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## Introducing Cattle Producer to the Hardin s World- Can Monopolies in Seed Markets Be Welfare Enhancing?

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# Introducing Cattle Producer to the Hardin's World- Can Monopolies in Seed Markets Be Welfare Enhancing?

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## Abstract

The paper investigates markets ridden by problems of common pool resources and asks how monopoly rights for inputs into those markets affect the welfare. The analysis rests upon the example of anti-pest innovations. The quintessential feature of such innovations is the possibility of them losing their effectiveness. Their application exerts evolutionary pressure on pests that eventually leads to them developing resistance to the innovation. The ensuing perishability of the innovation makes its common pool resource character visible. The paper develops a model of agricultural markets and discusses how monopolies, despite their underprovision of output may lead to increased welfare compared to generic industries. In this context, the optimal patent length is investigated.

*Key words:* monopolies, welfare, commons, pathogen resistance, market design.

*JEL classification:* Q58, Q16, L50.

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Preliminary version (Jan. 2016) - please do not quote.

## 1. Introduction

The pathogens<sup>1</sup> - viruses, bacteria, fungi, parasites etc., pose a great threat for agriculture. They cause damage in the crops which every year lead to significant losses in harvest. Oerke and Dehne [24] estimate that the loss potential varies from less than 50% (on barley) to more than 80% (on sugar beet and cotton). Applying anti-pest measures to prevent those losses from happening plays therefore a key role for the supply of staple foods.

There is a problem with the effectiveness of the measures over time, however, as the pathogens tend to quickly adapt to the new conditions and overcome the control measures. These adaptations are induced by the evolutionary pressure that causes the pathogens to evolve through accelerated natural selection and mutations. The more frequently an innovation gets employed, the higher the evolutionary pressure exerted on

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<sup>1</sup>In this paper, the word "pathogen" is used interchangeably with the word "pest".

the pathogens and the bigger the chance the pathogens will adapt to the new circumstances thus rendering the invention obsolete.<sup>2</sup> Consequently, individual use of a control measure creates externality in form of increased likelihood that the measure will cease to be effective. The resistance of pathogens to the control measures (the mirror image of the effectiveness of the anti-pest measures) can be thus thought of as the negative externality of current actions on future outcomes and the effectiveness of the anti-pest measures be modeled as a scarce biological resource.

In the past, the anti-pest measures were usually developed in a form of a "good practice" and so they tended to have an open-access form - anyone who heard about the measure could freely apply it. Therefore, like with the meadow from the seminal paper of Hardin on tragedy of the commons ([15]) their usage was doomed to be suboptimal. The existence of externalities combined with no coordination mechanism led to the tragedy of the commons - generated the "boom-and-bust" cycles of effective control<sup>3</sup> that were too short compared to the socially most desirable outcome.

The latest anti-pathogen innovations, however, have been different in that they have mainly been biotechnological developments<sup>4</sup> with the access to them available solely through markets. Only buying the proper seed/pesticide enables a farmer to apply the innovation. Consequently, the protection methods became private goods with access to them governed by the behaviour of the sellers of a particular method.

If the sellers operate in a perfectly competitive market (generic industry), they have no incentives to restrict the supply of a given innovation and the outcome is that of the open-access type.<sup>5</sup> On the other hand, if the seller of a particular innovation happens to be a monopolist (owns a patent for the innovation), we expect him to internalize the disease probability effect in the sales decisions.<sup>6</sup> In Hardin's world this would correspond to a situation in which farmers who wish that their cows graze the common would need

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<sup>2</sup>There seems to be no escape from the inexorable adaptation process, even for the most advanced innovations. For example, Fischer *et al.* [10] remarked in 2005 that, even though at that time there was no known pest resistance to Bt proteins (that are widely genetically engineered into crops due to their insecticidal action), the development of resistance was believed to be a matter of time only. Indeed, 2008 it was found that one of the insects - pink bollworm had become resistant to the first-generation Bt cotton [9].

<sup>3</sup>As new measures were found, the news about them spread quickly. Farmers were free to adapt the innovations, which they gradually did, thus increasing the share of protected crops ("boom") while raising the evolutionary pressure on pests. In the long term, this inevitably lead to the "bust" - the pests becoming fully resistant to the new measures and, consequently, the measures losing their effectiveness.

An example for such an adaptation connects to an observation that rotating maize with another crop breaks the life cycle of the western corn rootworm. The rotation had been used as a primary (and successful) rootworm management strategy in North America for almost two decades. In the 1990s, though, the insect seemingly adapted to crop rotation. A variant of western corn rootworm started laying eggs outside the maize fields and so the rotation management strategy became obsolete.[14]

<sup>4</sup>The new measures comprise mostly disease-resistant hybrids, genetically engineered seeds etc.

<sup>5</sup>It is worth noticing that in the Hardin's ([15].) paper, such a cattle supplier is assumed.

<sup>6</sup>Knowing that increased probability of advancement losing its effectiveness stifles willingness to pay for it, he restricts the supply accordingly and thus, seemingly, solves the commons problem.

to buy the cattle from a monopolistic cattle producer.<sup>7</sup>

Thus, while the problem of pathogen adaptation continues to be a serious threat, the associated tragedy of the commons can be addressed by means of market design. The design entails consequences not only the profits of the farmers but also for the crop provision and, subsequently, the welfare of the crop consumers. In particular, the latter may be of a great interest to the public given the dependence of many livelihoods on the staples.

The paper investigates under which conditions the concentration of upstream market power could be socially desirable (with a special emphasis on the consumer welfare).<sup>8</sup> The answer to that question has a very tangible implications for the regulation: the regulator chooses the length of monopoly rights by setting the patent length.<sup>9</sup> After the patent expires, the generic industry usually takes over the production.<sup>10</sup> Should the monopoly regime turn out to be welfare-enhancing (destroying), the patent length for the new anti-pest measures could be adjusted correspondingly. Therefore, the paper also solves for optimal patent length.

We develop a model that reflects the intertwined seed and harvest markets and explains the decisions of the market participants - suppliers of a particular (innovative) seeds; farmers who buy the seeds and sell the harvest and final consumers who purchase the harvest.

Firstly, a static version of the model with homogenous producers is presented. In the first stage of the model the (uniform) price for the anti-pest measure is set. Based on that price the farmers decide whether or not to apply the measure. Depending on how many farmers opted for the innovation, the pathogens may manage to overcome the protective measure (in this case the measure is worthless). Finally, the farmers harvest their crops (with the harvest size dependent on the efficacy of the innovation) and sell it on the competitive market to final consumers. This timing of the events that is underlying all of the models is illustrated in the graph 1. The model shows the countervailing forces behind the monopoly rights. As it is the only model with closed-form solutions, the intuition for the conditions for welfare superiority of the monopolists is explained here. That intuition extends to all other models as well.

Secondly, the assumption on the generic industry is weakened in the static model - with the help of Salop's framework we let generic industry operate in form of monopolistic

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<sup>7</sup>In the original paper ([15]) a competitive cattle supplier was assumed.

<sup>8</sup>While the concentration of market power in the downstream market (among the farmers) would potentially yield better welfare outcomes, we assume that this is hardly possible due to the extreme fragmentation of the market as well as the sheer impracticability of such an attempt.

<sup>9</sup>The only restriction for the patent length is that the company needs to be able to recover its R&D and other fixed costs within that time.

<sup>10</sup>The first of the commercial biotechnology innovations in the United States went "off-patent" and became "generic" in 2014 as Monsanto's Roundup Ready seeds licenses expired. The market has witnessed many agricultural universities, especially University of Arkansas, starting their own production of the seeds. Within the next years a wave of important plant genetic modifications will lose patent protection.

competition instead of perfect competition. The specification allows a heterogeneity of the farmers enabling one to explain the many developments that we observe on the "innovation markets".

