruments to resolving the problem of knowledge production. However, the four impacts noted above point to additional problems that arise in the use of patent-style IPR in the specific domain of crop improvement.

The environmental consequences of IPR in crop R&D

What is the environmental relevance of the problems of using IPR in the agricultural R&D process? This question requires an analysis of how the use of IPR to incentivise agricultural R&D impacts on land-use patterns and the management of the environment.

Environmental consequences of IPR problems

Impact 1 states that agricultural R&D in crops conducted under a patent-type system of rewards will result in insufficient investment in R&D on account of the negative impact that the presence of evolving pests and pathogens has on the expected returns on R&D investment. As a result of the suboptimal R&D effort by industry, demand for inputs into the R&D process will not reach the level expected under first-best. The market failure on the R&D output market therefore spills over into the input market. Brown and Swierzbinski (1988) show in a static model that this type of spill-over leads to an undervaluation of biodiverse resources on the market and consequently to lower returns on forms of land use that promote the conservation of such resources. Goeschl and Swanson (2003a) show that this effect holds to an even greater extent under dynamic considerations and that incentives to convert land to intensive production above what would be optimal persist over time. These deviations from optimal land-use patterns on account of insufficient demand for genetic resources generated by the private R&D sector therefore pose the first set of environmental problems associated with the use of IPR in crop development.

The second conclusion from the formal analysis of the R&D problem points to the direction of technological change. The models indicate that firms have no incentive to invest in technological trajectories that lead to lower rates of adaptation in pests and pathogens. The reason is that the benefits of pursuing these trajectories have strong positive externalities to other firms in the industry (on account of increasing their expected patent rent) and a first-order negative effect on the innovating company since its own expected patent rent is reduced on account of higher R&D investments by its competitors. From society's perspective, however, such technological trajectories are highly desirable[1]. The failure by private firms to pursue them leads – again – to lower R&D investment than would be optimal, further reducing the demand for R&D inputs and driving the management of the agro-ecological system away from technologies that manage evolutionary dynamics.

Not only does R&D conducted under patent-style IPRs lead to the pursuit of sub-optimal R&D trajectories, it also impacts on the pace of technological change and hence on the evolutionary pressure that is exercised on the agro-ecological system. The pace of technological change in dynamic models of agricultural R&D is captured in the step size of innovations, in other words the degree of novelty introduced by subsequent technological vintages into the agro-ecological system. Although the ecology of host plants and their pathogens does not give a clear indication about the impact of varying the pace of technological progress on the evolutionary response of the biological system (for an example, see the paper by Schubert et al. in this volume), the economic analysis of the problem demonstrates that whatever the response is, society will prefer to vary the pace inversely to the dynamics thereby induced. If a higher pace of technological progress increases the speed of the evolutionary response of the system, a reduction in the pace is the socially desired response and vice versa. Under some fairly general conditions it can be shown that an industry operating under an IPR system will – by contrast – be invariant to the evolutionary response of the

agro-ecological system to the chosen pace of technological change (Goeschl and Swanson 2003b). This implies a suboptimal management of the ecology of agricultural systems and a consequential welfare loss.

The last linkage posited by the analysis of the process of technological change under IPR is the mode of technological change. Against the background of the evolving nature of the agro-ecological system of hosts and pathogens, there are social gains from a coexistence of various technologies at any point in time in order to limit the evolutionary pressure on the system. The degree to which this coexistence is desirable depends on a number of factors, most importantly the instantaneous productivity loss from not using the first-best technology uniformly. On the other hand, the gains from a diversified portfolio of production technologies are not realized in an IPR system. The reason is that the rewards for successful innovation are mediated through a particular type of market structure, namely that of a monopoly. As previous research on the economics of industrial organization has demonstrated, deviations from this market structure towards those involving market sharing cannot be reconciled with the reward system's incentive function (Gilbert and Newbery 1982). Technological progress is therefore incentivized through the award of sequential monopolies. This implies that the predominant mode of technological progress is one of a non-diversified application of a single technology rather than an accumulation and simultaneous use of different technologies (Goeschl and Swanson 2002). Land-use patterns will reflect this mode of technological progress through a prevalence of monocultural applications in the productive sector.

