2016

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genetic improvement, intellectual property, seed industry, welfare analysis

Disciplines
Agricultural and Resource Economics | Economic History | Growth and Development | Industrial Organization

Comments
This article is published as Lence, Sergio H., Dermot J. Hayes, Julian M. Alston, and John Stephen C. Smith. "Intellectual property in plant breeding: comparing different levels and forms of protection." European Review of Agricultural Economics 43, no. 1 (2015): 1-29. 10.1093/erae/jbv007. Posted with permission.

European Review of Agricultural Economics Vol **43 (1)** (2016) pp. 1–29
doi:10.1093/erae/jbv007
Advance Access Publication 19 March 2015

Intellectual property in plant breeding: comparing different levels and forms of protection

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Received February 2014; final version accepted January 2015

Review coordinated by Steve McCorriston

Abstract

Welfare trade-offs between intellectual property (IP) protections provided by patents and by plant variety protection (PVP) are explored. PVP breeders' exemption weakens IP protection, but may speed the transfer of research gains across firms. A model is developed assuming firms optimise research given existing IP protection. A baseline scenario supporting each system is used to perform welfare analysis, and study how the balance is altered between systems. Survey data suggest patents are more appropriate for longer-term, higher-risk research, whereas PVP is better suited for traditional breeding. A scenario where patents and licensing co-exist dominates PVP in all commercially relevant areas.

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JEL classification: O31, O34, Q16

1. Introduction

There are pressing needs to sustainably increase agricultural productivity to meet expanding global demands for food (Dobermann and Nelson, 2013). Investments in plant breeding by both the private and public sectors have a proven track record of allowing more production per unit area of land and thus of significantly contributing to economic well-being (Fehr, 1984; Frisvold, Sullivan and Raneses, 1999; Duvick, 2005; Rubenstein *et al.*, 2005; British Society of Plant Breeders, 2010). Protection of intellectual property (IP) is a subject which interests both sectors, most particularly the private sector,

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which depends upon returns from investments to encourage future cycles of investments.

The field of IP protection as it relates to plant breeding and agricultural biotechnology is complex, dynamic and controversial. Briefly, IP protection can be provided in this field by trade secrets,[1] contract law, utility patents and by *sui generis* forms of protection such as the US Plant Patent Act of 1930 and Plant Breeders Rights or plant variety protection (PVP) under the auspices of the Union Internationale pour la Protection des Obtentions Végétales (UPOV).

Both PVP and the US Plant Patent Act have exceptions allowing for further breeding and commercialisation without requiring the permission of the owner of the initial variety (unless the new variety is predominantly or essentially derived from the initial variety) in respect of PVP under UPOV's International Convention (UPOV, 1991). The 1930 US Patent Act applies only to the protection of non-tuberous asexually propagated species. In 1980, the US Supreme Court ruled that plant varieties, parts of plants and plant genes were covered by the same utility patents that protect other US inventions. Utility patents have no exceptions allowing for further breeding in the United States, but may have a limited breeders' exemption in certain countries according to their specific patent laws. A limited breeder exception allows breeding without the need for a licence during the life of the utility patent, but does not allow commercialisation without the consent of the owner of the patent. Thus, this limited exception contrasts with the farmer's exemption and the full breeders' exemption allowing breeding and commercialisation which applies to PVP prescribed by UPOV.

Plant varieties per se are not eligible to be patented in the European Union (EU), but can be patented in the United States and in a few other countries. Specific traits, methods of breeding and products are eligible subject matter for utility patents in the United States. The EU appears reluctant to allow native traits to be eligible for patent protection, but will consider eligibility for patent protection if the trait is transgenic.

Firms operating under a PVP system benefit from exclusive rights during the introduction period, and in this sense they have exactly the same incentives as firms operating under a patent system. But under PVP, their competitors can access the research as soon as the variety is introduced and potentially release the improved variety to compete with the original improvement.

The breeders' exemption under PVP has gained increased attention among national seed associations and policy makers because the development of tools, such as ultra-high-throughput sequencing using molecular markers, has allowed researchers to speed the rate at which they can create new varieties. Utility patents generally provide 20 years of IP protection, while the length of protection under PVP is limited to the time it takes one firm to create a distinct new variety from germplasm introduced by the original research firm. With

1 Genetic use restriction technologies (GURTs) provide a means to protect trade secrets in the context of plant breeding (see, e.g. Lence *et al.* (2005), and references therein).

modern sequencing, the IP protection period under PVP is reported to be in a range of 5–7 years after the variety has been introduced.

Some in the US seed industry have been advocating for a revision of the current PVP system to include a phase-in period for the breeders' exemption that is crop-specific (Donnenwirth, Grace and Smith, 2004). The logic is to strengthen, or at least to re-assert, the original effective level of protection under plant breeders' rights, by extending the effective length of protection under PVP by a time period that offsets the increased speed at which distinct new varieties can be created.

A galvanising issue which frames the international discussion is whether new varieties should be protected by utility patents for plant varieties or by PVP. Pardey *et al.* (2013) suggest that PVP rules are weaker than utility patents due to the breeders' exemption and the farmer's exemption. However, Pardey *et al.* also mention that stronger PVP rules may restrain access to germplasm and slow the pace of innovation and decrease research and development (R&D) spillovers. This trade-off is at the heart of the present paper. If the original firm reduces overall research efforts in response to the expectation of eroded market power due to the breeders' exemption, the effect of the exemption on societal welfare may be negative. However, the absence of a breeders' exemption under utility patents will slow the adoption of inventions across research firms, which may slow overall progress. Here, we are interested in the economic incentives embedded in both systems, and the impact these incentive structures have on the pace of change on societal welfare.

The model presented below sets up a trade-off between the benefits associated with the rapid spread of research across firms under PVP and the incentive problems associated with the breeders' exemption. We analyse the outcome of the model by comparing societal welfare under patents and PVP.

The model we introduce to compare the two systems is one where each of several imperfectly competitive seed research firms optimises its research programme based on the strength and length of IP protection. Every firm can capture the benefits from its own research in the period after it was undertaken. In subsequent periods, firms continue to conduct research, and the productivity of this research is determined in part by the amount of research conducted in the first period. With patents, a firm can access only its own research in subsequent periods until the patent protection expires, whereas under PVP firms have access to all other firms' research. Firms anticipate this weaker level of IP when making their research decisions. Firms arrive at a symmetric Nash equilibrium and all conduct the same amount of research.

We choose model parameters for a baseline scenario that shows support for each system. We then use this baseline model to evaluate a series of technological, policy and market developments, and we show how these developments alter the balance between PVP and patents, and within both patents and PVP systems. The list of PVP scenarios includes a base case of PVP, an alternative case of PVP with a reduced time to develop a new variety and a PVP system in conjunction with trade secrets. These PVP scenarios are compared with one another and with various patent scenarios. The base-case scenario for

patents is also compared with a scenario where patents provide a shorter length of protection, with a trade secret, and with licensing.

The results show that patents dominate when (i) the research is time-consuming and specific, (ii) the expected commercial life of the improved variety is long and (iii) the research programme is path-breaking. PVP dominates when (i) the type of research is straightforward and applicable across many firms, (ii) the expected commercial life of the improved variety is short and (iii) research programmes make incremental gains.

We provide survey data from two large seed research firms on the cost and length of time it takes to complete different kinds of research and commercialisation programmes. Given the results from our model, these data suggest that patents are more appropriate when research is needed to bring in exotic germplasm and other longer-term, higher-risk research endeavours. Traditional breeding programmes, which are also conducted by these firms, have characteristics similar to those where PVP dominates so long as there are no trade secrets.

2. Previous work

Evenson and Gollin (1997) and Evenson (1989) show that before a new variety can be developed and released, the plant breeding sector must make substantial investments in R&D, which the sector can recoup by means of property rights that allow the developer to sell the resulting seed at a price that is above marginal production costs.

Alston and Venner (2002) propose a model in which the seed research firm chooses its research effort based on the level of IP protection. They hypothesise that if the US Plant Variety Protection Act of 1970 strengthened IP protection, then the US wheat sector should have experienced increased private sector investment and yields. They test this hypothesis using data on US wheat yields and research investments and do not find any evidence in support of the hypothesis. They point out that the breeders' exemption, as well as the farmers' right to sell and replant improved varieties without paying a royalty weakens the degree of IP appropriability. In a later paper, Kolady and Lesser (2009) use the same method as Alston and Venner (2002) and find that private wheat varieties introduced in response to PVP protections have contributed to genetic improvement in wheat varieties grown in Washington State. Naseem, Oehmke and Schimmelpfennig (2005) report similar results for cotton in the United States. The positive PVP results for wheat and cotton are attributed to the availability of some IP protection under PVP relative to the alternative of no IP protection.

Hayes, Lence and Goggi (2009) show that in the case of wheat, compared with the United States, countries that have offered more effective property rights (e.g. the United Kingdom and France) have experienced significant increases in yields and greater yield growth as a result of genetic gains from plant breeding. They argue that incentives for the private sector to conduct research on wheat varieties in the United States have been weakened by the breeders' exemption.

Swanson and Goeschl (2005) show that the research and yield outcomes observed for hybrid crops, such as corn and sorghum, can be used as an indicator

of what might happen if IP protection were strengthened in other crops. With hybrid crops farmers are required to purchase new seed each year, thereby creating the market conditions that attract private-sector investment. They show that yield growth has been fastest for crops (corn and sorghum) where this private-sector investment has been important.[2] Swanson and Goeschl make a strong case for appropriate private-sector incentives. They refer to the problem of the durable-goods monopolist (see, also, Perrin and Fulginiti, 2008) who will eventually face competition and erosion of market power from second-hand versions of their own goods—except that in this case the problem is exaggerated because the goods themselves are capable of reproduction. Kolady, Spielman and Cavalieri (2012) use data from India to show that yield trends for maize and pearl millet have outpaced those for wheat and rice. They attribute this difference to the use of hybrid seed, with associated IP protection, in maize and pearl millet, and the lack of IP protection in self-pollinated wheat and rice crops.[3]

Lence and Hayes (2005) show that IP fees that are charged in one country and not in the other are harmful to producers in the first country when research spillover between the two countries is high. This study also shows that R&D firms do not have the incentive develop technologies that can be easily adopted in countries with low IP protection. Thus, they conclude that equalising IP appropriability across countries gives R&D firms a strong incentive to conduct R&D of relevance to both countries.

Hayes, Lence and Goggi (2009) provide data that suggest that strong IP protection, such as that provided by patents, has a positive influence on genetic gains.

Moschini and Yerokhin (2008) develop a game-theoretic model of patents with and without a research exemption (analogous to a breeders' exemption in PVP) and show that when research is risky or expensive, the system with a research exemption will not provide sufficient incentives. They also show that when research costs are low, patents with a research exemption may improve on patents without it because it ensures a larger pool of research upon which to base subsequent improvements. They also show that a system with patents (without research exemption) and licensing weakly dominates patents with a research exemption.