Afterwards, both models specifications are transformed to the dynamic version where the core questions of the optimal patent length are asked. The solutions are provided using numerical simulations.

The contribution of the paper is twofold. Firstly, it investigates to what extent monopolies can achieve a second-best outcome in terms of welfare in a world plagued by problems of the commons when no other economic incentives are available that would bring the market outcome to the first best. The analysis relies on the example of anti-pathogen innovations, however, the conclusions are far more general and extend to other many applications where the common character of the goods poses a problem. Especially there, where the traditional instruments have failed to prevent their overexploitation (like in the example of fish stock) the findings may constitute an important enrichment for the economic toolbox.

Secondly, it shows how the optimal patent length should be chosen and how that length depends on the conditions of the world, especially the characteristics of the pest.<sup>11</sup>

From the agricultural perspective questions pursued seem highly relevant given the dependence of farming on pathogen control methods and havoc on the crop markets that could be induced by one of those methods losing its effectiveness.

This paper combines insights from biology and economics while contributing to the literature on the optimal anti-pest management and to the literature on common goods and market design.

To the best of author's knowledge, this study is the first to compare the welfare outcomes under different market structures for the measures against pests. Also, no paper has examined the seed choice of farmers in the presence of the resistance externality.

The next section reviews the relevant literature. Section 3 develops models of the intertwined agricultural markets - seed and harvest markets. Section 4 provides a discussion of the result and their possible extensions while section 5 concludes.

Throughout the paper we use the seeds as anti-pathogen innovation but the innovation could be any other productive input sold to the farmers.

## 2. Literature review

The nexus between evolutionary pressure and adaptation has been the subject of plentiful biological studies ([28], [20], [22]); in economic literature in the context of

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<sup>11</sup>Throughout the paper, we assume that the innovations are provided by the private sector and need to be rewarded at least by some  $t^{MIN}$  years of monopoly rights to cover their R&D expenses. However, some call for public provision of innovations, e.g., magazine *Nature*, when discussing coffee rust outbreak, prompts : "Governments in coffee -growing countries need to take coffee research as a priority and provide necessary resources" [8]. The discussion on possible welfare superiority of public provision of innovations is shifted to section 4.

agriculture, Weitzman [29], acknowledged how concentration on high-yielding varieties increases probability of new catastrophic infections. The interdependence between farmers' crop choices and the diversity has been discussed by Heal et al. [16]. Brock and Xepapadeas [3] develop a welfare measure of biodiversity given socially optimal and privately optimal management in a agroecological setup. They model the externality from using the most productive variety as speeding up the evolution of the pest population towards the most harmful genotype.

The first-best pest strategies given evolving pest resistance have been investigated since the 70's (e.g. [5], [6]). However, for long time the abstract social planner perspective was kept without paying attention to the market structure. Only in the 2000s did first such studies appear. Fischer and Laxminarayan [10] investigate how monopolists' incentives differ from those of social planner in case of sequential (and deterministic) exploitation of exhaustible resources. Munro [23] studies welfare effects of monopolization of high-yielding varieties but without explicitly account for the evolution and disease risk. The evolutionary mechanism is in the focus of a study performed by Goeschl and Swanson [11] who inquire how the adaptation of pests and pathogens influences the value of patents and what is the optimal patent policy for spurring innovation.

Anti-pathogen innovations share their tendency to lose efficacy with antibiotics and, consequently, analyses somewhat similar to this one can be found in the antibiotics literature. For example, the works of Herrmann and his colleagues ([18], [17], [19]) compare first best paths with the perfect competition and monopoly paths respectively. A very close work to this study is also Mechoulan [21] who in an extension of his model explicitly compares welfare under monopoly and competition and finds that, except for few pathological cases, the perfect competition is always socially preferred. However, one can expect the predictions for the pest innovations to be quite different. First of all, pathogen repellents are used preventively as opposed to application after an infection in case of antibiotics.<sup>12</sup> This alone changes the incentives for producers dramatically. Secondly, the associated markets are very distinct, both in terms of their structure (seed producer - farmer - harvest consumer vs. antibiotics producer - patient/doctor) and the coordination possibilities (the knowledge of the doctors).

The role of monopolies in decreasing the amount of externalities has long been recognized in the literature ([4], [2]). There have been studies that show welfare superiority of the monopolist in certain cases, e.g. Schoonbeek and de Vries [27] identify the conditions where the government prefers monopoly above duopoly and imposes a correspondingly high tax rate due to pollution externalities. However, to the best of the author's knowledge, no study explored it in the context of common-pool resources with two intertwined markets. The specificity of the agricultural market is a second aspect that makes this analysis distinct from the existing ones.

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<sup>12</sup>At least in case of humans the antibiotics are applied after the infection and this is the case discussed in the literature. To the best of the author's knowledge there are no relevant papers that deal with preventive application of antibiotics in farming.

### 3. Model framework

There are  $N$  farmers who face a cropping decision. Given that everyone already owns a field (whose size was normalized to one), a farmer  $i$  chooses what share of his field ( $s_i$ ) to assign to high yielding variety (HY) of a given crop. On the rest of the field,  $(1 - s_i)$ , a natural variety (NV) is planted. The main difference between the two varieties is that HY has a mechanism of protection against certain pathogens grafted into it (e.g. a specific resistance gene) and, as a result, it gives higher expected yields. The amount of harvest from one unit of field is  $\alpha$  but  $(1 - R)$  of it gets destroyed by pests if there is no protection against them. Consequently,  $R$  can be interpreted as the usual fraction of crop that is preserved in the absence of man-made resistance mechanisms ("natural survival rate") and  $\alpha$  is the "seed productivity".

Obtaining HY from the proper producer is costly (the price is denoted by  $r$ ) as opposed to using the abundant natural varieties that are available for free.<sup>13</sup> Besides, the investment into seed is performed one period before the harvest and the parameter  $\rho$  captures the intertemporal discounting.

Importantly, the pathogen protection offered by HY is not ceaseless but can be broken, should the pathogens manage to adapt adequately. The probability of this happening depends on the evolutionary pressure exerted on pathogens - the less habitat is available, the more probable the adaptation. The probability of pathogen innovation losing efficacy ( $\tau$ ) is delineated as a function of the share of the fields where the the innovation gets applied,  $s$ .

For simplicity, we abstain from analyzing the spatial spread of the adaptation of pathogen and assume that once the resistance is broken, the innovation loses its efficiency for all the farmers.

The farmers make cultivation choices with the objective of maximizing the expected profits given the prices prevailing at the market when the efficacy is kept ( $p_{nd}$ ) and when the efficacy is lost ( $p_d$ ). The number of farmers is so large that they neglect the effect of their behaviour on the survival rates (and crop prices). The maximization problem is thus given by:

$$\max_{s_i} \alpha(1 - \tau)p_{nd}(s_i + (1 - s_i)R) + \alpha\tau p_d R - s_i(1 + \rho)r.$$

A farmer will cultivate both HY and NV only when the value of the extra harvest generated by HY equals the costs of the seed. Assuming linear demand for harvest ( $p = g - \beta Q$ ) and linear functional form of  $\tau$ :  $\tau = \frac{s}{m}$  for  $s < m$  ( $m > 0$ )<sup>14</sup> equilibrium is achieved when:

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<sup>13</sup>Throughout the model it is assumed that upstream interactions happen with the help of the "market interface" with uniform contractual terms (no bilateral contracting and negotiations take place).

<sup>14</sup>The interpretation of  $m$  parameter is that if the innovation is applied on more than  $m$  of the fields, the pathogens for sure become resistant to it. The  $m$  will therefore be referred to as "threshold share".

