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# Plant Breeders' Rights, Patents, and Incentives to Innovate

Adrien Hervouet and Corinne Langinier

Both patents and Plant Breeders' Rights (PBRs) can protect plant innovations. Unlike patents, PBRs allow farmers to save part of their harvest to replant. We analyze the impact of this exemption on prices and innovation in a monopoly setting. In a PBR regime, a monopolist might let farmers self-produce, and he over- or under-invests compared to socially optimal investments. Under a PBR and patent regime, large (small) innovations are more likely to be patented (protected with PBRs), but self-production is not completely prevented, private investments are often socially optimal, and incentives to innovate are boosted. However, overall effects on welfare are ambiguous.

*Key words:* durable good, innovation, patents, plant breeders' rights, seed saving

Before the twentieth century, varietal creations were obtained by conventional plant breeding: Farmers would save part of their harvest (the best-looking seeds) to plant for the next year. Today, private companies (e.g., Monsanto or Pioneer) develop new varieties of crops that provide higher yields for farmers or lower environmental threats (e.g., reduce pest or diseases). However, because crops self-reproduce, the output of crop research is nonexcludable. If it is not explicitly forbidden,<sup>1</sup> farmers can save part of their harvest to self-produce because seed traits remain unchanged after several harvesting periods. Therefore, seed saving has an impact on pricing strategies and seed producers' incentives to innovate.

As farmers can save seed for the next period, seed varieties can be seen as durable goods (Coase, 1972; Bulow, 1982; Waldman, 2003). A producer can make the seed durable by choosing prices such that farmers buy the seed once and self-produce in the next periods, or he can choose prices such that farmers buy during each period (Ambec, Langinier, and Lemarié, 2008). Thus, depending on the pricing strategy, seeds may or may not be durable goods.

As seed saving decreases the seed producer's innovation appropriation, his incentive to invest in innovation is altered. To address this "public" good issue, a certain level of appropriation is needed for firms to innovate. Without intellectual property rights (IPRs) that allow the establishment of necessary appropriation for private creation (Scotchmer, 2004), there is a lack of private incentives to innovate. IPRs provide a temporary monopoly power to innovators, which leads to a static welfare loss necessary from a dynamic perspective (Menell and Scotchmer, 2005).

Once a producer has developed a new crop variety, he can protect his innovation with a patent or a Plant Breeders' Right (PBR).<sup>2</sup> Many countries (e.g., Canada, France) do not allow innovators

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<sup>1</sup> Through a contract or because the crop is sterile due, for instance, to genetic modification.

<sup>2</sup> The Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) allows members of the World Trade Organization (WTO) to protect innovation in living organisms. PBR (also called Plant Variety Right, PVR) is a *sui generis* system, a unique (stand-alone) system for living organisms.

**Table 1. IPRs, Self-Production and Royalty for Different Countries**

|           | PBR/Patent | Self-Production   | Royalty |
|-----------|------------|-------------------|---------|
| Australia | both       | 90% (small grain) | Royalty |
| U.S.      | both       | 66% (wheat)       | –       |
| Argentina | PBR        | 40% (wheat)       | Royalty |
| Canada    | PBR        | 80% (wheat)       | Pending |
| Germany   | PBR        | 57% (cereals)     | Royalty |
| U.K.      | PBR        | 42%               | Royalty |
| France    | PBR        | 49% (wheat)       | Royalty |

to patent their plant varieties; only PBRs can be used. Other countries (e.g., the United States, Japan, Australia), allow patent and PBR systems to coexist;<sup>3</sup> firms protect their plant innovations with patents and PBRs.<sup>4</sup> These two types of property rights have some similarities but also major differences (for details see Lesser, 1999, 2000; Louwaars et al., 2005; Trommetter, 2008).

For an innovation to be granted a patent, the main criteria are novelty and nonobviousness. A patent involves exclusive rights to make, use, sell, and distribute the invention. In the United States, asexual reproductions of plants have been patentable since 1930 under the Plant Patent Act (PPA), while inventors have been able to obtain PBRs for other plants since 1970 under the Plant Variety Protection Act (PVPA). Moreover, U.S. Supreme Court decisions in 1980 and 2001 enable seed producers to patent new varieties (either asexual or sexual) using a utility patent.<sup>5</sup>

The current PBR system was established in 1961 by the International Union for the Protection of New Varieties of Plants (UPOV) to homogenize internationally the protection of seed varieties. The main requirements for PBRs are novelty and the Distinction, Uniformity and Stability (DUS) Test. A PBR involves exclusive rights similar to those granted by a patent, with two notable exceptions: (i) private research with commercial purposes and (ii) seed saving.

The first exemption, called the “research exemption,” allows another producer to use proprietary seeds to create and commercialize a new variety without any agreement or license on the first varieties. The second exemption, called the “farmers’ exemption,” allows a farmer to save part of his harvest to sow for the next period, even if the variety is the property of a producer (farmers cannot resell protected seeds). Producers can reduce the attractiveness of self-production by producing hybrid seeds because saving them involves a high yield loss. However, hybrid seeds are not yet well developed for some species (e.g., wheat). As a result, 40%–70% of wheat seeds worldwide come from seed saving (see table 1, based on Curtis and Nilsson, 2012).