Eaton and van Tongeren (2005) develop a model to examine the impact of a slow phase-in of the breeder's exemption. They use a two-stage game model of vertical product differentiation, in which two profit-maximising breeding firms

2 Alston, Gray and Bolek (2012) suggested that Australia's use of end-point royalties for wheat varieties, collected when the grain is delivered to the elevator, has encouraged private-sector investment in wheat-breeding in Australia and is likely to lead to future research investment-cum-innovation patterns in Australian wheat more like those observed for hybrid corn in the United States.

3 An anonymous reviewer pointed out that plant breeders who do little creative breeding like to be able to use new varieties of others to breed small variants, but they do not want to have to compete with their own customers. So they tend to support PVP but not utility patenting.

choose the quality and then the price of their respective seed varieties. One firm is a quality leader and the other is a follower. Firms increase quality by spending on research along a quadratic cost function. The phase-in scenario of the breeders' exemption in plant breeder's rights is introduced by means of increasing the second firm's costs due to delayed access to the leading firm's research. Reduced access to the leading firm's research leads to increased profits for the leading firm, but decreases in varietal quality and farm profits.

Pardey *et al.* (2013) provide a rich data set showing applications for plant patents in the United States increasing gradually from 1930 to 1980, and then increasing at a very rapid rate until the present day. Their data show that applications for utility patents increased dramatically after 1990 and have outpaced and substituted for PVP applications since then. In the period prior to the introduction of PVP and utility patent protections, ornamental crops and fruits accounted for the great bulk of applications. In the more recent data, cereals and oilseeds (primarily corn and soybeans) account for 87 per cent of utility patents and approximately half of the PVP applications. The large number of PVP applications for cereals and oilseeds at a time when utility patents were available is explained by a 2001 US Supreme Court ruling that allowed dual protection using both PVP and utility patents.

Our results are in agreement with the discussion provided in Pardey *et al.* (2013) and with the theoretical results derived in Moschini and Yerokhin (2008). Each of the two primary IP protection systems has advantages and disadvantages, and neither of them is better than the other under all possible circumstances. Unlike the two earlier papers, our model has enough structure to describe the specific parametric conditions under which one IP protection system dominates the other. We are also able to consider subtle changes such as licensing and changes in the effective length of IP protection and show how these alter the results. Our results disagree with Eaton and van Tongeren (2005) in that their paper leads to an unambiguous conclusion about welfare and ours does not. In our model all firms are similar in terms of research budgets whereas in the Eaton and van Tongeren model one firm dominates in terms of research achievements. Three of our simulation results are in agreement with Moschini and Yerokhin, even though their model is very different from ours.[4] Our results on the benefits of a finite patent-life mirror the key result in Koo and Wright (2010). Their paper differentiates between *ex ante* and *ex post* negotiations of licensing agreements and shows that a finite patent-life is optimal when licensing is negotiated *ex post*.

4 In Moschini and Yerokhin's model there are only two firms who play two games sequentially. In the initial game (which is only played once), they invest in R&D until one of them succeeds at obtaining an innovation. The nature of the second game depends on whether there is a research exemption or not. If there is no exemption, the loser of the first game quits, and the successful innovator becomes a monopolist. If there is an exemption, the two firms play an improvement game, in which the innovation resulting from the first game reduces the cost of obtaining additional improvements.

time

Date	$t-1$	t	$t+1$
Firm n's optimal amount of genetic research:	$x^*_{n,t-1}$	$x^*_{n,t}$	$x^*_{n,t+1}$
Firm n's genetic improvement:	$\phi_{n,t-1} = \phi(x^*_{n,t-2})$	$\phi_{n,t} = \phi(x^*_{n,t-1})$	$\phi_{n,t+1} = \phi(x^*_{n,t})$
Firm n's genetic research cost:	$c(x_{n,t-1}, \Theta_{n,t-1})$	$c(x_{n,t}, \Theta_{n,t})$	$c(x_{n,t+1}, \Theta_{n,t+1})$
Genetic stock available to firm n:	$\Theta_{n,t-1} = \Phi_{n,t-1} + \omega\,\rho^{\tau}\,\Phi_{n,t-1-\tau}$	$\Theta_{n,t} = \Phi_{n,t} + \omega\,\rho^{\tau}\,\Phi_{n,t-\tau}$	$\Theta_{n,t+1} = \Phi_{n,t+1} + \omega\,\rho^{\tau}\,\Phi_{n,t+1-\tau}$
Genetic stock produced by firm n:	$\Phi_{n,t-1} = \rho\,\Phi_{n,t-2} + \phi_{n,t-1}$	$\Phi_{n,t} = \rho\,\Phi_{n,t-1} + \phi_{n,t}$	$\Phi_{n,t+1} = \rho\,\Phi_{n,t} + \phi_{n,t+1}$
Firm n's net revenues from genetic improvement:	$\sum_{j=0}^{T} b(\rho^j\phi_{n,t-1-j}; \rho^j\phi_{m,t-1-j})$	$\sum_{j=0}^{T} b(\rho^j\phi_{n,t-j}; \rho^j\phi_{m,t-j})$	$\sum_{j=0}^{T} b(\rho^j\phi_{n,t+1-j}; \rho^j\phi_{m,t+1-j})$

Fig. 1. Timing framework of decisions and outcomes for the nth R&D firm.

3. A model of genetic improvements by private R&D firms

The impact of the existing IP protection regime on the rate of genetic improvement achieved by private R&D firms is assessed by means of a non-stochastic infinite-horizon dynamic model consisting of N private R&D firms.[5] The model is ambitious, but a number of simplifying assumptions are made to be able to obtain numerical solutions. First, the model assumes a single country with no trade, an exogenously given number of R&D firms (N), no randomness (e.g. in the production of genetic improvements from research) and no simultaneous availability of different types of IP protection.[6] Second, all R&D firms are identical, which allows us to focus on the numerical solution consisting of the steady-state symmetric pure-strategy Nash equilibrium associated with each IP regime.[7] In addition, genetic research is assumed to yield a 'generic' improvement, thus ignoring different types of genetic improvements (e.g., horizontally versus vertically differentiated).

The timing of the decisions and outcomes involving the nth R&D firm are outlined in Figure 1. In the first period in Figure 1, research is conducted. In the second period, the firm has exclusive commercialisation rights, either because competitors have not yet adapted the variety or because they are prohibited from doing so. In the third period, firms operating under PVP are faced with competition from other firms who have adapted the variety. Competition does not occur with patents or with trade secrets.

5 As pointed out by an anonymous reviewer, in the United States there tends to be more patents than PVP when the private sector dominates a crop segment (Kolady and Lesser, 2009), which suggests that the developer of the technology is an important factor in deciding the type of protection. Our model does not account for this issue because it focuses only on the incentives of private firms whose goal is to maximise profits.

6 Since the type of IP protection regime is given, we cannot address the central question of whether firms choose one type of IP regime over another.

7 This set of assumptions is perhaps the most critical one to obtain a workable model, because one only needs to solve for the optimal action of one firm given that in equilibrium all other firms take the same action. Note that the research outcomes from different firms are different from an agronomic standpoint, but yield the same level of economic benefits (in the same way that two different assets may yield the same return).

At time t, the nth R&D firm chooses the amount of genetic research $x_{n,t}$. Such research takes time and results in a genetic improvement of $\phi_{n,t+1} = \phi(x_{n,t})$ ($\partial\phi(\cdot)/\partial x_{n,t} > 0$, $\partial^2\phi(\cdot)/\partial x_{n,t}^2 \leq 0$) that can be marketed after one period. In the model, one unit of time is defined as the amount of time it takes to obtain a genetic improvement (and bring it to market). The survey data shown later suggest that in the case of traditional breeding this period is from 3 to 7 years. The postulated transformation of research into genetic improvement also implies that it is always possible to obtain improvements regardless of the level of genetic stocks. Therefore, there are no secular trends towards yield plateaus or the like.

Genetic research $x_{n,t}$ involves a cost of $c(x_{n,t}, \Theta_{n,t})$, which is increasing at an increasing rate with the amount of research ($\partial c(\cdot)/\partial x_{n,t} > 0$, $\partial^2 c(\cdot)/\partial x_{n,t}^2 > 0$), and decreasing at a decreasing rate with the amount of genetic stock available to the nth firm ($\partial c(\cdot)/\partial \Theta_{n,t} < 0$, $\partial^2 c(\cdot)/\partial \Theta_{n,t}^2 > 0$). To ensure an interior solution to the nth firm's optimisation problem, it is also assumed that the cost of performing research for $x_{n,t} > 0$ is strictly positive, regardless of how large available genetic stocks are (i.e. $c(x_{n,t} > 0, \Theta_{n,t} \to \infty) > 0$).

The genetic stock that is available to firm n and allows it to reduce the cost of genetic improvements ($\Theta_{n,t}$) consists of the stock of firm n's own past improvements ($\Phi_{n,t}$), plus the stocks of all other firms' improvements that are available to firm n ($\rho^{\tau}\Phi_{\tilde{n},t-\tau}$) not overlapping with $\Phi_{n,t}$

$$\Theta_{n,t} = \Phi_{n,t} + \omega\rho^{\tau}\Phi_{\tilde{n},t-\tau}, \tag{1}$$

where subscript $\tilde{n}$ denotes all firms other than firm n. Parameter $\omega \in [0, 1]$ reflects the extent to which the other firms' genetic stocks that are available to firm n can be effectively used by the latter to reduce the cost of its own improvements. At one extreme, $\omega = 0$ means that other firms' genetic stocks are of no use to firm n, whereas the other polar case of $\omega = 1$ represents the situation where other firms' genetic stocks are fully exploited by firm n. Parameter $\rho \in [0, 1]$ denotes the survival rate of the genetic stocks; that is, genetic stocks decay at the rate of $(1 - \rho)$ per unit of time. In this model, decay occurs because of, for example, co-evolving pests and diseases.[8]

According to Equation (1), the genetic stocks of other firms are made available to firm n to reduce the cost of its genetic improvements with a lag of $\tau \in \{0, 1, 2, \ldots\}$ periods. The case of $\tau = 0$ yields $\Theta_{n,t} = \Phi_{n,t} + \omega\Phi_{\tilde{n},t}$ and is meant to represent the scenario of PVP, where the plant breeder's exemption allows firm n to access other firms' stocks as soon as they are brought to market, so that it can incorporate them into its own R&D programme. The other polar situation of $\tau = \infty$ would be exemplified by a trade secret, in which case Equation (1) simplifies to $\Theta_{n,t} = \Phi_{n,t}$. In this instance, firm n can only use the past outcomes of its own research programme to reduce the cost

8 'Cumulative' improvements are not ruled out, but they are assumed to be outweighed by decay. Otherwise, it would be meaningless to attempt to obtain a steady-state solution to the model, because stocks would grow without bound.

of further improvements, as it is prevented forever from accessing the genetic stocks developed by its competitors.

The evolution of the genetic stock produced by firm n is represented by

$$\Phi_{n,t} = \rho\,\Phi_{n,t-1} + \phi_{n,t}. \tag{2}$$

That is, the genetic stock produced by firm n decays at the rate $(1-\rho) \in [0, 1]$ per unit of time, but is augmented by firm n's genetic improvement ($\phi_{n,t} = \phi(x_{n,t-1})$), which is the outcome of the research conducted in the previous period.