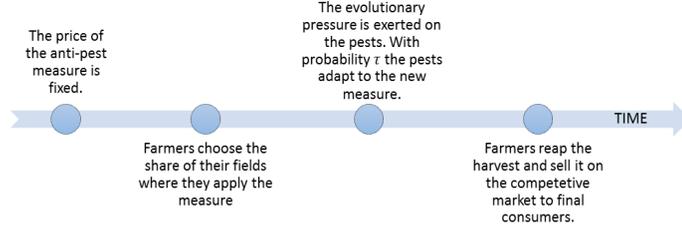


Figure 1: Timing of the events in the static game.

$$\left(1 - \frac{s}{m}\right)\alpha[g - \beta N\alpha(s + (1 - s)R)](1 - R) = (1 + \rho)r.$$

The equilibrium condition gives the inverse demand schedule - the price the farmers are willing to pay for the innovative seed given the share of fields planted with HY,  $r(s)$ .

### 3.1. Static model

To obtain the intuition we assume for now that the innovation is given like manna from heaven and simply ask, from the static perspective, who would do a better job in terms of social welfare bringing the innovation to the market - generic industry or a monopolist. Those assumptions will be relaxed in the following subsections.

#### 3.1.1. Homogenous farmers

The monopolistic seed producer, who is assumed to be equipped with CRS technology with marginal costs  $k$ , would pick the land share,  $s_s^M$ , that maximizes his profits<sup>15</sup>:

$$\max_s r(s)sN - sNk, \quad (1)$$

implying that at the optimum  $r'(s_s^M)s_s^M + r(s_s^M) = k$ ; whereas at the perfectly competitive market the equilibrium condition would be that:

$$r(s_s^{PC}) = k. \quad (2)$$

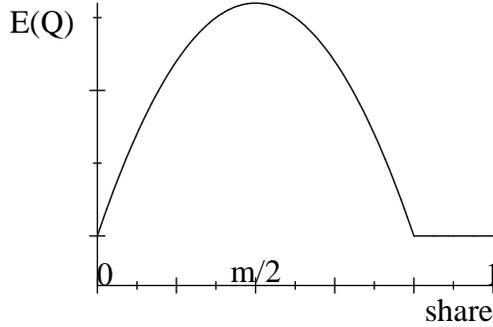
Consequently, the share of HY under the perfect competition would always be higher than under monopolistic regime:  $s_s^{PC} < s_s^M$ .<sup>16</sup>

The increased share of high yielding variety may or may not translate into higher expected harvest. This is due to the endogenous probability of pathogen innovation

<sup>15</sup>Choosing the land share,  $s$ , to be supplied is the same as is the same as choosing the quantity sold as the amount of land (and the number of farmers) is fixed.

<sup>16</sup>The lower index (e.g. in  $s_s^{PC}$ ) points to the static setup, the upper index refers to the regime:  $PC$  for generic industry and  $M$  for a monopoly.

losing its efficacy. With the above specification the expected harvest is a function of  $s$  that reaches its maximum when the share of fields planted with HY is  $s^* = \frac{m}{2}$  (as illustrated in the graph below).



Expected harvest as a function of HY share (with  $m = 0.8$  and  $R = 0.9$ ).

It is easy to notice that the monopolist would never sell more than  $s^*$ . Combining that with the observation of symmetry of the above function, one can foresee which regime would produce higher expected harvest. And namely, the monopolist would ensure higher expected harvest if the share of the fields where HY gets applied ( $s_s^M$ ) is closer to the optimal share  $s^*$  than the perfectly competitive share would be ( $s_s^{PC}$ ) which can be written as:

$$\left| \frac{m}{2} - s_s^M \right| \leq \left| \frac{m}{2} - s_s^{PC} \right| \quad (3)$$

From the perspective of a risk-averse crop consumer, it is not only the expected harvest (and consequently the expected price and amount available) that matters but also the whole distribution of the harvest. In this context, the condition (3) can be seen as a very conservative measure of superiority of monopoly (when looking at consumer welfare). When (3) holds with equality (implying same expected crop) the distribution of outcomes under the monopolistic regime second-order stochastically dominates that under generic industry. Consequently, whenever condition (3) is met, not only is the expected outcome (weakly) higher but also less risky. It seems plausible to assume that the consumer would prefer a less risky and weakly higher in expected value outcome and so the monopolistic market for HY seed would make him better-off. On the other hand, in cases when (3) fails to hold, the consumer could nevertheless enjoy the competitive regime less due to its riskiness but the proposed measure would not show that.<sup>17</sup>

**Corollary 1.** *If under the monopolistic regime the share of the fields where HY gets applied,  $s_s^M$ , is closer to the optimal share  $s^*$  than the generic industry's share,  $s_s^{PC}$ , would*

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<sup>17</sup>One could use other measures for comparing the two regimes outcomes from the perspective of consumers. The expected consumer's surplus, though, is usually inappropriate for representing the preferences over price lotteries as shown among others in Schlee [26]. Alternative measures would require pinning down the utility function, especially the magnitude of risk-aversion of consumers which the author intended to avoid.

be, the final consumer would always prefer the monopolist to manage the innovation. The opposite statement is true only for risk aversion of the consumers being small enough.

It is also worth noticing that cultivation of HY does not influence the yields and prices for the case when the innovation loses its value but only affects the probability of this happening,  $\tau$ , and prices in case when resistance is preserved, of  $p_{nd}$ .

Solving equations (1) and (2) gives the corresponding HY shares under the two regimes. The ensuing optimality condition is rather intransparent, therefore we simulate the results.<sup>18</sup>

Given that the model is highly stylized, it is hard to come up with the optimal parameters to look at. We concentrate at the damage rate,  $R$ , and threshold share,  $m$ , as they are crucial from the ecological point of view. The damage rate is picked to meet the estimates of average damages inflicted by the popular pathogens on different crops (based on [24]). The greatest uncertainty focuses on the values of threshold share,  $m$  therefore in the simulations most of the conceivable values were used. It appears that threshold needs to be less than one otherwise there would be a chance of completely eliminating a pest just by applying the innovation to all crops, it cannot be also too low as we see innovations used on significant shares of fields without the efficacy being directly lost. The demand function parameters  $(g, \beta)$  come from calibration based on different crop markets. The unit costs of HY seeds ( $k$ ) are allowed to vary significantly.

Figure 2 reports the parameter combinations for which monopoly is the regime strictly preferred according to the condition 3 (the blue dots). The black dots mark the configurations where both regimes would yield the same expected harvest (mostly cases when the HY seeds would be too costly to apply). The subfigures represent different demand schedules and seed productivities; the values of threshold share,  $m$ , damage rate,  $R$ , and unit costs of seeds,  $k$ , are varied on the  $x$ -,  $y$ - and  $z$ -axes respectively. It turns out that, indeed, a monopolist at the anti-pathogen innovation markets can be good news for the crop consumers, especially if the unit costs are (relatively) low. The intuition for that result is that with perfect competition there is no mechanism to prevent the shares of HY from growing (well) beyond the social optimum, thereby overly increasing the risk of innovation losing its efficacy and pushing down the expected harvest. This is especially visible in the case of zero unit costs - the share of HY seeds grows to  $m$  rendering the innovation completely ineffective. The monopolist, on the other hand, is aware of the disease probability channel and internalizes it into his decision while trying to maximize the profits.

**Corollary 2.** *With decreasing unit costs of the anti-pest measure the room for welfare-enhancing role of monopolies expands. In extreme case of zero unit costs, the monopolist is always (weakly) welfare superior.*

To deepen the intuition we also approximate linearly the demand for HY innovation around  $s = \frac{m}{2}$ . The ensuing (simplified) optimality condition is:

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<sup>18</sup>The condition is given in appendix.