In sum, recent research on the linkages between patent-style reward systems and the environment points towards a number of problem areas. Firstly, the volume and type of R&D outputs generated will usually deviate from the R&D outputs society would want to generate under first-best conditions. Environmentally problematic are the effects that the specific rate, direction, pace and mode of technological progress embodied in new crop plants have on the agro-ecological system with which these crops interact. Patent-style IPR systems imply a tendency on the one hand to carry out less R&D than would be optimal and on the other hand to apply R&D outputs in a way that does not optimally manage the evolutionary dynamics of the agro-ecological system. Secondly, the organization of the R&D process through patent-style IPR impacts negatively on the demand for biodiversity from outside the intensive-production sector. One would expect this to lead to lower returns on conservation of R&D inputs and hence to a reduction in preservation activity. The R&D outputs pursued under patent-style IPR and their impact on R&D inputs are therefore the key areas of concern over the environmental impact of patent-style IPR.

Determinants of the deviation from the social optimum

The previous section attempted to demonstrate the presence of deviations from a social optimum in the case of biotechnological R&D under patent-style IPR. This discussion has left open the factors that determine the extent of environmental problems thus generated. The literature examines a number of biological, technological and legal determinants that impact on the extent to which R&D activities will deviate from the social optimum. The biological determinants focus on the response of the agro-ecological system of hosts and pathogens. The first is the exogenous adaptation rate of pathogens. This measures the extent to which pathogens have solutions available to the innovations contained in new cultivars. The source of these solutions is either the presence of successful counterstrategies in the genetic pool of the pathogens (Munro 1997) or the generation of new counterstrategies

through mutative processes (Weitzman 2000). The second determinant is the induced evolution function, namely the extent to which evolving adaptations spread through the pathogen population as a result of the scale of application of a new crop and as a result of the pace of technological change embodied. While the positive impact of the scale of application on the rate of adaptation is a well-established fact in the ecological literature, the impact of the pace of technological change on the rate of response is less well understood and more speculative.

The technological determinants focus on the characteristics of the R&D process. There, the first feature is the so-called 'hit rate' in the R&D process. This is a measure of the probability of a research success such as a lead for a new molecular entity that actually results in a final product approved for sale. In some areas, this hit rate has a very precise interpretation such as the ratio of successful leads to screens in pharmaceutical research (Artuso 1994), but in general, it denotes the quality of the search process for new solutions and is thus an indicator of the underlying knowledge base in the R&D process (Rausser and Small 2000). The second feature is the innovation function, which is a traditional knowledge-production function that transforms measures of R&D inputs (such as the volume of genetic resources processed, the amount of labour involved, etc.) into a probability of generating a new product. Various studies have analysed the marginal factor productivity of different inputs into this knowledge-production function in the plant-breeding sector (for example Evenson 1995). The innovation function governing this process can therefore be based on well-defined and quantifiable characteristics.

The legal determinant is the extent to which the IPR system allows the innovator to exclude others from using the innovation, once in place. This exclusion translates into the rent appropriability of the R&D process and is determined by design choices in the IPR systems such as the breadth or length of time over which exclusion can be exercised. The extent to which these design choices impact on the long-run incentives for R&D depends critically on the time horizon of the analysis (see O'Donoghue 1998), but at least in the short run, stronger rights to exclude increase R&D incentives. In the next section we analyse the differential impacts of transgenic crops by reference to the changes in the determinants of the environmental effects of R&D outputs that a trend towards transgenic technologies entails.