Genetic improvement $\phi_{n,t}$ $(=\phi(x_{n,t-1}))$ yields net revenues to firm n over $T+1 \geq 1$ periods. Over the period when improvement $\phi_{n,t}$ is introduced, firm n receives net revenues represented by the function $b(\phi_{n,t};\ \phi_{\#,t})$, which is assumed to increase at a decreasing rate in the nth firm's own genetic improvement ($\partial b(\cdot)/\partial\phi_{n,t} > 0$, $\partial^2 b(\cdot)/\partial\phi_{n,t}^2 < 0$). Firm n's net revenues are also assumed to be negatively affected by the genetic improvements achieved by its competitors, such that $\partial b(\cdot)/\partial\phi_{\#,t} < 0$. Because of the decay in the genetic stock, firm n's net revenues from improvement $\phi_{n,t}$ are lower for period $t+j$ $(j = 1, \ldots, T+1)$, and described as $b(\rho^j\phi_{n,t};\ \rho^j\phi_{\#,t})$.

With the aforementioned model structure, and assuming that the other firms' genetic stocks ($\Phi_{\#,t-\max(T,\tau)}$) and the sequences of genetic improvements ($\phi_{\#,t}$, $\phi_{\#,t-1}, \ldots, \phi_{\#,t-\max(T,\tau)}$) are known to firm n, the optimisation problem for firm n at period t consists of

$$\begin{aligned}
&v(\phi_{n,t}, \phi_{n,t-1}, \ldots, \phi_{n,t-T}, \Phi_{n,t};\ \phi_{\#,t}, \phi_{\#,t-1}, \ldots, \phi_{\#,t-\max(T,\tau)}, \Phi_{\#,t-\tau}) \\
&\quad = \max_{x_{n,t}\geq 0}\left\{\sum_{j=0}^{T} b(\phi_{n,t-j};\ \phi_{\#,t-j}) - c(x_{n,t},\ \Phi_{n,t} + \omega\rho^{\tau}\Phi_{\#,t-\tau})\right. \\
&\quad +\delta v[\phi(x_{n,t}),\ \phi_{n,t}, \ldots, \phi_{n,t-T+1},\ \rho\Phi_{n,t} + \phi(x_{n,t});\ \phi_{\#,t+1},\ \phi_{\#,t}, \ldots, \\
&\quad \left.\phi_{\#,t-\max(T,\tau)+1},\ \rho\Phi_{\#,t-\tau} + \phi_{\#,t-\tau+1}]\right\},
\end{aligned} \tag{3}$$

where $\delta \in [0, 1]$ is the discount rate. The solution to Equation (3) yields the optimal amount of genetic research firm n should undertake at time t, $x^*_{n,t} \equiv x^*(\phi_{n,t}, \ldots, \phi_{n,t-T}, \Phi_{n,t};\ \phi_{\#,t}, \ldots, \phi_{\#,t-\max(T,\tau)}, \Phi_{\#,t-\tau})$, as a function of its own record of genetic improvements ($\phi_{n,t}, \ldots, \phi_{n,t-T}, \Phi_{n,t}$) and the record of its rivals ($\phi_{\#,t}, \ldots, \phi_{\#,t-\max(T,\tau)}, \Phi_{\#,t-\tau}$). In the scenarios discussed later such implicit function cannot be expressed analytically; hence, it is obtained by computational methods.

The notation in optimisation (Equation (3)) is relatively involved because of the complexities the model aims to capture. However, Equation (3) has the canonical structure of the Bellman equation for infinite-horizon continuous-state dynamic optimisation problems under certainty (see, for example, Miranda and Fackler, 2002: 190–191), namely,

$$v(\underline{s}) = \max_x\{f(x, \underline{s}) + \delta v[\underline{g}(x, \underline{s})]\}, \tag{4}$$

where $v(\cdot)$ is the value function (i.e. the maximum sum of current and future rewards), the vector of state variables $\underline{s} \equiv [s_1 \ldots s_S]$ represents the state of the economic system known by the decision maker when taking action x, function $f(x, \underline{s})$ is the decision maker's instantaneous reward from taking action x in state $\underline{s}$, and the vector of transition functions $g(x, \underline{s}) \equiv [g_1(x, \underline{s}) \ldots g_S(x, \underline{s})]$ determines the state at time $t+1$, given the state at time t and the action taken by the agent at time t (i.e. if x_t and $\underline{s}_t$ denote the action and state corresponding to time t, then $s_{j,t+1} = g_j(x_t, \underline{s}_t)$ for $j = 1, \ldots, S$). From the comparison of Equations (3) and (4), it is straightforward to conclude that the former is a special case of the latter.[9] By having our model conform to the canonical Bellman equation (Equation (4)), we are able to apply standard techniques to obtain a solution.

Model (3) is a dynamic game because each rival firm faces a problem analogous to the one faced by firm n, and its solution requires simultaneously solving for all of the N firms' optimal genetic improvements. Numerical methods to solve dynamic games are discussed in Miranda and Fackler (2002, Chapters 8 and 9). We assume that all firms are identical and solve numerically for the steady-state symmetric pure-strategy Nash equilibrium associated with alternative policy regimes. That is, defining $\Omega_i \in \Omega$ as the specific underlying functional forms and parameters of the model meant to represent the ith policy regime, we compute the scalar $\bar{x}_i \equiv x^*_{n,t}(\Omega_i)$ denoting the optimal genetic research for firm n at time t under policy i. Scalar $\bar{x}_i$ is the same for all firms and times because firms are identical, the model involves an infinite horizon and there is no uncertainty.

3.1. Welfare measures

The proposed model is used to analyse the implications of different policies towards R&D on genetic improvements and welfare. The model is simulated to compute the following measures associated with a change from policy regime i to policy regime j,

$$\Delta\bar{X}_{ji} \equiv N_j\bar{x}_j - N_i\bar{x}_i, \tag{5}$$

$$\begin{aligned}\Delta\bar{V}_{ji} \equiv\ & N_j(1-\delta)v[\cdot|\phi_{n,t} = \phi(\bar{x}_j)\,\forall\, n, t] \\ & - N_i(1-\delta)v[\cdot|\phi_{n,t} = \phi(\bar{x}_i)\,\forall\, n, t],\end{aligned} \tag{6}$$

$$\Delta\bar{U}_{ji} \equiv U[\cdot|\phi_{n,t} = \phi(\bar{x}_j)\,\forall\, n, t] - U[\cdot|\phi_{n,t} = \phi(\bar{x}_i)\,\forall\, n, t]. \tag{7}$$

9 To see this point, let the vector $\underline{s}_t$ in Equation (4) consists of the following $[T + \max(T, \tau) + 4]$ state variables: $s_{j,t} = \phi_{n,t-j+1}$ for $j = 1, \ldots, T+1$; $s_{T+2,t} = \Phi_{n,t}$; $s_{j+T+2,t} = \phi_{\bullet,t-j+1}$ for $j = 1, \ldots, \max(T, \tau) + 1$ and $s_{T+\max(T,\tau)+4,t} = \Phi_{\bullet,t-\tau}$. With such definitions, it is clear that Equation (3)'s reward function is the sum of benefits minus the cost (i.e. $f(x_t, \underline{s}_t) = \sum_{j=1}^{T+1} b(s_{j,t}; s_{j+T+2,t}) - c(x_t, s_{T+2,t} + \omega\rho^{\tau} s_{2T+4,t})$). Finally, it can be inferred from Equation (4) that the model's $[T + \max(T, \tau) + 4]$ transition functions are the arguments of Equation (3)'s last term. More specifically, given the aforementioned state variables, and since $s_{j,t+1} = g_j(x, \underline{s}_t)$ by definition of the jth transition function, the discussion leading to Equation (3) implies the following expressions for the transition functions: $s_{1,t+1} = \phi_{n,t+1} = \phi(x_{n,t}) = g_1(x, \underline{s}_t)$; $s_{j,t+1} = \phi_{n,t-j+2} = s_{j+1,t} = g_j(x, \underline{s}_t)$ for $j = 2, \ldots, T+1$; $s_{T+2,t+1} = \Phi_{n,t+1} = \rho\Phi_{n,t} + \phi_{n,t+1} = \rho\ s_{T+2,t} + \phi(x_{n,t}) = g_{T+2}(x, \underline{s}_t)$; $s_{j+T+2,t+1} = \phi_{\bullet,t-j+2} = s_{j+T+3,t} = g_{j+T+2}(x, \underline{s}_t)$ for $j = 1, \ldots, \max(T, \tau) + 1$; and $s_{T+\max(T,\tau)+4,t+1} = \Phi_{\bullet,t-\tau+1} = \rho\Phi_{\bullet,t-\tau} + \phi_{\bullet,t-\tau+1} = \rho\ s_{T+\max(T,\tau)+4,t} + s_{T+\tau+3,t} = g_{T+\max(T,\tau)+4}(x, \underline{s}_t)$.

where $U(\cdot)$ denotes the function measuring per-period net benefits from genetic improvements to society, excluding benefits to R&D firms. Variable $\Delta\bar{X}_{ji}$ quantifies the additional aggregate genetic improvement under regime j compared with regime i. Variable $\Delta\bar{V}_{ji}$ shows the additional per-period net profits of the R&D firms under regime j compared with regime i. Finally, $\Delta\bar{U}_{ji}$ measures the additional per-period net benefits to society (except for R&D firms) under regime j compared with regime i.[10] The per-period net benefits to all of society can be calculated as the sum of benefits to R&D firms and others in society (i.e. $\Delta\bar{V}_{ji} + \Delta\bar{U}_{ji}$).

4. Simulation specification and parameterisation

To obtain numerical solutions for the proposed model, it is necessary to postulate specific forms for the function reflecting the transformation of genetic research into genetic improvements ($\phi_{n,t} = \phi(x_{n,t-1})$, the net revenue function ($b(\phi_{n,t}; \phi_{n,t})$), and the function representing the cost of performing genetic research ($c(x_{n,t}, \Theta_{n,t})$). Quantifying societal welfare also requires the specification of a functional form for society's utility $U(\cdot)$. In addition, parameters must be set at values reflecting the scenarios of interest. These issues are discussed in the next subsections, starting with the specification of the societal benefit function $U(\cdot)$.