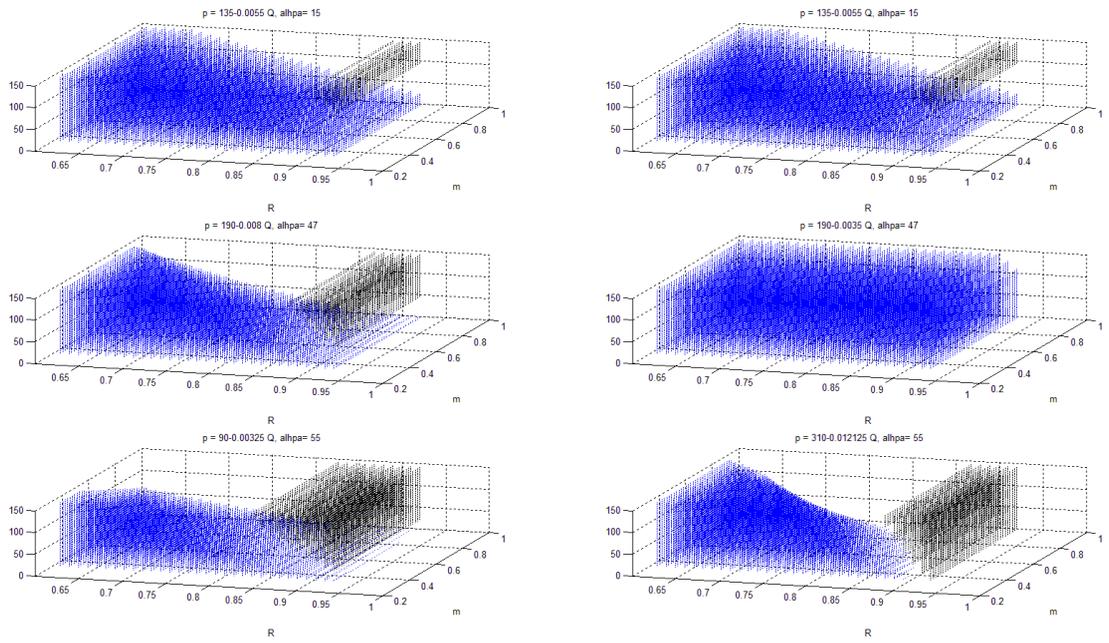


Figure 2: Comparison of expected harvest under monopolistic and competitive regime. Blue dots mark parameter combinations with superior monopolistic regime, black dots marks parameters combination with same expected harvest of the both regimes. The z-axis represents the marginal costs of seeds,  $k$ , the other two axes - damage rate,  $R$ , and threshold share,  $m$ . The subfigures differ in terms of demand schedules and seed productivities.

$$\frac{g - N\alpha\beta(0.75R + 0.25)}{g - NR\alpha\beta} \geq \frac{k(\rho + 1)}{\alpha(g - NR\alpha\beta)(1 - R)} + 0.375(1 + \rho)^2, \quad (4)$$

where the left-hand side resembles the ratio of expected prices for the harvest if  $s$  is close to 0.5 and  $s = 0$  and therefore captures how quickly the incentive to buy HY dies out with increasing  $s$ . The slower it happens (the higher the ratio) the higher the  $s_s^{PC}$  grows and the more probable the monopoly is the welfare supreme regime. This effect is mostly driven by  $R$  - with a significant pest problem (low  $R$ ) the drop in value of innovation with increasing  $s$  will be higher for most of the cases making the farmers more conscious of the "externality" and pushing the welfare superiority towards perfect competition.

The right-hand side, on the other hand, relates to the (relative) costs of investing into the HY technology. The first of the terms compares the cost of HY technology under perfect competition with the maximum premium that the farmers can earn for using it. The second term echoes the intertemporal costs of using HY. The higher the costs of investing in HY the more probable that the perfect competition will lead to superior outcomes. Here the other effect of  $R$  is noticeable - the lower the  $R$ , the higher the premium for using the HY seeds and the more farmers will want to apply it pushing the share of HY "too high" under perfectly competitive seed markets. Those countervailing effects of  $R$  and the resulting non-monotonicity of welfare in  $R$  is well visible in the simulations.

When approximating, the threshold for using HY,  $m$ , drops out completely from the formula (4). And indeed, graph 2 attests that  $m$  does not play a role in most of the cases.

Within the framework of the derived model, a monopolist on an innovation market may well outperform a perfectly competitive generic industry when the welfare of crop consumers is a major policy objective. On the other hand, the market structure has reversed impact on the well-being of the farmers. Their expected profits drop down with the increased yields and so, depending on the weighting of farmers' versus consumer surplus, the evaluation of market structure may change.<sup>19</sup>

Obviously, monopoly rights give yields to monopoly rents to their owner. However, they are disregarded in the welfare analysis as the monopolist may be foreign-based.

### 3.1.2. *Heterogenous farmers*

The assumption of perfectly competitive market for the production of seeds made in the previous section may seem too strong given high fixed costs associated with offering such seeds. Monopolistic competition seems to be closer to what we observe on such markets. One could argue, that potentially the welfare-superiority of monopoly in the model could be an artefact of that modeling choice with the assumption of price of the measures being equalized to their unit production cost for the generic industry. Therefore, that assumption needs to be relaxed.

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<sup>19</sup>Framer's profits come into being through the scarcity of land.

Besides, when we observe innovations, they are usually marketed not as one homogeneous product but rather as a whole lineup of products (seeds) differing slightly in terms of their maturity time, tolerance for drought etc.<sup>20</sup> This is, at least partly, due to the fact that farmers are endowed with fields varying in terms of the soil fertility, climatic conditions and other features and therefore, some product differentiation (adjustment of the seed to the prevailing conditions) is highly valuable from the perspective of the farmers.

Against this background it occurs that extending the previous model to the Salop's [25] framework could enhance the understanding of the markets. Not only does it allow for incorporating the heterogeneity of the farmers but also it enables some market power of the competitive seed producers. Therefore, the generic industry is modeled in form of monopolistic competition with firms located on the perimeter of the Salop circle supplying horizontally differentiated seeds. All of those seeds have the resistance innovation grafted into them (HY seeds). Inside the circle natural varieties (NV) are available for free - they reflect the existence of "traditional" seeds with no resistance built in against pathogens.

Assume the  $N$  different farmers are located uniformly on a circle<sup>21</sup> according to the qualities of their fields. They aim to obtain one unit of seeds for sowing. They choose among different High-Yielding seeds offered on the circle at price  $p_i$ . Should they decide for one of the HY seeds, they also need to incur the associated adjustment costs,  $T(x) = tx_{ij}$ , where  $x$  denotes the distance between the farmer  $j$  and the chosen seed  $i$ . The distance  $x_{ij}$  could be interpreted as how well adjusted the seed  $i$  is for conditions prevailing at the field of the farmer  $j$ . Farmers can also pick a natural variety that is available inside the circle and has no adjustment costs. Importantly, the choice of the seed affects only the production technology but not the final harvest that is homogenous and sold on a one common market.

In order for our model to generate both farmers who end up purchasing the HY seeds and farmers who choose natural varieties it must be that the sales of perimeter firms takes place in monopoly region of demand curve they face (cf. [25], p. 143) so there will be no consumer indifferent between two different HY seeds. In general this could be generated, e.g. by sufficiently high fixed costs of offering a new HY product. Within our framework this will always be the case due to the endogenously determined value of HY. Figure 3 shows how such a market could look like.

Given that  $L$  different HY seeds are offered the maximum price that the farmer  $j$  located at a distance  $x_{ij}$  from the product  $i$  is willing to pay can be found keeping in mind that the farmer has the option of obtaining natural variety. The maximum price should make him just indifferent between  $HY_i$  and NV and is consequently characterized by the following condition:

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<sup>20</sup>For example Monsanto sells multiple genetically modified corn seeds that are resistant to the herbicide Roundup, among others, Roundup Ready® Corn GA21 and Roundup Ready® Corn NK603.

<sup>21</sup>The perimeter of the circle is normalized to one.