The differential impact of patents on transgenic crops

The environmental impacts described in the previous section are generic in the sense that any agricultural R&D process directed at crops and conducted under a set of conventional IPR will generate these types of impacts. These impacts therefore highlight the linkages that exists between the choices of an incentive system to reward R&D activity, but they also underline that these linkages are by no means specific to transgenic crops. At the same time, differences in the productivity of transgenic R&D, the productivity of R&D outputs embodying transgenes, their treatment in IPR law and various other changes in the technological characteristics of crop development will interact with the particular system of R&D rewards implied by IPR. What shape this interaction between the biotechnological trend to transgenic crops and the IPR regime under which these technologies are regulated will take remains to be seen in full, but a number of plausible developments will be charted below.

Focussing on the land-use impacts of patents on transgenic crops, the crucial question is how differences in the determinants of R&D between conventional crops and transgenic crops impact on the marginal returns to land in agricultural production

and the changes on returns to land in conservation. This is critical since the marginal returns to different forms of land use are a major determinant of land-use patterns. Table 1 sets out the plausible impacts of the expected changes in key determinants of the R&D process on the rents generated in the intensive and the reserve sector and on the welfare loss associated with using an IPR regime (relative to a first-best reward system under perfect information).

Table 1 illustrates that in terms of land use, the expected differential impact of transgenic crops is the net impact implied by the expected differences in the key determinants of the R&D process. This net impact is highly ambiguous: while improvements in rent appropriability are expected to give additional incentives for preservation and to decrease the net rent to land in intensive use (thus increasing the optimal reserve size), other changes can be expected to shift the optimal combination of intensive and reserve use in the opposite direction by virtue of increasing returns on intensive use (such as increased productivity) and decreasing returns on preservation. This means that in terms of land-use impacts, the question of whether harm will increase is mostly an empirical one and cannot be answered merely on the basis of analytical deduction.

Table 1. Plausible differential impact of transgenic technologies in agricultural crops

Determinant	*Expected difference of transgenic to conventional crop*	*Economic impact*	*Land-use rent impact*	*Differential welfare loss*
Adaptation rate	None	None	None	None
Induced evolution function	Ambiguous	Lower or higher returns to R&D at industry level possible	Lower returns on intensive use	Increased
Hit rate in R&D	Higher	Higher demand for R&D inputs	Higher return on conservation	Reduced
Innovation function	Higher marginal rate of innovation	*First order*: higher demand for R&D inputs *Second order*: greater innovation size	*First order:* Higher return on conservation *Second order:* Higher return on intensive use	*First order*: Reduced *Second order*: Increased
Rent appropriability	Higher by virtue of better legal and technological opportunities to exclude	Higher returns on R&D output and higher demand for R&D inputs	Lower return on intensive use and higher return on conservation	Reduced

In terms of the management of the agro-ecological system, the trend towards transgenic technologies will not impact on the direction of technological change since genetic modification does not alter the fundamental lack of incentives to firms to generate technologies that address the adaptation dynamics of pathogens. Likewise, we would not expect an impact of the availability of transgenic manipulation on the mode of technological change: the fundamental incentives remain to phase

technologies in the form of sequentially uniform applications rather than the accumulation of a diversified portfolio of differentiated technologies.

In sum, therefore, the expected impact of moving towards transgenic crops in terms of the environmental impact of patent-style IPR is ambiguous. There are a number of factors that point to transgenic crops actually decreasing some of the environmental impacts experienced under the combination of IPR and conventional breeding techniques such as the new technology's ability to increase rent appropriability and higher productivity of R&D. However, these effects are modulated through an asymmetric system of property rights (see section Intellectual property rights in crop R&D) and the net effect of the differential impacts is not obvious. Negative impacts can be postulated in terms of managing the adaptive dynamics of pathogen population and if transgenic crops induce a shift in the balance of the extensive and intensive margins in land use towards additional conversion of lands to agriculture. However, there are also significant areas such as the direction and mode of technological change that are unlikely to be affected by a trend towards transgenic crops.