4.1. Societal welfare

We postulate that benefits to society at time t from genetic improvements are measured by the utility derived by a representative consumer from the genetic improvements achieved by the different R&D firms. The specific functional of such utility is

$$U(\phi_{n,t-j}; n = 1, \ldots, N; j = 0, 1, 2, \ldots) = \frac{1}{1 - 1/\varepsilon} \sum_{j=0}^{\infty} (\rho^j \hat{\phi}_{t-j})^{1-1/\varepsilon}, \quad (8)$$

where

$$\hat{\phi}_{t-j} \equiv \left[\frac{1}{N} \sum_{n=1}^{N} \phi_{t-j,n}^{(\sigma-1)/\sigma} \right]^{\sigma/(\sigma-1)} \quad (9)$$

is an index of the aggregate amount of genetic improvements achieved at time $(t - j)$, $\sigma > 0$ is the elasticity of substitution between the contemporaneous

10 Equations (5) and (6) imply that the number of firms differs between policy regimes if $N_i \neq N_j$. However, as noted earlier, for tractability reasons the number of R&D firms in a particular regime is taken to be exogenous. This assumption may be less realistic than desired, and prevents us from exploring whether some IP protection regimes are more conducive to a larger number of R&D competitors than others.

genetic improvements obtained by any two different firms, and $\varepsilon > 1$ is a parameter that can be interpreted as the absolute value of the own-price elasticity of demand for (the index of) each period's genetic improvements.[11,12]

The choice of function (8) to measure welfare deserves further attention. As noted earlier, adopting specific functional forms is unavoidable, because the numerical analysis cannot proceed otherwise. Therefore, the chosen functional forms should be sufficiently flexible to allow one to represent critical real-world features and derive results driven by such features rather than the arbitrariness of the adopted function. However, the chosen form also needs to be parsimonious enough to enable parameterisation based on the literature or economic reasoning, and tractable to render the numerical problem solvable.

The advocated utility (8) meets the aforementioned conditions. First, utility (8) increases with current and past aggregate genetic improvements ($\partial U(\cdot)/\partial\hat{\phi}_{t-j} = \rho^{j(1-1/\varepsilon)}\,\hat{\phi}_{t-j}^{-1/\varepsilon} > 0$), but it does so at a decreasing rate ($\partial^2 U(\cdot)/\partial\hat{\phi}_{t-j}^2 = -\varepsilon^{-1}\rho^{j(1-1/\varepsilon)}\hat{\phi}_{t-j}^{-(1+1/\varepsilon)} < 0$). Second, the benefits from a specific vintage's aggregate genetic improvement decay over time at the rate $(1-\rho^{1-1/\varepsilon})$, which is determined by the rate of decay of genetic stocks $(1-\rho)$.[13] Third, the aggregate genetic improvement index (Equation (9)) implies a constant elasticity of substitution σ between the benefits from the improvements obtained by any two firms. Thus, situations where improvements of different firms tend to overlap can be modelled in a parsimonious manner, by setting appropriate values for parameter σ. Fourth, the improvements of different firms enter symmetrically into the aggregate index (Equation (9)), which is reasonable given the assumption that all firms are identical.[14] Fifth, the utility function (Equation (8)) involves parameters with intuitive economic interpretation, and whose values are relatively easy to set based on the literature. Finally, utility (8) yields a functional form representing firm n's net revenues featuring desirable properties for the simulation exercise, as elaborated in the next subsection.

11 $\varepsilon > 1$ is required for societal utility to be finite in the stationary state because $\rho \in [0, 1)$. Letting $\varepsilon < 1$ yields $\rho^{1-1/\varepsilon} > 1$, which means that $\rho^{j(1-1/\varepsilon)} \to \infty$ as $j \to \infty$.

12 Suppose society can be characterised by a representative consumer with the quasilinear utility function $U(z, \hat{\phi}_t, \hat{\phi}_{t-1}, \hat{\phi}_{t-2}, \ldots) \equiv z + [\Sigma_{j=0}^{\infty}(\rho^j\hat{\phi}_{t-j})^{1-1/\varepsilon}]/(1-1/\varepsilon)$ subject to the budget constraint $W = z + \Sigma_{j=0}^{\infty}P_{t-j}\hat{\phi}_{t-j}$, where z denotes a numeraire composite good (i.e. its price equals one), W is the consumer's wealth and P_{t-j} is the price of $\hat{\phi}_{t-j}$. Solving the budget constraint for z and plugging the resulting expression into the utility function to get $U(W-\Sigma_{j=0}^{\infty}P_{t-j}\hat{\phi}_{t-j}, \hat{\phi}_t, \hat{\phi}_{t-1}, \hat{\phi}_{t-2}, \ldots) = W - \Sigma_{j=0}^{\infty}P_{t-j}\hat{\phi}_{t-j} + [\Sigma_{j=0}^{\infty}(\rho^j\hat{\phi}_{t-j})^{1-1/\varepsilon}](1-1/\varepsilon)$, the first-order necessary condition (FOC) corresponding to the optimal consumption of date-$(t-j)$ aggregate genetic improvements is $\partial U^*/\partial\hat{\phi}_{t-j} = \rho^{j(1-1/\varepsilon)}\hat{\phi}_{t-j}^{*-1/\varepsilon} - P_{t-j} = 0$. This means that $\varepsilon = -(P_{t-j}/\hat{\phi}_{t-j}^*)(\partial\hat{\phi}_{t-j}^*/\partial P_{t-j})$, as claimed.

13 Note that a genetic improvement of ϕ achieved at time t contributes by $\phi^{1-1/\varepsilon}/(1-1/\varepsilon)$ units to time-t utility, but by only $(\rho^j\phi)^{1-1/\varepsilon}/(1-1/\varepsilon)$ units to utility at time $(t+j)$. Benefits decay over time at the rate $(1-\rho^{1-1/\varepsilon})$ rather than $(1-\rho)$ because benefits increase with genetic improvements at a decreasing rate.

14 It is very difficult to justify asymmetric benefits from the improvements of different firms when firms are identical. If benefits are symmetric, utility will be a function of some aggregate index of improvements across firms, as assumed in Equations (8) and (9).

4.2. R&D firms' net revenues

The analysis in footnote 12 also implies that FOC $\partial U^{*}/\partial \phi_{n,t}$ can be used to derive the inverse demand for genetic improvement $\phi_{n,t-j}$. Letting $P_{n,t-j}$ denote the price of $\phi_{n,t-j}$, the expression for such inverse demand is

$$P_{n,t-j} = \frac{1}{N}\rho^{j(1-1/\varepsilon)}\,\hat{\phi}_{t-j}^{\,1/\sigma-1/\varepsilon}\phi_{n,t-j}^{-1/\sigma}. \tag{10}$$

Given Equation (10), the function representing firm n's net revenues at time t, from the genetic improvements it obtained at time $(t-j)$, consists of

$$\begin{aligned} b(\phi_{n,t-j};\, \phi_{\#,t-j}) &= \mu_{\mathrm{IP},t-j} P_{n,t-j}\phi_{n,t-j}, \\ &= \mu_{\mathrm{IP},t-j}\frac{1}{N}\rho^{j(1-1/\varepsilon)}\hat{\phi}_{t-j}^{\,1/\sigma-1/\varepsilon}\phi_{n,t-j}^{1-1/\sigma}. \end{aligned} \tag{11}$$

In expression (11), parameter $\mu_{\mathrm{IP},t-j} \in [0,1]$ denotes the share of the time-t net revenues from the genetic improvement achieved by R&D firm n at time $(t-j)$ that are actually captured by firm n.

Parameter $\mu_{\mathrm{IP},t-j}$ is strongly influenced by the extent to which IP is protected. For example, $\mu_{\mathrm{IP},t-j} = 1$ for $j = 0, \ldots, p$ when there is statutory protection over $p \geq 1$ periods (i.e. IP is fully protected for p periods). Parameter $\mu_{\mathrm{IP},t-j} = 0\ \forall$ $j > p$ if there is a large number of competitors preventing firm n from exerting any market power over its own genetic improvements after the statutory protection period.[15] The expression for net revenues reported in Figure 1 implies $\mu_{\mathrm{IP},t-j} = 0\ \forall\, j > T$.

4.3. Cost of genetic research

The functional form for the cost of genetic research used for the reported simulations consists of

$$c(x_{n,t},\, \Theta_{n,t}) = \frac{x_{n,t}^{\alpha}}{2}[1 + \exp(-\gamma\Theta_{n,t})], \tag{12}$$

where $\alpha \geq 1$ is the elasticity of research costs with respect to genetic research, and $\gamma \geq 0$ captures the effect of the genetic stocks available to firm $n(\Theta_{n,t})$ on its research costs. The elasticity of research costs with respect to genetic research also represents the degree of convexity of research costs as a function of genetic research. The results reported here were obtained by setting the cost elasticity equal to $\alpha = 2$, but simulations were also performed for other values of α.

The choice of specification (12) was guided by the theoretical assumptions (i.e. the requirements that $\partial c(\cdot)/\partial x_{n,t} > 0$, $\partial^2 c(\cdot)/\partial x_{n,t}^2 > 0$, $\partial c(\cdot)/\partial \Theta_{n,t} < 0$, $\partial^2 c(\cdot)/\partial \Theta_{n,t}^2 > 0$, and $c(x_{n,t} > 0, \Theta_{n,t} \to \infty) > 0$), parsimony,

15 Note that genetic improvements may become obsolete so soon after they are obtained that the effective protection period may be shorter than the statutory protection period. In the present model, such situation would be represented by a sufficiently high rate of decay of genetic stocks $(1-\rho)$.

ease of calibration and interpretation, and numerical tractability. Simulations were also performed for generalisations of function (12), and for alternative cost functions satisfying the key theoretical assumptions.[16] They are omitted to preserve space, as they yielded the same qualitative results as specification (12).

According to function (12), research costs are highest when available genetic stocks are zero ($c(x_{n,t},\ \Theta_{n,t} = 0) = x_{n,t}^{\alpha}$), and lowest when stocks are very large ($c(x_{n,t},\ \Theta_{n,t} \to \infty) = 0.5\, x_{n,t}^{\alpha}$). In other words, the genetic stocks available to firm n have the potential to reduce its research costs by as much as half. *Ceteris paribus*, the larger the value of parameter γ, the lower are research costs. To appreciate the relationship between γ and research costs, re-write expression (12) as

$$c(x_{n,t},\ \Theta_{n,t}) = c(x_{n,t},\ \Theta_{n,t} = 0)\,(1 - \nabla), \tag{13}$$

where $\nabla \equiv 0.5\ [1 - \exp(-\gamma\Theta_{n,t})] \in [0, 0.5]$ is the proportional reduction in research costs when genetic stocks rise from zero to $\Theta_{n,t}$. Since $\gamma = -\ln(1 - 2\nabla)/\Theta_{n,t}$, γ increases monotonically with the proportional reduction in costs due to any given stock increase from zero. Alternatively, note that the semi-elasticity of research costs with respect to genetic stocks is given by

$$\frac{1}{c(x_{n,t},\ \Theta_{n,t})}\frac{\partial c(x_{n,t},\ \Theta_{n,t})}{\partial \Theta_{n,t}} = -\gamma[1 + \exp(\gamma\Theta_{n,t})]^{-1}. \tag{14}$$

Thus, parameter γ is equal to (minus) twice the semi-elasticity of research costs with respect to genetic stocks evaluated at zero stocks ($\Theta_{n,t} = 0$).