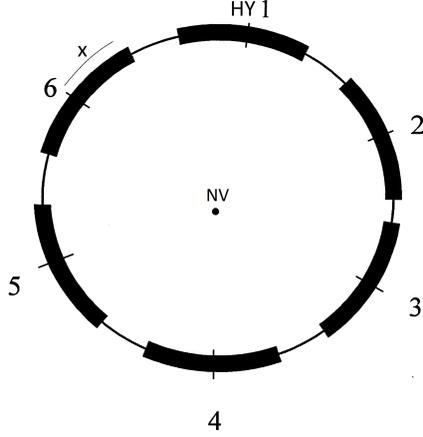


Figure 3: Exemplary Salop circle with 6 different HY products offered whose market shares are indicated with bold arcs. The NV variety is consequently used by  $(1 - 12x)$  percent of the farmers.

$$(1 - \tau)p_{ND}\alpha(1 - R) = tx_{ij} + r(1 + \rho) \quad (5)$$

The probability of the innovation losing efficacy,  $\tau$ , is modeled, as previously, as a linear function of share  $s$  of framers applying the innovation. Assuming that the seeds are symmetric and that the price characterized by the condition 5 is paid by the farmers located at the distance  $x$  from the products, we notice that the share of HY is simply  $s = 2xL$ . Subsequently, plugging in the information about the final demand for the harvest and we rewrite 5 as:

$$r(x, L) = \frac{m - 2Lx}{m(1 + \rho)}(g - \alpha\beta N(R + 2Lx(1 - R)))\alpha(1 - R) - \frac{t}{1 + \rho}x$$

For the producers offering a product necessitates incurring a fixed expense connected to R&D,  $c$  in addition to the products' unit costs  $k$ .

Assume first that the patent for an anti-pathogen innovation is granted to one firm that can offer discretionarily many seeds products based on the patent. The monopolist needs to make two decisions at the same time, namely how many products to choose and how much of the market share should each of the products attract (and, consequently, what pice can be charged for it):

$$\max_{x,L} 2NLx[r(x, L) - k] - cL$$

Given that  $L$  can take only integer values, no closed-form solution exists, however the optimal choices can easily be simulated. Figure 4 summarizes the choice of the monopolist by presenting the share of the market ( $s = 2Lx$ ) that he would choose to serve given different values of  $R$  and  $m$  (and some examples of demand schedules and costs).

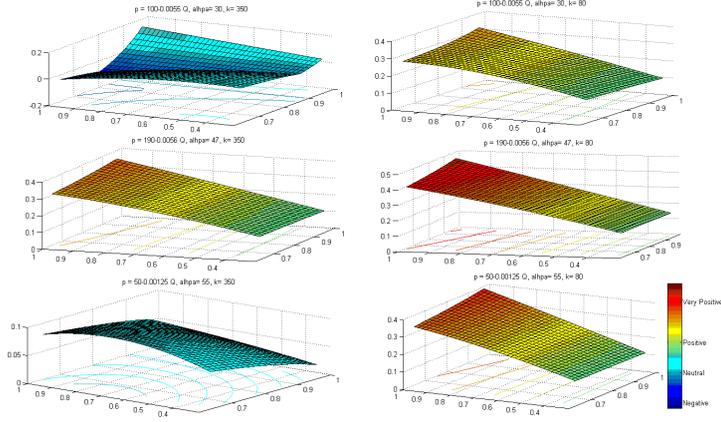


Figure 4: Share of the Salop circle that the monopolist would choose to supply for varying parameters  $R$  and  $m$  (for different demand schedules and costs).

In case when the know-how about the innovation is publicly available, e.g. after a respective patent has expired or after the research results have been made available by public institution, the market can be described as monopolistic competition with the outcome being a subgame perfect Nash equilibrium of a following four stage game:

- Stage one:  $L$  perimeter firms locate equidistantly on the circle, incurring fixed cost of  $c$ .
- stage two: the  $L$  firms choose simultaneously how much market to serve ( $x_i$ ,  $i = 1 \dots L$ ) taking into consideration the existence of freely available natural varieties.
- Stage three: farmers choose the preferred seed given the prices determined by the shares picked by the firms.
- Stage four: harvest takes place with yields dependent on whether or not the innovation kept its efficacy. The harvest is sold on the competitive market to the final consumers at prices determined by the demand schedule:  $p = g - \beta Q$ .

The backward induction analysis starts with the harvest market and farmers' planting decisions. Given that the seed sales are "monopolistic" as discussed previously, the last two stages of the game are summarized by the previously developed condition 5 that characterizes the willingness to pay of the farmers. In the presence of  $(L - 1)$  other perimeter firms but free of direct competition a seed producer solves the following problem:

$$\max_{x_i} 2Nx_i[r(x_i, x_{-i}, L) - k] - c$$

and pick the market share defined implicitly by:

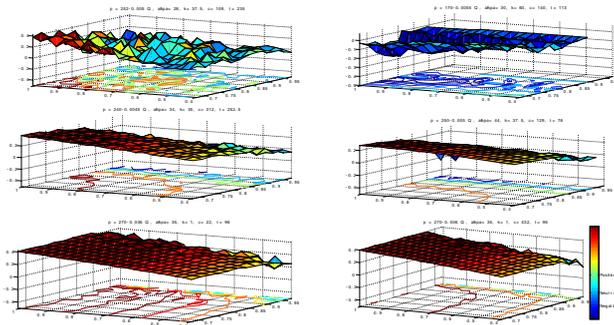


Figure 5: Market outcomes under the monopolistic competition and monopoly regime on the Salop curve.

$$\alpha(1-R)\left(1-\frac{2x}{m}(L+1)\right)(g-\alpha\beta NR) - 2\alpha^2\beta Nx(1-R)^2\left(L+1-\frac{2Lx}{m}(L+2)\right) - 2tx = k.$$

The number of firms,  $L$ , is determined through the condition that a new firm entering the market would make losses.<sup>22</sup> The general pattern is similar to that observed previously but with higher shares. The major difference is also that monopolist offers considerably fewer products but with much higher market shares as he attempts to keep the R&D expenses for individual products low.

To assess the welfare implications of the two regimes we use the difference in distances between the respective shares of HY and the first best (like in formula (3)). Figure 5 presents the results. The bigger the difference (the value from formula (3)), the more red the colour. With decreasing difference, the color turns to blue.

As previously, the costs play a crucial role.

**Corollary 3.** *In presence of (relatively low) unit and R&D fixed costs, generic industry overly pushes the share of innovative seeds decreasing therefore their expected efficacy (and value) below the social optimum.*

Monopolist restricts the supply of HY products below the first best, but the expected consumer surplus is higher than in presence of competition.

The additional welfare aspect that is not present with homogenous farmers is are the different profits made by various farmers depending on their location on the circle, especially on whether they are close to the one of the products (within the distance  $x_{ij} < x$  for some  $i$ ). The total sum of extra profits that farmers obtaining HY make is given by  $\frac{1}{2}Ltx^2$ . Whenever consumer surplus / food security are not the only policy goals, they could be considered in the analysis. The observation made previously that monopoly tends to choose higher  $x$  combined with higher expected harvest under monopoly regime

<sup>22</sup>Due to the discrete number of firms it may be that the firms already located on the circle make some (relatively modest) profits.

indicates that not only the sum of extra profits made changes but also there will be some strong redistributive effects between the farmers.