Conclusions

This paper has examined the linkages between the system that society uses to incentivize R&D by private innovators in the particular area of crop improvement on the one hand and the environment on the other. This examination is an important addition to the technology-assessment exercise conducted in the context of transgenic crops since it focuses on the organization of the R&D process rather than on its outputs. The paper first demonstrates that design choices with respect to the system of rewards under which crop improvement is carried out determine important characteristics of the outputs of the R&D process, namely both volume and type of R&D outputs pursued. The paper shows that choosing a particular type of reward system has implications for the rate, direction, pace and mode of technological change in the agricultural system. It draws on ongoing research that has shown that, in general, applying such a system of rewards to R&D processes the outputs of which interact with evolving ecological systems, implies deviations from the social optimum along several dimensions of technological change.

While the presence of these deviations from the social optimum is a generic characteristic of carrying out R&D under patent-style IPR, the extent of these deviations differs between conventional and transgenic crops and is determined by the nature of some key determinants of a biological, technological and legal nature. A comparison of the differences in these key determinants between conventional and transgenic crops shows that there are some areas in which there is no difference between conventional and transgenic crops, in particular with respect to the mode and direction of technological progress. In those areas where we do find differences, the differential environmental impact of moving from conventional to transgenic crops is ambiguous.

These results have two major implications: The generic results highlight the need to re-evaluate the use of patent-style IPR in the area of crop development in general, and not just in the context of transgenic crops. The public perception in Europe that transgenic crops represent a discontinuity in the technological trajectory may offer a political opportunity to carry out such a re-assessment and to consider whether alternative forms of rewarding R&D activity in the domain of crop improvement might be preferable. Whether superior systems are available is not obvious, but

certainly merits additional investigation. The specific results of the paper offer guidance in the differential evaluation of transgenic crops relative to conventional outputs of the R&D process. It will have to depend on the empirical results of this evaluation whether it is concluded that the combination of patent-style IPR and transgenic crops results in outcomes that are clearly undesirable from a social perspective. On the basis of theoretical analysis alone, this evaluation appears ambiguous and therefore ultimately inconclusive.

References

Arrow, K., 1962. Economic welfare and the allocation of resources for invention. *In:* Nelson, R. ed. *The rate and direction of inventive activity*. Harvard Business School Press, Cambridge.

Artuso, A., 1994. *An economic and policy analysis of biochemical prospecting*. PhD dissertation, Department of Economics, Cornell University, Ithaca.

Brown, G. and Swierzbinski, J., 1988. Optimal genetic resources in the context of asymmetric public goods. *In:* Smith, V.K. ed. *Environmental resources and applied welfare economics*. Resources for the Future RFF, Washington, 293-312.

Busch, L., Lacy, W.B., Burkhardt, J., et al., 1991. *Plants, power, and profit*. Blackwell, Oxford.

Buttel, F., 1999. Agricultural biotechnology: its recent evolution and implications for agrofood political economy. *Sociological Research Online,* 4 (3), 292-309.

Coase, R., 1952. The nature of the firm. *In:* Stigler, G. and Boulding, K. eds. *Readings in price theory*. RD Irwin, Chicago, 331-351.

Conner, A.J., Glare, T.R. and Nap, J.P., 2003. The release of genetically modified crops into the environment. Part II. Overview of ecological risk assessment. *The Plant Journal,* 33 (1), 19-46.

Evenson, R., 1995. *The valuation of crop genetic resource preservation, conservation and use*, Paper prepared for the Commission on Plant Genetic Resources, Rome.

Fuglie, K., Ballenger, N., Day, K., et al., 1996. *Agricultural research and development: public and private investments under alternative markets and institutions*. Economic Research Service, United States Department of Agriculture, Washington DC. Agricultural Economics Report no. 735. [http://www.ers.usda.gov/publications/aer735/]

Gilbert, R.J. and Newbery, D.M.G., 1982. Preemptive patenting and the persistence of monopoly. *American Economic Review,* 72 (3), 514-526.