4.4. Transformation of genetic research into genetic improvements

The structure of the canonical Bellman equation (Equation (4)) is such that the value function remains unchanged if the decision variable is defined to be a concave and strictly increasing monotonic transformation of variable x (i.e. $z \equiv h(x)$ satisfying $h'(\cdot) > 0$ and $h''(\cdot) < 0$). This assertion holds true as long as the reward function and the transition function vector are correspondingly modified to $F(z, \underline{s}) \equiv f[h^{-1}(z), \underline{s}]$ and $\underline{G}(z, \underline{s}) \equiv \underline{g}(x, \underline{s})$, where $h^{-1}(\cdot)$ is the inverse of function $h(\cdot)$. Because of this result, for simplicity we set the transition function representing the transformation of genetic research into genetic improvements ($\phi_{n,t} = \phi(x_{n,t-1})$) equal to $\phi_{n,t} = x_{n,t-1}$.[17] In other words, the adopted transition function implies that one unit of genetic research yields one unit of genetic improvement.

16 For example, we run simulations using $c(x, \Theta) = (\gamma_1 x + 0.5\gamma_2 x^{\alpha})\,[1 + \gamma_3 \exp(-\gamma_0\Theta)])$ and $c(x, \Theta) = (\gamma_1 x + 0.5\gamma_2 x^{\alpha})\,[1 + \gamma_3/(1 + \gamma_0\Theta)]$.

17 To illustrate that the specific choice of the transition function $\phi(\cdot)$ is inconsequential (provided it meets the stated conditions), note that we would obtain identical results as reported later if instead of letting $\phi_{n,t} = x_{n,t-1}$ and $c(x, \Theta)$ be given by Equation (12), we had set $\phi_{n,t} = x_{n,t}^{\alpha}$ and $c(x, \Theta) = 0.5(x_{n,t}^{\alpha})^2[1 + exp(-\gamma\Theta_{n,t})]$ for $\alpha \in (0, 1)$.

4.5. Parameterisation and specific scenarios

As noted in the previous section, the model is such that one period is defined as the amount of time it takes to obtain a genetic improvement (and bring it to market). To make the model representative of real-world experience, each period is assumed to last 5 years. The simulations are performed by setting the discount factor $\delta = 0.8587$ $(=0.97^5)$, which implies an interest rate of 3 per cent per year. We let the cost parameter γ and the rate of depreciation of the genetic stocks take values over the ranges $\gamma \in [0, 8]$ and $(1 - \rho) \in [0.2, 1]$. For the base simulations, parameters N and ω are fixed at $N = 4$ and $\omega = 0.5$. This assumption means that the genetic R&D industry consists of four identical firms, and that each firm can effectively use only 50 per cent of its competitors' available genetic stocks to reduce the cost of its own improvements. In addition, for the base simulations the elasticity of demand (ε), the elasticity of substitution (σ) and the revenue share parameter ($\mu_{\mathrm{IP},t-j}$) are, respectively, set equal to $\varepsilon = 1.5$, $\sigma = 2$ and $\mu_{\mathrm{IP},t-j} = 1$ for $j = 0, \ldots, T$.[18]

Obtaining numerical solutions for the model can be challenging, even after simplifying the problem by assuming identical firms and solving only for the stationary pure-strategy symmetric Nash equilibrium values. In particular, if either the genetic improvement yields net revenues to its developer over many periods (but less than infinity), or competitors' genetic stocks are available to a firm only after many periods (but less than infinity), the problem is numerically intractable. If either T or τ is large (but $T < \infty$ or $\tau < \infty$, respectively), the value function (Equation (3)) depends on a large number of state variables, in which case the problem suffers from the curse of dimensionality. Therefore, simulations are performed for a selected number of (T, τ) combinations meant to represent the main scenarios of interest.

The parameterisations used for the reported scenarios are summarised in Table 1. The parameterisation ($T = 0$, $\tau = 0$, $\omega = 0.5$, time unit = 5 years) is taken to be most representative of PVP and is used as the base case of PVP. In this scenario, firms can exclusively exploit the genetic improvement over a relatively short period (i.e. during the period t in Figure 1, or 5 years under the parameterisation being used). This scenario corresponds to $T = 0$. The plant breeder's exemption allows firms to use their competitors' improvements to conduct research to enhance their own genetic improvements immediately ($\tau = 0$), and to commercialise these improvements during period $t + 1$. But firms do not possess enough knowledge about their competitors' stocks to exploit them to their full extent ($\omega = 0.5$).

An alternative case of PVP is simulated by also setting ($T = 0$, $\tau = 0$, $\omega = 0.5$), but fixing the period lengths at 2.5 years (instead of 5 years in the base PVP). This scenario, labelled 'short PVP', is analysed to investigate the impact of reducing the amount of time to improve genetic stocks and the

18 Our simulations represent PVP without farmers' rights. The farmers' rights provision of PVP weakens IP protection, thus implying $\mu_{IP,t-j} < 1$ for $j = 0, \ldots, p$. Because of space constraints, we only report results for $\mu_{IP,t-j} = 1$ for $j = 0, \ldots, p$, which in the case of PVP can be interpreted as no farmers' rights.

Table 1. Summary of parameterisations corresponding to reported simulation scenarios

Scenario	Time unit (years)	Number of periods over which a genetic improvement provides net revenues to its developer ($T+1 \in \{1, 2, \ldots\}$)	Number of periods until a firm can use competitors' genetic stocks ($\tau \in \{0, 1, 2, \ldots\}$)	Extent to which a firm can effectively use available competitors' genetic stocks ($\omega \in [0, 1]$)
PVP	5	1 ($\Rightarrow T = 0$)	0	0.5
Short PVP	2.5	1 ($\Rightarrow T = 0$)	0	0.5
Patents	5	2 ($\Rightarrow T = 1$)	2	0.5
Short patents	5	1 ($\Rightarrow T = 0$)	1	0.5
Trade secrets	5	2 ($\Rightarrow T = 1$)	∞	Irrelevant
Licensing	5	2 ($\Rightarrow T = 1$)	0	1

Note: All of the reported simulations assume that the genetic R&D industry consists of four identical firms ($N = 4$), a discount factor implying an interest rate of 3 per cent per year ($\delta = 0.97$), a demand elasticity of 1.5 ($\varepsilon = 1.5$), an elasticity of substitution equal to two ($\sigma = 2$), an elasticity of research costs with respect to genetic research equal to two ($\alpha = 2$) and a revenue share parameter equal to one ($\mu_{\text{IP},t-j} = 1$ for $j = 0, \ldots, T$).

commercial life of genetic improvements. The short PVP is analogous to the base PVP, but with periods that last half as long. Hence, to be consistent with an annual interest rate of 3 per cent, the short-PVP discount factor is set equal to $\delta = 0.9267$ ($=0.97^{2.5}$). Similarly, when comparing the base PVP with the short PVP, the per-period rate of decay of the genetic improvements, the amount of genetic improvements per period and the flow of benefits per period are adjusted so as to be consistent with each other when measured in years.

The base case of patents is represented by the scenario characterised by ($T = 1,\ \tau = 2,\ \omega = 0.5$). In this instance, firms are able to commercially exploit the genetic improvement over a longer interval ($\tau = 1$), and they cannot use their competitors' improvements to enhance their own genetic improvements before patents expire ($\tau = 2$). As with PVP, under a patent regime a firm's genetic stock may overlap with the stocks of its competitors ($\omega = 0.5$). To explore the effect of modifying the life of patents, a short-patent scenario is also simulated by cutting the base-case patent-life in half (i.e. by setting $T = 0$ and $\tau = 1$, while maintaining $\omega = 0.5$).

Importantly, the strength of IP protection also depends on the type of reproduction. Other things equal, hybrids enjoy stronger IP protection than self-pollinated varieties (Lence *et al.*, 2005; Swanson and Goeschl, 2005; Kolady, Spielman and Cavalieri, 2012). Lence *et al.* (2005: 952) also note that

> ... hybrids are difficult to copy for a farmer reseeding harvested seed, but a hybrid that has similar agronomic attributes to a protected variety (a look-alike) can be created by breeding—especially where IPP rights allow for access by breeders (e.g. under PVP) and where breeders make use of new technologies to target genes and/or cut generation time from, e.g., ten

years to four years. In these circumstances, a look-alike can be on the market five years after the protected variety was commercialized (and while the initial hybrid still would have had fifteen years of its protected life left under a utility patent).

Therefore, the framework proposed here can also be used to investigate the cases of hybrids with or without patents. More specifically, hybrids with (without) patents are essentially the same as the scenario with (short) patents.

In the presence of trade secrets, firms are unable to use their competitors' genetic improvements to develop their own genetic improvements as long as they are kept secret. We model the base case for trade secrets by setting $T = 1$ and $\tau = \infty$. Results from this set of simulations are independent of parameter ω, as expression (1) implies that $\tau = \infty$ renders ω irrelevant.

Finally, the impact of licensing is modelled by fixing ($T = 1$, $\omega = 1$), and reducing τ from $\tau = 2$ to $\tau = 0$. That is, this set of simulations assumes that firms receive revenues from their genetic improvements over two periods ($T = 1$) and that competitors' improvements can be exploited to their full extent when available ($\omega = 1$). Thus, reducing τ from $\tau = 2$ to $\tau = 0$ implies that competitors' genetic improvements can be used immediately to reduce a firm's improvement costs, rather than having to wait for two periods to do so.[19]

5. Survey results

The results that are to follow are sensitive to two key parameters. The first is parameter γ, which measures the degree to which previous genetic research reduces the cost of, or leverages, obtaining genetic improvements in a particular period. Projects that require a high degree of prior research will have a high value for γ. Intuitively, γ is a measure of the degree of research complexity. The second key parameter is $(1 - \rho)$, the rate at which genetic improvements depreciate. The rate of depreciation of genetic improvements is a standard measure, but the research complexity term γ is specific to the present paper.

In order to better understand the size of γ across different improvements, we asked two of the largest seed research firms to rank various genetic improvements with respect to their interpretation of this parameter. Because the scientists were not familiar with the method used to derive γ, the way we chose to ask them about research complexity was for them to describe each type of improvement as a proportion of the time and cost involved in incorporating exotic

19 To motivate this approach to the modelling of licensing, suppose that by charging a licence fee of $\lambda_{n,t}$ to firm $j \neq n$ at period t, firm n allows firm j to access its genetic improvement $\phi_{n,t}$ for research purposes over periods t through $(t + \tau)$. Similarly, suppose firm n can access firm j's ($j \neq n$) genetic improvement $\phi_{j,t}$ for research purposes over periods t through $(t + \tau)$ by paying firm j the licence fee $\lambda_{j,t}$ at period t. In a stationary pure-strategy symmetric Nash equilibrium, $\lambda_{n,t} = \bar{\lambda}$ for all firms n and all periods t. Therefore, for an individual firm n the revenues from selling licences to the other firms in any single period are equal to $(N - 1)\bar{\lambda}$ and are exactly offset by the aggregate amount paid by firm n to each of the other firms to obtain their licences. The direct revenues and costs stemming from the licences exactly cancel each other; however, licensing also reduces the cost of obtaining improvements for each firm from $c(x_{n,t}, \Phi_{n,t} + \omega\rho^{\tau}\Phi_{\#,t-\tau})$ to $c(x_{n,t}, \Phi_{n,t} + \Phi_{\#,t})$.