### 3.2. Dynamic model

The previous subchapter has shown what the market outcomes would be if the HY seeds would be used for one season only. The interesting questions arise, however, when we consider how the efficacy of the innovation is preserved over time. In particular, the question of optimal patent length is a crucial one. Assume therefore that an anti-pest innovation can be applied in every period as long as its efficacy has not been broken. Once the pest have developed the resistance, though, the innovation becomes obsolete forever.<sup>23</sup>

#### 3.2.1. Homogenous farmers

Firstly, it can be easily noticed that both the behaviour of the generic industry and the farmers is not affected by imposing the dynamic structure and so the condition (2) is still valid. Consequently, the market share of HY fields would not change ( $s_{t=1}^{PC} = \dots = s_{t=T}^{PC} = s_s^{PC}$ ). The maximization problem alters for a monopolist who was granted monopoly rights for  $T$  years. The possibility of the innovation losing efficacy not only decreases the willingness to pay of the farmers but also leads to possible foregone profits in the consecutive years  $T - t$  years - once the efficacy is lost, the innovation loses its value forever. That implies that the monopolist will become more conservative in his decisions on the amount of HY products sold in all the periods for which he has the patent right but the last one:  $s_t^{M(T)} \leq s_s^{M(T)}$  for  $t < T$ . In the last period,  $T$ , the monopolist's behaviour does not influence his future profits anymore as the production will be taken over by a generic industry. Therefore he will behave myopically as if he was facing a static problem (with  $s_{t=T}^{M(T)} = s_s^M$ ).

Formally, the monopolist maximizes his expected profits of the form:

$$\max_{\{s\}_{i=1}^T} (r(s_1) - k)Ns_1 + \sum_{t=2}^T \beta^t (r(s_t) - k)Ns_t \prod_{i=1}^{t-1} \left(1 - \frac{s_i}{m}\right) \quad (6)$$

and the exact path chosen can be pinned down with the help of  $T$  first order conditions of the form:

$$r'(s_t^{M(T)})s_t^{M(T)} + r(s_t^{M(T)}) = k + \frac{\beta}{m}F_t,$$

where  $F_t$  are the expected future profits of the monopolist (conditional on the innovation preserving its efficacy at least till period  $t + 1$ ). In the period when the patent

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<sup>23</sup>It was also checked what would change upon assuming that after the resistance is developed, a new HY innovation (with exactly the same properties as the existing one) is brought to the market. That new innovation entails a high fixed costs that the society needs to cover (e.g. due to R&D costs and the costs of technology change). Such assumption does not change implications of the analysis qualitatively. However, it complicates the calculations a lot so for the sake of brevity it is not shown here.

expires, the policy is identical with that of a static monopolist,  $s_s^M$ , as  $F_T = 0$ . In case of sufficiently long patent time, the monopolist chooses a certain steady state share,  $s^{M(\infty)}$  (a share that we would choose if the patent right was given forever) for most of the time and within the last periods adjusts quicker and quicker to the static share,  $s_s^M$ .

How do the paths of production under the different regimes affect the harvest and the consumers? If there would be no innovation in place, the harvest would stay forever at the level of  $NR\alpha$ . With the effective innovation, the farmers who employ it do not lose their harvest to pests and gather additional  $(1 - R)$  of crop from their fields which with probability  $(1 - \frac{s_t}{m})$ . This translates into the total harvest increasing in expectations by  $(1 - R)s_t\alpha N(1 - \frac{s_t}{m})$ . We maintain the view developed in subsection 3.1.1 that whenever the monopolist regime leads to higher expected harvest, it will be preferred by the consumer. Assuming that the consumer discounts the harvest consumption between periods at  $\gamma$ , the modified condition (3) for superiority of monopoly form the viewpoint of consumers reads now (derivations are given in the appendix):

$$\sum_{t=1}^T \gamma^{t-1} [s_t^{M(T)} \prod_{i=1}^t (1 - \frac{s_i^{M(T)}}{m}) - s^{PC} (1 - \frac{s^{PC}}{m})^t] + [\prod_{i=1}^T (1 - \frac{s_i^{M(T)}}{m}) - (1 - \frac{s^{PC}}{m})^T] s^{PC} \sum_{t=T+1}^{\infty} \gamma^{t-1} (1 - \frac{s^{PC}}{m})^{t-T} \geq 0 \quad (7)$$

The first element compares the harvest outcomes before the expiration of the patent. The sign of it depends on the parameters of the system and  $T$ , e.g. for zero-unit cost of innovation, the first term would be positive. The second element, on the other hand, is always positive - it reflects the benefits of higher chances of efficacy being preserved beyond the assigned monopoly right time,  $T$ .

Whereas the farmers' choices and the outcome of perfectly competitive market do not hinge on the number of periods considered, the monopolist's behaviour will be strongly affected by it. His sales strategy will become more conservative when the number of operating periods increases as he will consider additional the potential future profits lost when the resistance is broken. Therefore manipulations of the length of the patent change the expected welfare outcomes for the consumer and the measure of welfare superiority introduced in condition (7). The longer the patent period, the higher the potential underprovision in the first periods. On the one hand, once the resistance among pests appears, the innovation loses its efficacy forever. With a very short patent time it can well be that the monopolist chooses innovation quantity above the optimum,  $s_t^{M(T)} > s^*$ , as he has no incentives to internalize the future periods' outcomes. Should it be the case that in the first period the monopolist produces "too much",  $s_1^{M(T)} > s^*$ , for some patent length  $T$ , than we can be certain that in such an economy the monopolist can improve welfare compared to generic industries. For such cases, prolonging the monopoly brings the economy closer to the first best. If the monopolist is too restrictive from the very beginning, i.e.  $s_1^{M(T)} < s^*$  for some analyzed period length,  $T \in [1, \infty)$ , it may still be welfare-enhancing to lengthen the patent if that difference is relatively low.

On the other hand, were the patent granted forever, the monopolist would surely put the supply level in all periods below the socially optimal levels,  $s_t^*$ . It must be,

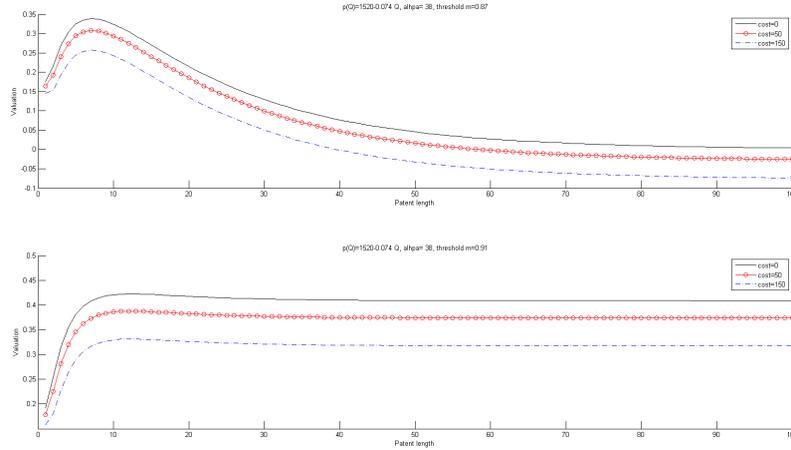


Figure 6: Examples for dependence between welfare superiority of monopoly as measured by condition (7) and increasing length of the patent.

consequently, that beyond some patent length,  $T^*$ , the welfare decreases.

**Corollary 4.** *The monopolist can be welfare-superior if and only if granting a patent for one period would improve the outcome for consumers compared to having no monopolists at all.*

Corollary 4 is based on the observation that with increasing the patent length, the monopolist becomes more and more conservative in the first periods. Therefore, if for one period patent the monopolist produces "too little",  $|s_1^{M(1)} - s^*| > |s^{PC} - s^*|$ , extending the patent length can only increase the consumers' welfare losses.

**Corollary 5.** *If having a monopolist can ever be welfare-superior policy (conditional on an innovation having been made), there exist a patent length,  $T^* \in [1, \infty)$ , below which the consumer welfare (weakly) increases with increasing  $T$ . Beyond that point, the welfare will (weakly) decrease with  $T$ .*

Figure 6 illustrates the predictions.