Goeschl, T. and Swanson, T.M., 2002. *Lost horizons: the noncooperative management of an evolutionary biological system*. Fondazione Eni Enrico Mattei, Milano. FEEM Working Paper no. 89-2002. [http://ssrn.com/abstract=344322]

Goeschl, T. and Swanson, T.M., 2003a. The interaction of dynamic problems and dynamic policies: some economics of biotechnology. *In:* Laxminarayan, R. ed. *Battling resistance to antibiotics and pesticides: an economic approach*. Resources for the Future, Washington, 293-329.

Goeschl, T. and Swanson, T.M., 2003b. *On biology and technology: the economics of managing biotechnologies*. Fondazione Eni Enrico Mattei, Milano. FEEM Working Paper no. 42-2003. [http://ssrn.com/abstract=419080]

Goeschl, T. and Swanson, T.M., 2003c. Pests, plagues, and patents. *Journal of the European Economic Association,* 1 (2/3), 561-575.

Holden, J., Peacock, J. and Williams, T., 1993. *Genes, crops and the environment*. Cambridge University Press, Cambridge.

Jaffe, A.B. and Trajtenberg, M., 2002. *Patents, citations, and innovations: a window on the knowledge economy*. MIT Press, Cambridge.

Merges, R.P. and Nelson, R.R., 1990. On the complex economics of patent scope. *Columbia Law Review,* 90 (4), 839-916.

Milgrom, P. and Roberts, J., 1992. *Economics, organization, and management*. Prentice-Hall International, Englewood Cliffs.

Munro, A., 1997. Economics and biological evolution. *Environmental and Resource Economics,* 9 (4), 429-449.

Nap, J.P., Metz, P.L.J., Escaler, M., et al., 2003. The release of genetically modified crops into the environment. Part I: Overview of current status and regulations. *The Plant Journal,* 33 (1), 1-18.

Nordhaus, W.D., 1969. *Invention, growth, and welfare: a theoretical treatment of technological change*. MIT Press, Cambridge.

O'Donoghue, T., 1998. A patentability requirement for sequential innovation. *Rand Journal of Economics,* 29 (4), 654-679.

Oerke, E.C., Dehne, H.W., Schönbeck, F., et al., 1994. *Crop production and crop protection: estimated losses in major food and cash crops*. Elsevier, Amsterdam.

Palladino, P., 1996. *Entomology, ecology, and agriculture: the making of scientific careers in North America 1885-1985*. Taylor and Francis, London.

Rausser, G.C. and Small, A.A., 2000. Valuing research leads: bioprospecting and the conservation of genetic resources. *Journal of Political Economy,* 108 (1), 173-206.

Ruttan, V.W., 2001. *Technology, growth and development: an induced innovation perspective*. Oxford University Press, New York.

Swanson, T.M., 1995. Uniformity in development and the decline of biological diversity. *In:* Swanson, T.M. ed. *The economics and ecology of biodiversity decline: the forces driving global change*. Cambridge University Press, Cambridge, 41-54.

Swanson, T.M., 1999. The management of genetic resources for agriculture: ecology and information, externalities and policies. *In:* Peters, G.H. and Von Braun, J. eds. *Food security, diversification and resource management: refocusing the role of agriculture?* Ashgate, Aldershot, 212-231.

Swanson, T.M. and Goeschl, T., 2000. Property rights issues involving plant genetic resources: implications of ownership for economic efficiency. *Ecological Economics,* 32 (1), 75-92.

Weitzman, M.L., 2000. Economic profitability versus ecological entropy. *Quarterly Journal of Economics,* 115 (1), 237-263.

[1] One pertinent illustration of the conflict between societal and industry interests regarding the direction of technology implementation exists in the form of U.S. Environmental Protection Agency regulations on refuge requirements. See Hurley elsewhere in this volume for results derived against the background of a static market structure.