Table 2. Time to product commercialisation for different types of genetic improvements

Genetic improvement	Index time to product commercialisation[a]		
	Pioneer corn	Pioneer soybeans	Monsanto
Single-gene backcrossed into elite material	0.200	0.300	0.378
Single-gene backcrossed into elite recurrent parent. Example would be converting line to glyphosate resistance	0.300		
Common breeding programme Elite × Elite	0.350	0.400	
Germplasm enhancement Exotic × Elite	0.700	0.600	
Develop second-generation transgenes + regulatory			0.778
No public programme. Company works through un-adapted germplasm to identify trait of interest Exotic × Exotic	1.000	1.000	1.000

[a]The index measures time to commercialisation relative to time to develop the improvement.

germplasm into maize. This proportional measure was chosen so as to protect business confidential information and because the incorporation of exotic germplasm was the most complex programme currently ongoing at both of the companies. The transition from research complexity to the time and cost index is intuitive. When a company funds a research project that is expected to take 15 years, it may do so with an expectation that applicable results will become available sometime within the last 5 years, whereas a project that has a life expectancy of only 5 or 10 years must begin to pay off sooner. Projects that take 15 years to develop will typically have a long expected commercial life compared with projects that take only 5 years. If this were not the case then the firm would not undertake the multiyear investment.

The survey results are shown in Table 2. The link between the survey results and γ is far from perfect. Nevertheless, the results suggest that single-gene backcrossing and traditional breeding programmes are those with a low value of γ. Second-generation transgenes and the introduction of exotic germplasm have much greater complexity or γ. An IP protection system that favours high γ research is therefore likely to favour second-generation transgenes and the incorporation of exotic germplasm.

6. Simulation results

In Figure 2, panels A and B compare genetic improvement under PVP (panel A) and patents (panel B). Both methods of IP protection lead to a maximum genetic improvement when research is complex and the expected shelf life of the technology is long. Both exhibit reduced genetic improvement when research is less complex. The intuition here is that when research is complex there is little

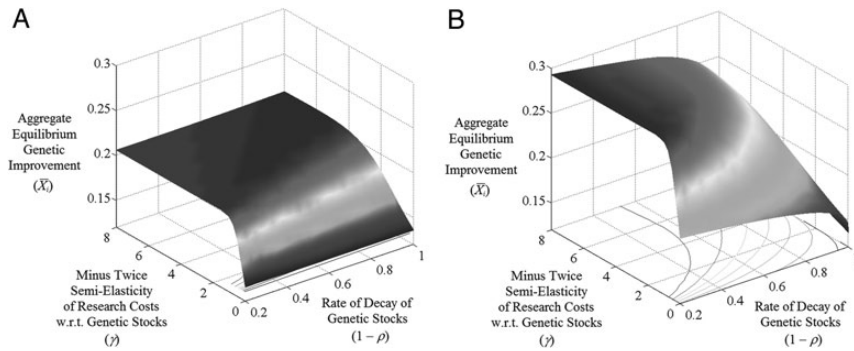

Fig. 2. Aggregate equilibrium genetic improvement under PVP and patents. (A) PVP and (B) patents.

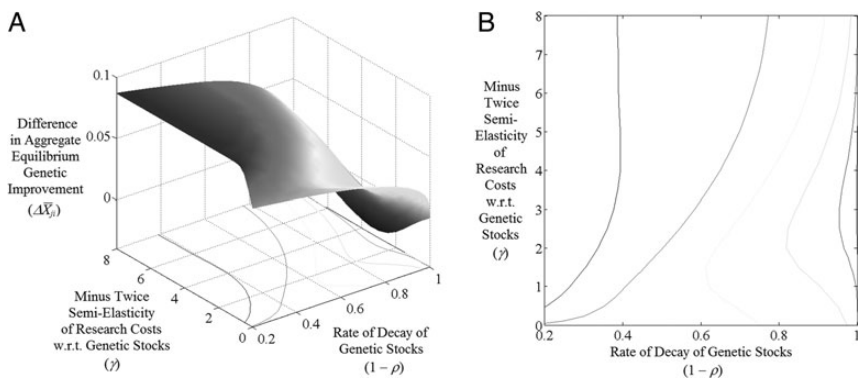

Fig. 3. Aggregate equilibrium genetic improvement under patents minus aggregate equilibrium genetic improvement under PVP. (A) Three-dimensional representation and (B) two-dimensional representation.

incentive to develop long-run research programmes, because these programmes do not deliver cost savings in subsequent periods. Differences between the two systems will be described below.

In Figure 3, panel A compares the genetic improvement for PVP and patents and represents the difference between the two welfare measures in three dimensions. Panel B is a two-dimensional projection of this difference. The vertical axis in panel A of Figure 3 is the genetic improvement under a patent minus the genetic improvement under PVP. A positive value suggests that patents dominate and a negative value is supportive of PVP.

The blue line that starts at the right-hand corner of Figure 3, panel B and extends to the left and then turns to the right is an iso-line showing the combinations of parameters where patents and PVP provide the same genetic improvement. Points to the left of this iso-line favour patents and points to the right favour PVP. Note that we can choose the cut-off points for parameters γ and $(1 - \rho)$ to favour either system; therefore, this difference should be viewed as an ordinal and not a cardinal measure.

Starting from the bottom right-hand corner of panel B in Figure 3, with a 100 per cent depreciation rate, the new variety is fully depreciated by the end of the period when it is introduced. In this area, the protection provided by the patent in periods after its introduction is not relevant. Therefore, firms operating under a patent system have no incentive to perform any research other than to obtain commercial benefits during the introduction period. Under PVP, competitor firms can access the research as soon as it is introduced and release these varieties in the following period. As the latter improved varieties are sold, genetic improvements in subsequent periods will be larger than under a patent. In the extreme case represented by the bottom right-hand corner of panel B in Figure 3, the degree to which competitors can gain from research conducted by other firms is zero because γ is zero. In this instance, both systems provide the same genetic improvement and the same amount of social welfare.

Staying with a 100 per cent depreciation rate ($1 - \rho = 1$), the PVP system begins to dominate as γ grows. The dominance of PVP in this region reflects the research and commercial development that is conducted by competitors immediately after a variety's introduction, as is legal under PVP but illegal under patents (unless licensed by the patent owner).[20] PVP allows these short-lived commercial varieties to yield the maximum genetic improvement and social welfare by ensuring that these varieties reach as many breeders as possible, even before the protection on these varieties expires. PVP dominates patents for all values of γ along this vertical line.

Now shift the vertical comparison line slightly to the left to $1 - \rho = 0.98$, so that the improved variety has some useful life after the period when it is introduced. Here the incentive system afforded by patents starts to assert itself. Firms recognise the benefits of having exclusive commercial benefits after the introduction period, and they ramp up research programmes in response. Patents dominate both when γ is small and when it is large. At small values of γ the diffusion process is not important because there is little value in other firms' research, and at large values of γ diffusion has reached its upper limit because of diminishing marginal returns built into the research production function.

Moving towards the left of this panel to $1 - \rho = 0.5$ where varieties have longer shelf lives, patents dominate regardless of the value of γ. Here, the strong incentives provided by long-lived varieties and long-lived protection dominate the diffusion advantages of the PVP system. Note also that the greater is the size of γ, the greater is the advantage of patents. Firms have greater incentive to fund highly complex (cumulative), long-term research programmes when the research product is of long-lasting value and they know that they can exclude others from appropriating the benefits.

Figure 4A and B show the societal welfare measures (excluding benefits to R&D firms) associated with PVP and patents, respectively. These measures are tilted in favour of research that has a long shelf life. The societal welfare

20 The research and commercial development conducted by competitors also represents the R&D spillovers mentioned by Pardey *et al.* (2013).

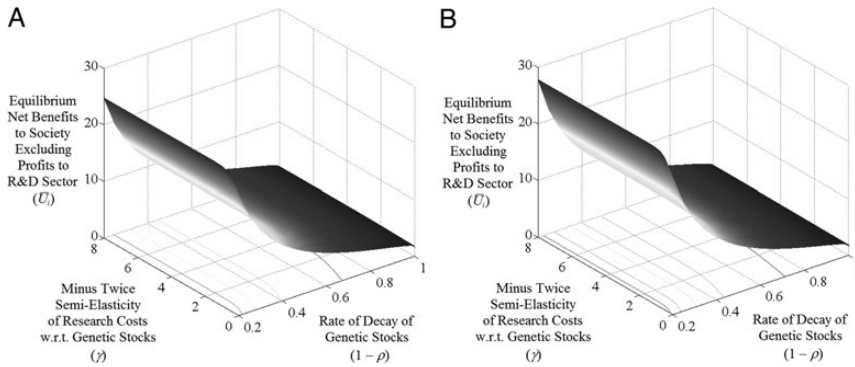

Fig. 4. Equilibrium net benefits to society (excluding profits to R&D sector) under PVP and patents. (A) PVP and (B) patents.

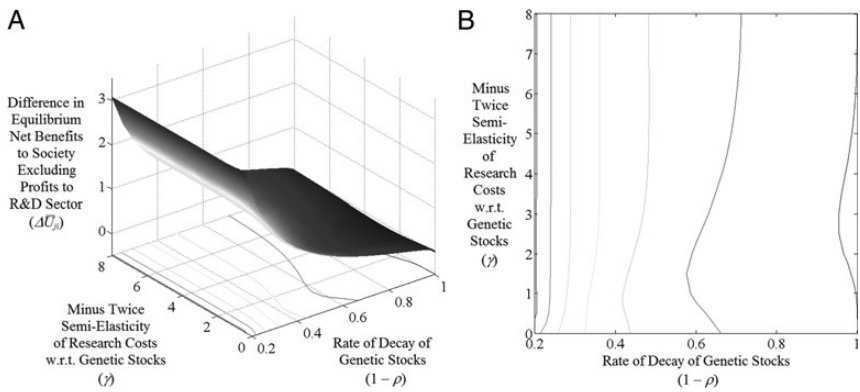

Fig. 5. Equilibrium net benefits to society (excluding profits to R&D sector) under patents minus equilibrium net benefits to society (excluding profits to R&D sector) under PVP. (A) Three-dimensional representation and (B) two-dimensional representation.

measure represents the current value of the research for its entire commercial life (see expression (8)), which is longer when genetic improvements depreciate slowly.