Now, assume that creating a new anti-pest measure is a stochastic process whereby both the timing and the exact cost of innovation are unknown *ex ante*, only the expected costs,  $F$ , and expected time,  $t^{inn}$  are given. No company will ever want to innovate unless patents of length  $T \geq T^{MIN}(F, t^{inn})$  are granted, where  $T^{MIN}$  is the minimum time span that would allow them to recover their R&D costs. The standard economic prescription would be to issue patents for a period of  $T^{MIN}$  and allow the generic industry to take over the market afterwards. However, when negative externalities arise from the application of the new measures, the monopoly rights may also improve efficacy. In combination with corollary 5, assuming that no public provision of anti-pest measures is possible we get that:

**Corollary 6.** *To maximize the welfare of the consumers, the policymaker would choose  $T^*$  as the patent length whenever  $T^* \geq T^{MIN}(F, t^{inn})$  and  $T^{MIN}(F, t^{inn})$  otherwise.*

Obviously, the welfare outcomes could be much higher if the policymaker was able to re-grant or prolong the patent without the monopolist having expected it.<sup>24</sup> In that case, it would be optimal to always assign  $T^{R*} \leq T^*$  years of monopoly rights and always renew it after a passage of one year. The  $T^{R*}$  would be chosen to minimize:

$$\min_{T^{R*}} |s_1^{M(T^{R*})} - s^*|.$$

However, since such a solution is rather unpracticable (especially the firms not expecting the prolongation), it is not discussed here further.

### 3.2.2. Heterogenous farmers

The preferred specification of the model investigates the optimal length of the patent when after its expiry a generic industry in a form of monopolistic competition takes over.

Again, the dynamic character of the new situation does not affect the decisions of the farmers. For the competitive monopolists firms there would be no change either - all of them would incur the R&D costs in the first period and operate in the market as long as the innovation does not lose its efficacy.

From the monopolist's view the decision is much more complex compared to static version. For example, when deciding about the timing of the R&D costs, the future benefit from an additional product<sup>25</sup> need to be balanced against the increased probability of losing the future profits due to the innovation losing its efficacy.

[Results here]

## 4. Discussion and extensions

The above presented results suggest that monopolies may play a positive role in increasing welfare while preventing the tragedy of the commons. Obviously, the monopolist can never reach the first-best. Besides, the concerns mount concerning the role that such anti-pest measures providers (mostly seed producers) play given the huge market power they have gained across different markets.<sup>26</sup>

Possibly as a consequence of that some voices arise that clamour for public provision of innovation. Assuming that the state is as efficient in providing innovation as the private firms, that the marginal costs of public funds are relatively low and that the

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<sup>24</sup>The possibility of a patent scheme where patent duration is based on resistance levels (for antibiotics) is discussed, among others, by [21].

<sup>25</sup>If R&D  $cL_1$  expenses were incurred in period one, in the next period the monopolist will be already able to offer  $L_1 + L_2$  products while incurring the cost of  $cL_2$  only.

<sup>26</sup>An EU report [7] estimates that in 2012 the world's top three corporations (Monsanto, DuPont, Syngenta) controlled almost half (44.5%) of the world's commercial seed market. Some sub-industries exhibit even stronger concentration, e.g. in U.S. Monsanto aimed in 2013 at 40% share in the corn market.[1]

social planner is able to manage the usage of the innovation freely, the first-best could be reached.

However, it seems that execution of the management of the publicly provided innovations tends not to be performed optimally. For example, the seeds for virus-resistant papaya that was developed within a cooperation of universities as a response to Papaya Ringspot Virus outbreak in Hawaii<sup>27</sup> were given to farmers for free for some time (afterwards, a low fee was introduced).<sup>28</sup> We can safely assume that such a provision schedule is similar to what would be the case for competitive industry.<sup>29</sup>

Similarly, if the innovation was provided as a publicly available know-how, we could expect a direct emergence of a generic industry.<sup>30</sup>

In both cases, the problems of the tragedy of the commons problem are implied and possibly incentivising the private provision through proper monopoly rights could improve the welfare.

Unfortunately, the model shown here discards genetic underpinnings of the of the resistance spread and the spatial aspects of it. Grafting the epidemiological content (SIS-model) would partly overcome that shortcoming. It seems, though, that extending the model accordingly would not change the insights dramatically but rather decrease the tractability even more and introduce additional parameters. Nevertheless, it is intended as the next step of the study.

## 5. Conclusions

This paper stresses the perishability of anti-pathogen innovations due to their common pool character and points to the effects of market structure on it. The study brings forward the argument that monopolies may enhance consumer welfare by preserving the functioning of the harvest boosting innovations. The derived models of interconnected seed and harvest markets show how this effect depends on ecological and market parameters, especially the cost structure. The positive effect of monopoly seem to prevail for a large spectrum of conceivable parameter values. Consequently, manipulations of patent lengths can improve welfare.

The strategy to use related markets to affect some certain market could be well applied to other issues for which no easy solutions have been found. One example would be overfishing, especially that performed with the help of the huge fishing trawlers. As

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<sup>27</sup>Papaya is the second most important commercial crop in Hawaii and the Hawaiian production accounts for virtually all the commercial US papaya market. The PRV is very damaging. As Gonsalves [13] puts it: "When infected at the seedling stage or within two months after planting, trees do not normally produce mature fruit. Production of fruit by trees infected at progressively later stages is severely reduced and of poor quality".

<sup>28</sup>The problem of Papaya Ringspot Virus and the subsequent development of the disease-resistant papaya has been well described by D. Gonsales and coauthors (among others in [13] and [12]).

<sup>29</sup>Possibly, such a sub-optimality stems from the common expectation that no market power should be used for products whose development costs were paid from public money.

<sup>30</sup>Such a provision of know-how is expected for the research on coffee rust that plagues the coffee plantages.

the vessels are usually produced in few major countries, some coordination on the supply of the trawlers could be possible that would (at least temporarily) decrease the pressure on the fish stock.

## References

- [1] Agrimoney.com. Monsanto Lifts Profits Guidance as Corn Sales Soar, 2013.
- [2] A H. Barnett. The Pigouvian Tax Rule under Monopoly. *American Economic Review*, 70(5):1037–1041, 1980.
- [3] William A Brock and Anastasios Xepapadeas. Valuing Biodiversity from an Economic Perspective : A Unified Economic , Ecological , and Genetic Approach. *The American Economic Review*, 93:1597–1614, 2003.
- [4] James M . Buchanan. External Diseconomies, Corrective Taxes, and Market Structure. *The American Economic Review*, 59(1):174–177, 1969.
- [5] H N Comins. The management of pesticide resistance. *Journal of Theoretical Biology*, 65:399–420, 1977.
- [6] Hugh Comins. Analytic Methods for the Management of Pesticide Resistance. *Journal of Theoretical Biology*, 77:171–188, 1979.
- [7] European Comission. Proposal for a Regulation of the European Parliment and of the Council on the Production and Making Available on the Market of Plant Reproductive Material (Plant Reproductive Material Law), 2013.
- [8] Daniel Cressy. Coffee rust regains foothold Researchers marshal technology in bid to thwart fungal outbreak in Central America . *Nature*, 493:587, 2013.
- [9] Sanyasi Dhurua and Govind T. Gujar. Field-Evolved Resistance to Bt Toxin Cry1Ac in the Pink Bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae), from India. *Pest Management Science*, 67:898–903, 2011.
- [10] Carolyn Fischer and Ramanan Laxminarayan. Sequential development and exploitation of an exhaustible resource: do monopoly rights promote conservation? *Journal of Environmental Economics and Management*, 49:500–515, 2005.
- [11] Timo Goeschl and Timothy Swanson. Pests, plagues, and patents. *Journal of the European Economic Association*, 1:561–575, 2003.
- [12] C Gonsalves, D R Lee, and D Gonsalves. The Adoption of Genetically Modified Papaya in Hawaii and its implications for Developing Countries The Adoption of Genetically Modified Papaya in Hawaii and Its Implications for Developing Countries. *Journal of Development Studies*, 43:177–191, 2007.