To better compare the differential effect of the IP protection system on societal welfare, Figure 5 depicts the equilibrium welfare under patents minus the equilibrium welfare under PVP. Panels A and B, respectively, provide three- and two-dimensional representations of such difference. In panel B, the iso-welfare line that starts at the south-east corner (i.e. where $\gamma = 0$ and $1 - \rho = 1$) denotes the (γ, $1 - \rho$) parameter combinations that leave society indifferent between PVP and patents. The iso-line separates the region where PVP yields greater welfare than patents (to the east of the iso-line) from the region where patents result in larger welfare than PVP (to the west of the iso-line). The (γ, $1 - \rho$) combinations corresponding to the welfare indifference iso-line in panel B of Figure 5 are identical to (γ, $1 - \rho$) combinations

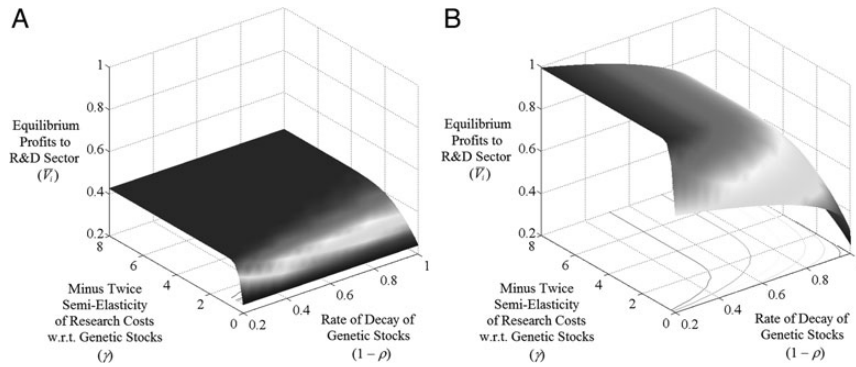

Fig. 6. Equilibrium profits to R&D sector under PVP and patents. (A) PVP and (B) patents.

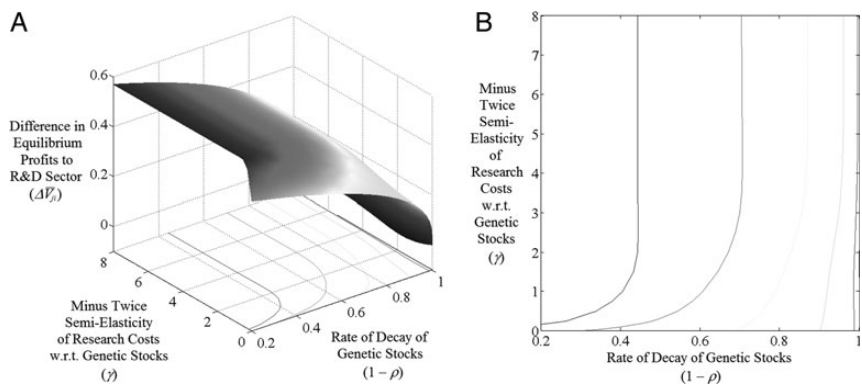

Fig. 7. Equilibrium profits to R&D sector under patents minus equilibrium profits to R&D sector under PVP. (A) Three-dimensional representation and (B) two-dimensional representation.

leading to the same genetic improvements for PVP as for patents in panel B of Figure 3. This result is to be expected, because the measure of societal welfare in expression (8) simplifies to $\hat{\phi}^{1-1/\varepsilon}/[(1-1/\varepsilon)(1-\rho^{1-1/\varepsilon})]$ in stationary equilibrium. That is, *ceteris paribus*, societal welfare is monotonically increasing in stationary equilibrium genetic improvements.

Graphical representations of the surpluses for the R&D industry under PVP and patents are provided in panels A and B, respectively, of Figure 6. Under PVP, R&D surplus increases substantially with γ for low levels of γ, but it quickly reaches a plateau. PVP R&D surplus is not sensitive to the speed of genetic stock decay, because PVP firms only capture commercial benefits over a single period. In contrast, R&D surplus under patents strongly increases with the commercial life of the genetic improvements, because firms holding patents can obtain commercial benefits over an additional period and their profits over this period increase with the life of the genetic improvement.

The differences in R&D surplus under patents and PVP are shown in Figure 7A and B, corresponding to the three- and two-dimensional

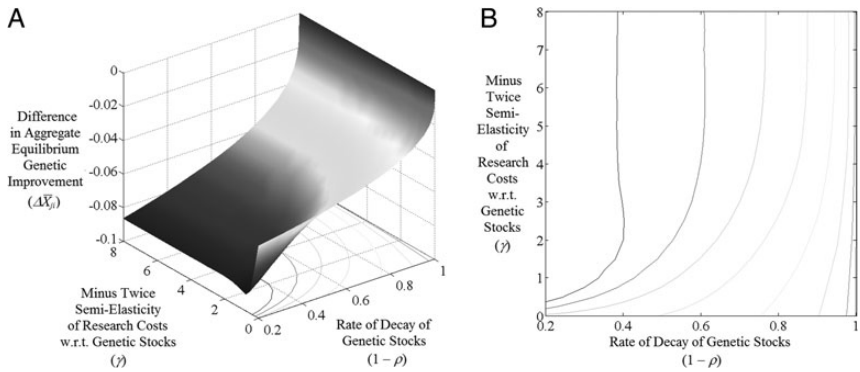

Fig. 8. Aggregate equilibrium genetic improvement under 5-year patents minus aggregate equilibrium genetic improvement under 10-year patents. (A) Three-dimensional representation and (B) two-dimensional representation.

representations, respectively. In panel B, the area to the right of the iso-line going through the point ($\gamma = 0, 1 - \rho = 1$) represents ($\gamma, 1 - \rho$) combinations for which R&D surplus under PVP is greater than R&D surplus under patents, and the opposite is true for the area to the left of such iso-line. The most important insight provided by Figure 7 is that, in terms of R&D surplus, patents clearly dominate PVP when both γ and expected commercial life are large. This result suggests that if R&D firms could choose γ and $(1 - \rho)$, patents would provide much stronger incentives than PVP to perform genetic research involving large γ and longer commercial life (i.e. smaller $(1 - \rho)$). Relatedly, if genetic research involves fixed costs increasing with γ and with commercial life, it is straightforward to demonstrate plausible situations in which a system with patents would support genetic improvements involving large γ and longer commercial life, but a system with PVP would not.

6.1. Reducing the length of patent protection

Figure 8 compares genetic improvements under two patent systems. The first patent system represents the base case 10-year patent discussed earlier, and the second has a 5-year patent protection. A negative value indicates that the longer patent dominates. This result is true for all of the parameter values, except for the extreme depreciation rate of $(1 - \rho) = 1$. With depreciation rates approaching 100 per cent, there is no commercial value to be captured with a longer patent. The advantage afforded by a longer patent is lowest when the degree of research specialisation (γ) is small. In this instance, firms have little incentive to build long-term research projects because there is little carryover benefit from previous research.

6.2. Reducing the time needed to create a new variety under PVP

Here we examine how a reduction in the length of time it takes to generate a distinct new variety influences the PVP results. The scenario involves two

offsetting forces. Firms realise that they will have a shorter period to capture the benefits of any research prior to the release of competitor's varieties, which reduces their incentive to fund research. However, a higher speed at which new varieties can be created increases the productivity of all research, including original research driven by IP, as well as research designed to leverage original research done by other firms. Unlike the other scenarios, the nature of the scenario itself influences the results because the scenario is about faster science, and faster science has obvious benefits.

The results depend very much on how we address the faster science question. If we compare genetic improvements between scenarios where the same amount of science can be conducted (i.e. 5 years for one scenario and half of that for the second scenario), then genetic improvements under the 5-year scenario clearly dominate due to the lower IP protection under the shorter protection period.

However, if we compare genetic improvements over identical periods (i.e. two 2.5-year periods for the faster scenario versus one 5-year period for the slower scenario), the results show that there is a trade-off between the reduced incentive to conduct research and the overall pace of research. The system that dominates depends on the rate at which research costs are increasing with the amount of genetic research. If costs are strongly convex in research, then genetic improvements increase as the time needed to generate a new variety falls. If costs are linear or close to linear in genetic research, then the longer scenario clearly dominates. The intuition here is that under the shorter period firms can complete two research projects at a lower overall cost than firms operating under the longer period can complete one research project.

In reality, firms will be able to find ways around strongly convex cost functions, such as by running many smaller research projects simultaneously. Therefore, the most appropriate scenario is the one where we hold constant the amount of science that can be completed and in this scenario societal welfare falls as firms discover faster ways to introduce new varieties.

6.3. The impact of trade secrets

With patents, competitors can access the material in the patent application, and, when it is legal for them to do so, they can use this patented information for their own commercial purposes. With a trade secret they never access the original science. The welfare impacts of the two models are remarkably similar with the exception of long-lived technologies and less-complex research where patents dominate because other firms benefit from information contained in the patent. Because of the similarity of the results they are not presented here.

6.4. PVP systems versus trade secrets

We also compared a PVP system with a system of trade secrets. This comparison produces results that are very similar to those where we compare patents with PVP. The logic here is that the opportunity to protect research with a trade secret incentivises long-term, complex research in much the same way as patents do. But the use of trade secrets also reduces dissemination in much

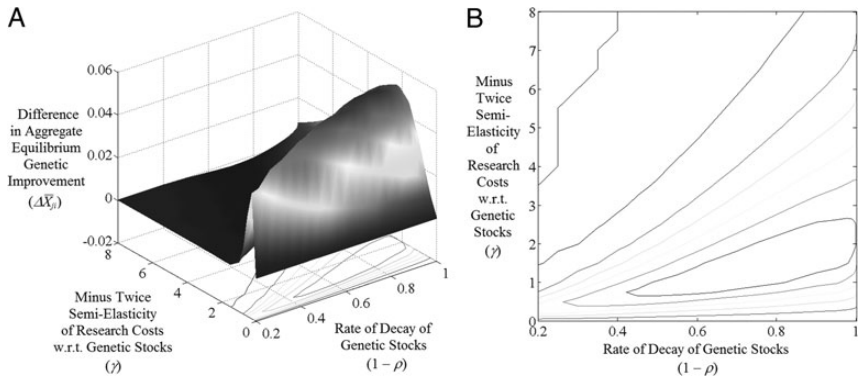

Fig. 9. Aggregate equilibrium genetic improvement under patents with licensing minus aggregate equilibrium genetic improvement under patents without licensing. (A) Three-dimensional representation and (B) two-dimensional representation.

the same way that patents do. Consequently, reliance on trade secrets (e.g. to protect parental lines) begins to be detrimental to social welfare when the period of trade secret protection extends beyond the time-frame provided either by PVP or by patents.

6.5. Patents with licensing

Figure 9 compares a system of patents with no licensing agreements against a system of patents with licensing agreements. Licensing dominates for a large set of combinations of γ and $(1 - \rho)$. The intuition here is that licensing allows society to access the new inventions in the same way as under PVP, but this system rewards the firm that created the technology by way of licence fees. Note that a system of patents with licences dominates a system of patents without licences for a range of parameters that are similar to those where PVP dominates patents. This result makes sense because licences offer a way to allow the technology to diffuse in much the same way that PVP does. Patents plus licensing maintains the strong incentive to conduct research of a long-term and complex nature, while also allowing that research to be quickly disseminated.

6.6. Is there a first-best outcome?

The licensing results are the most intriguing of the set because they seem to suggest that one can obtain the best of both worlds under a patent plus licensing system. Figure 10 compares genetic improvements under patents with licensing against the maximum (best) genetic improvement attained under the alternative systems (i.e. patents without licensing, PVP and secrets). The results indicate that the patents with licensing scenario dominate the maximum of the alternatives for a wide range of parameters. For the remaining parameter values

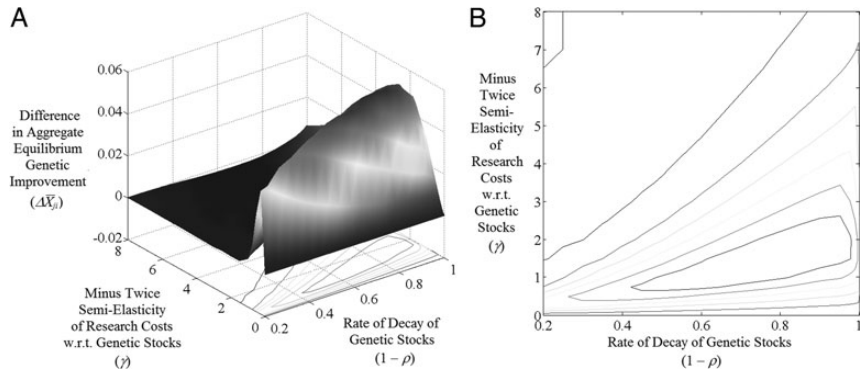

Fig. 10. Aggregate equilibrium genetic improvement under patents with licensing minus maximum aggregate equilibrium genetic improvement under all other regimes. (A) Three-dimensional representation and (B) two-dimensional representation.

there is no significant difference between patents with licensing and the maximum of all of the others.

Moving from right to left across the range of depreciation rates for an intermediate complexity level (e.g. $\gamma = 3$), the system that maximises genetic improvement at the right-hand side is one where firms share via licensing and patents. This result makes sense, because improvements become obsolete very quickly. When depreciation is high, licensing is good because it allows a firm to use other firms' improvements right away to reduce its own research costs. In other words, without licensing, by the time an improvement can be used by other firms, it is too late to dent those firms' research costs. In the middle range of depreciation rates, pure patents provide about the same incentive for research as patents with licensing. In this range the extra benefit of being able to use other firms' improvements right away rather than waiting until patent expiration is much smaller, because other firms' improvements depreciate little while waiting until patent expiration. At the left hand side, where the rate of depreciation is very slow, trade secrets provide approximately the same incentive to conduct research as patents and patents with licensing. In this region, the extra benefit from using others' research after patent expiration is very small, and all three systems of IP protection provide approximately the same amount of incentives to perform research.

There is a microscopic region where PVP dominates patents with licensing. This region involves very high γ and 100 per cent depreciation. The logic here is that the marginal benefit of conducting high γ research in a world where the technology will be redundant in one period is very small. The rate at which the marginal benefit falls off in this area is higher for patents than for PVP. High γ research makes most sense when research conducted today goes on to improve research productivity for several periods. The area where this result occurs is not economically relevant, because one would not expect firms to consider high γ research for a variety that is expected to have a commercial life of one period.

In our model, all firms are identical and they optimally choose to license under the patents with licensing scenario. This may not reflect the marketplace, either because one firm has a dominant position or chooses not to license for strategic reasons. Therefore, it is more accurate to say that in a marketplace where firms are similar in size, a scenario where firms license dominates, or, is equivalent to all other forms of IP protection.

7. Summary and conclusions

We develop an economic simulation model of the seed sector that allows us to compare the welfare and genetic improvements under subtle changes in the IP system. The motivation for this model is the spirited and ongoing debate on this issue. Many seed companies, policy makers and scientists in the EU generally favour PVP while those in the United States generally favour patent laws. Our results show that there are circumstances under which both perspectives are correct. Patents can incentivize firms to conduct expensive and long-lasting research programmes of the type that lead to the development of transgenic plants and the introduction of exotic germplasm into commercial products by the private sector. PVP leads to faster diffusion across research firms, and in circumstances where the improvement is expected to have a short life and the research technology is easily transferable, this diffusion dominates the weaker IP protection implicit in PVP.

Transgenic plants are not yet a commercial success in the EU and governments there have typically funded much of the basic work of introducing exotic germplasm which has largely been directed towards specific quality or disease and insect resistance genes. Therefore, the traditional breeding programmes conducted by the private sector in the EU are typically favoured under a PVP system. Improvements made by any one firm are quickly made available to other firms, so long as the latter use the research to generate distinct new varieties. Horizontal diffusion fuels the rate of genetic progress (which is also dependent upon the magnitude of incremental improvements), but it reduces the incentive to participate in more expensive, long-lived projects.

The utility patent structure in the United States has the potential to slow genetic improvement from more-traditional breeding programmes, because the patent allows the original firm exclusive rights to its own research and this slows horizontal diffusion. Our results suggest that this problem can be resolved with a licensing programme so long as it results in a complete market for access to the varieties on reasonable terms—whether it emerges voluntarily or is mandated.

The results also compare patents of different lengths and show that the optimal patent length is less than infinity and more than a single development period.

We show that when the period needed to generate a distinct new variety under a PVP system is reduced then genetic improvement and social welfare fall for all reasonable parameterisations.

The results of this research show that flexible approaches to IP protection, for example by adjusting the breeders' exemption, or by reducing incentives to

utilise trade secrets beyond PVP or patent terms, are warranted. The results also support a tentative conclusion that utility patents coupled with licensing dominates, or is equivalent to, all other forms of IP protection.

References

Alston, J. M., Gray, R. S. and Bolek, K. (2012). Farmer-Funded R&D: institutional innovations for enhancing agricultural research investments. Working Paper. Canadian Agricultural Innovation and Research Network. http://www.ag-innovation.usask.ca/cairn_briefs/publications%20for%20download/CAIRN_2012_FarmerFundedRD_AlstonGrayBolek.pdf. Accessed 16 November 2014.

Alston, J. M. and Venner, R. J. (2002). The effects of the US plant variety protection act on wheat genetic improvement. *Research Policy* 31(4): 527–542.

British Society of Plant Breeders. (2010). Economic Impact of Plant Breeding in the UK. Manchester, UK: DTZ, 24 pp. http://plantbreedingmatters.com/sg_userfiles/BSPB_Impact_Final_Report.pdf. Accessed 16 November 2014.

Dobermann, A. and Nelson, R. (2013). Opportunities and solutions for sustainable food production. Background paper for the 'High-Level Panel of Eminent Persons on the Post-2015 Development Agenda', 24 pp. Sustainable Development Solutions Network, A Global Initiative for the United Nations, New York. http://www.post2015hlp.org/wp-content/uploads/2013/05/Doberman-Nelson_Solutions-for-Sustainable-Food-Production.pdf. Accessed 16 November 2014.

Donnenwirth, J., Grace, J. and Smith, S. (2004). Intellectual property rights, patents, plant variety protection and contracts: a perspective from the private sector. *IP Strategy Today* 9: 19–34.

Duvick, D. N. (2005). The contribution of breeding to yield advances in maize (*Zea mays* L.). *Advances in Agronomy* 86: 83–145.

Eaton, D. and van Tongeren, F. (2005). Should Europe further strengthen intellectual property for plant breeders? Paper presented at the XIth International Congress of the EAAE (European Association of Agricultural Economists), 'The Future of Rural Europe in the Global Agri-Food System'. Copenhagen, Denmark, August 24–27.

Evenson, R. E. (1989). Spillover benefits of agricultural research: evidence from us experience. *American Journal of Agricultural Economics* 71: 447–452.

Evenson, R. E. and Gollin, D. (1997). Genetic resources, international organizations, and rice varietal improvement. *Economic Development and Cultural Change* 45(3): 471–500.

Fehr, W. (ed.). (1984). *Genetic Contributions to Yield Gains for Five Major Crop Plants* (Special Publication No. 7). Madison, WI: Crop Science Society of America and American Society of Agronomy.

Frisvold, G., Sullivan, J. and Raneses, A. (1999). Who gains from genetic improvements in US crops? *AgBioForum* 2: 237–246.

Hayes, D. J., Lence, S. H. and Goggi, S. (2009). Impact of intellectual property rights in the seed sector on crop yield growth and social welfare: a case study approach. *AgBioForum* 12(2): 155–171.

Kolady, D. E. and Lesser, W. (2009). But are they meritorious? Genetic productivity gains under plant intellectual property rights. *Journal of Agricultural Economics* 60(1): 62–79.

Kolady, D. E., Spielman, D. J. and Cavalieri, A. J. (2012). The impact of seed policy reforms and intellectual property rights on crop productivity in India. *Journal of Agricultural Economics* 63(2): 361–384.

Koo, B. and Wright, B. D. (2010). Dynamic effects of patent policy on sequential innovation. *Journal of Economics & Management Strategy* 19(2): 489–512.

Lence, S. H. and Hayes, D. J. (2005). Technology fees versus GURTs in the presence of spillovers: world welfare impacts. *AgBioForum* 8: 172–186.

Lence, S. H., Hayes, D. J., McCunn, A., Smith, S. and Niebur, B. (2005). Welfare impacts of intellectual property protection in the seed industry. *American Journal of Agricultural Economics* 87: 951–968.

Miranda, M. J. and Fackler, P. L. (2002). *Applied Computational Economics and Finance*. Cambridge: MIT Press.

Moschini, G. and Yerokhin, O. (2008). Patents, research exemption, and the incentive for sequential innovation. *Journal of Economics & Management Strategy* 17(2): 379–412.

Naseem, A., Oehmke, J. F. and Schimmelpfenning, D. E. (2005). Does plant variety intellectual property protection improve farm productivity? Evidence from cotton varieties. *AgBioForum* 8(#2&3): 100–107.

Pardey, P., Koo, B., Drew, J., Horwich, J. and Nottenburg, C. (2013). The evolving landscape of plant varietal rights in the United States, 1930–2008. *Nature Biotechnology* 31(1): 25–29.

Perrin, R. K. and Fulginiti, L. E. (2008). Pricing and welfare impacts of new crops: the role of IPRs and Coase's conjecture revisited. *AgBioForum* 11(2): 134–144.

Rubenstein, K. D., Heisey, P., Shoemaker, R., Sullivan, J. and Frisvold, G. (2005). Crop genetic resources: an economic appraisal. USDA, Economic Research Service, Economic Information Bulletin No. 2. http://www.ers.usda.gov/media/465162/eib2_1_.pdf. Accessed 16 November 2014.

Swanson, T. and Goeschl, T. (2005). Diffusion and distribution: the impacts on poor countries of technological enforcement. In: K. Maskus and J. Reichman (eds), *International Public Goods and Transfer of Technology Under a Globalized Intellectual Property Regime*. Cambridge: Cambridge University Press.

Union Internationale pour la Protection des Obtentions Végétales (UPOV). (1991). International Convention for the Protection of New Varieties of Plants of December 2, 1961, as Revised at Geneva on November 10, 1972, on October 23, 1978, and on March 19, 1991. http://www.upov.int/en/publications/conventions/1991/act1991.htm. Accessed 16 November 2014.