- [13] Dennis Gonsalves. Control of Papaya Ringspot Virus in Papaya: A Case Study. *Annual Review of Phytopathology*, 36:415–437, 1998.
- [14] Michael E. Gray, Thomas W. Sappington, Nicholas J. Miller, Joachim Moeser, and Martin O. Bohn. Adaptation and Invasiveness of Western Corn Rootworm: Intensifying Research on a Worsening Pest. *Annual Review of Entomology*, 54:303–321, 2009.
- [15] Garrett Hardin. The Tragedy of the Commons. *Science*, 162:1243–1248, 1968.
- [16] Geoffrey Heal, Brian Walker, Simon Levin, Kenneth Arrow, Partha Dasgupta, Gretchen Daily, Paul Ehrlich, Karl-Goran Maler, Nils Kautsky, Jane Lubchenco, Steve Schneider, and David Starrett. Genetic diversity and interdependent crop choices in agriculture. *Resource and Energy Economics*, 26:175–184, 2004.
- [17] Markus Herrmann. Monopoly pricing of an antibiotic subject to bacterial resistance. *Journal of Health Economics*, 29:137–150, 2010.
- [18] Markus Herrmann and Gérard Gaudet. The economic dynamics of antibiotic efficacy under open access. *Journal of Environmental Economics and Management*, 57:334–350, 2009.
- [19] Markus Herrmann, Bruno Nkuiya, and Anne Renée Dussault. Innovation and antibiotic use within antibiotic classes: Market incentives and economic instruments. *Resource and Energy Economics*, 35:582–598, 2013.
- [20] Donald A. Levin. The University of Chicago Pest Pressure and Recombination Systems in Plants. *The American Naturalist*, 109:437–451, 1975.
- [21] Stephane Mechoulan. Market Structure and Communicable Diseases. *Canadian Journal of Economics*, 40:468–492, 2007.
- [22] C C Mundt. Use of Multiline Cultivars and Cultivar Mixtures for Disease Management. *Annual Review of Phytopathology*, 40:381–410, 2002.
- [23] Alistair Munro. Monopolization and the Regulation of Genetically Modified Crops: an Economic Model. *Environment and Development Economics*, 8:167–186, 2003.
- [24] E. C. Oerke and H. W. Dehne. Safeguarding Production - Losses in Major Crops and the Role of Crop Protection. *Crop Protection*, 23:275–285, 2004.
- [25] Steven C Salop. Monopolistic Competition with Outside Goods. *The Bell Journal of Economics*, 10:141–156, 1979.
- [26] Edward E. Schlee. Surplus maximization and optimality. *American Economic Review*, 103(6):2585–2611, 2013.

- [27] Lambert Schoonbeek and Frans P. de Vries. Environmental taxes and industry monopolization. *Journal of Regulatory Economics*, 36(1):94–106, 2009.
- [28] A. J. Ullstrup. The Impacts of the Southern Corn Leaf Blight Epidemics of 1970–1971. *Annual Review of Phytopathology*, 10:37–50, 1972.
- [29] Martin L. Weitzman. Economic Profitability Versus Ecological Entropy. *Quarterly Journal of Economics*, 115:237–263, 2000.

## 6. Appendix

The exact optimality condition in the formula (3) is given by:

$$\left| \frac{m}{2} - \frac{1}{3N\alpha\beta(1-R)} \left( -\sqrt{\frac{g - N\alpha\beta(R - m + Rm)}{g^2 + N^2R\alpha^2\beta^2(R - Rm + m) + N^2m^2\alpha^2\beta^2(1 - R)^2 - N\alpha\beta(2R + m - Rm) + 3Nkm\beta(1 + \rho)}} \right) \right| \leq \left| \frac{m}{2} - \frac{1}{2N\alpha\beta(1-R)} \left( -\sqrt{\frac{g - N\alpha\beta(R - m + Rm)}{g^2 + N^2R^2\alpha^2\beta^2(1 - m)^2 + mN^2\alpha^2\beta^2(m - 2mR + 2R) - 2N\alpha\beta(R + m - Rm) + 4Nkm\beta(1 + \rho)}} \right) \right|$$

The derivations for condition (7):

A regime  $W$  that gives rise to innovations shares of  $\{s_t^W\}_{t=1}^{t=\infty}$  will lead to the following expected harvest:

$$\begin{aligned} E(H^W) &= NR\alpha + s_1^W\alpha(1-R)N\left(1 - \frac{s_1^W}{m}\right) + \gamma NR\alpha + \gamma s_2^W\alpha(1-R)N\left(1 - \frac{s_1^W}{m}\right)\left(1 - \frac{s_2^W}{m}\right) \\ &\quad + \gamma^2 NR\alpha + \gamma^2 s_3^W\alpha(1-R)N\left(1 - \frac{s_1^W}{m}\right)\left(1 - \frac{s_2^W}{m}\right)\left(1 - \frac{s_3^W}{m}\right) + \dots \\ &= E(H^{NI}) + \alpha N(1-R) \sum_{t=1}^{\infty} \gamma^{t-1} s_t^W \prod_{i=1}^t \left(1 - \frac{s_i^W}{m}\right) \end{aligned}$$

where  $E(H^{NI})$  denotes the harvest that would be achieved without the innovation. For every year in which the innovation is preserved, the additional harvest due to the protection from the pests is:  $s_t^W\alpha(1-R)$  - on the fields where the innovation is applied, no harvest is lost to the pests and so  $\alpha(1-R)$  is kept that otherwise be lost. The probability of the innovation preserving its effectiveness is independent between every period and, conditional on being preserved up to the period  $t$ , the chance that its efficacy will be kept in period  $t$  as well is  $(1 - \frac{s_t^W}{m})$ . Unconditional probability is therefore given by  $\prod_{i=1}^t (1 - \frac{s_i^W}{m})$ .

Monopolist who was assigned a patent for  $T$  years (after which the generic industry takes over) produces higher expected harvest than generic industry provided that:

$$\alpha(1 - R) \sum_{t=1}^{\infty} \gamma^{t-1} s_t^M \prod_{i=1}^t \left(1 - \frac{s_i^M}{m}\right) > \alpha(1 - R) \sum_{t=1}^{\infty} \gamma^{t-1} s_t^{PC} \prod_{i=1}^t \left(1 - \frac{s_i^{PC}}{m}\right)$$

Knowing that the outcome of the generic industry,  $s_t^{PC}$ , is constant over time we can simplify the left-hand side significantly. The RHS can be transformed to reflect the expectation that under "monopoly regime" after  $T$  periods, a generic industry will take over the production:

$$\sum_{t=1}^T \gamma^{t-1} s_t^M \prod_{i=1}^t \left(1 - \frac{s_i^M}{m}\right) + \sum_{t=T+1}^{\infty} \gamma^{t-1} s^{PC} \prod_{i=T+1}^t \left(1 - \frac{s^{PC}}{m}\right) \prod_{i=1}^T \left(1 - \frac{s_i^M}{m}\right) > \sum_{t=1}^{\infty} \gamma^{t-1} s^{PC} \left(1 - \frac{s^{PC}}{m}\right)^t$$

This can be further simplified to get:

$$\sum_{t=1}^T \gamma^{t-1} \left[ s_t^M \prod_{i=1}^t \left(1 - \frac{s_i^M}{m}\right) - s^{PC} \left(1 - \frac{s^{PC}}{m}\right)^t \right] + \left[ \prod_{i=1}^T \left(1 - \frac{s_i^M}{m}\right) - \left(1 - \frac{s^{PC}}{m}\right)^T \right] \sum_{t=T+1}^{\infty} \gamma^{t-1} s^{PC} \left(1 - \frac{s^{PC}}{m}\right)^{t-T} > 0$$