As the standards for obtaining a patent are supposedly higher and given these major exemptions, the PBR system can be seen as weaker than the patent system. It is also cheaper to obtain a PBR than a patent (Wright et al., 2007). In 2016, a U.S. patent (renewed for 20 years) cost approximately \$15,160, compared to \$5,150 to obtain a PBR.<sup>6</sup>

Furthermore, in countries that are members of UPOV, self-producing farmers must compensate producers for the incurred loss by paying a royalty fee on farm-saved seed (FSS) to comply with its

<sup>3</sup> These are called “utility patents” in the United States and Japan and “standard patents” in Australia. Patenting a seed variety in Australia and Japan is relatively rare due to strong patent requirements.

<sup>4</sup> Since 1998, Monsanto has obtained 148 PBRs and 45 patents on wheat varieties, and 555 PBRs and 1,543 patents on maize varieties. Meanwhile, Pioneer Hi-Bred has obtained 116 PBRs and 106 patents on wheat varieties and 765 PBRs and 1946 patents on maize varieties (USPTO and UPOV websites).

<sup>5</sup> *Diamond v. Chakrabarty* in 1980 on patenting micro-organisms (see <http://caselaw.findlaw.com/us-supreme-court/447/303.html>) and *J.E.M. Ag Supply, Inc. v. Pioneer Hi-Bred International, Inc.* in 2001 (see <http://caselaw.findlaw.com/us-supreme-court/534/124.html>).

<sup>6</sup> In 2016, a patent from EPO cost (at least) €28,540, and a PBR cost €7,180 (EPO, USPTO, USDA websites). See Appendix A and appendix table A1 for a detailed description of patenting and PBR costs.

most recent version, UPOV-91.<sup>7</sup> Table 1 summarizes the system in place in several countries, the reported percentage of self-production, and the different methods of compensation.

Even though both the research and the farmers' exemptions are likely to have an impact on the functioning of seed markets, we focus solely on the farmers' exemption (i.e., competition from farmers) in order to disentangle the channels through which incentives to innovate are affected.

Our contribution addresses three sets of related research questions: (i) In a system in which only PBRs are allowed (similar to Canada or France, called hereafter a "PBR regime"), what is the pricing strategy of a seed producer who faces competition from farmers? How does this pricing strategy affect his decision to invest in innovation? What is the impact of a self-producing royalty fee on the investment? Compared to what would be socially optimal, does the seed producer over- or under-invest? (ii) In a system in which both PBRs and patents are allowed (similar to the United States, called a "PBR and patent regime"), what is the seed producer's IPR choice? How will this choice affect the pricing strategy? For what kind of innovation is a PBR preferred to a patent? How does this choice affect the investment? Does the seed producer over- or under-invest? (iii) The third set of questions is related to policy issues. What is the impact of having a PBR regime or a PBR and patent regime on the incentive to innovate? What is the impact on total welfare? How would the European system be affected if seed producers were allowed to patent their innovations? What policy tools can be used to provide incentives to innovate?

To investigate the impact of the farmers' exemption on seed prices and innovation, we consider a monopoly setting in which farmers buy seeds or use their own saved seed (if allowed), in which case they pay a royalty fee on self-production (if it exists) to the producer. At the outset, the producer invests in a seed innovation. Once a (large or small) innovation has been discovered, he chooses to protect it with a PBR or a patent (if available) and chooses prices for two periods.<sup>8</sup> If protected by a costly patent, the innovation cannot be replanted by farmers, because self-production is prohibited. This is the main difference between patents and PBRs: A patent is costlier, but it prevents self-production.

If only PBRs are available, depending on the royalty fee and the productivity of self-producing farmers, the producer adopts different pricing strategies (Ambec, Langinier, and Lemarié, 2008): either a "durable good" strategy, in which farmers self-produce in the second period, or a "nondurable good" one, which makes self-producing not attractive to farmers. In the former case, the producer sets a high second-period price, such that farmers self-produce, and captures the farmers' surplus with an appropriate first-period price. In the latter case, he sets the second-period price such that farmers buy rather than self-produce. The producer's pricing strategies affect his investment decision. When he uses a durable (nondurable) good strategy for a large (small) innovation, he has more to gain from a large innovation than farmers do, and he over-invests compared to what is socially optimal. When farmers gain more from a large innovation than the producer does (with nondurable good strategies), he under-invests.

If both PBRs and patents are available, the producer can adopt a patenting strategy to prevent self-producing. However, because patenting is costly, he also uses PBRs and, thus, patenting does not completely eliminate self-production. Nevertheless, when patenting prevents self-production, the socially optimal investment level is restored. The producer invests more often at a suboptimal level under a PBR regime rather than under a PBR and patent regime, but the effect of having both PBRs and patents on total welfare is ambiguous. An inappropriate royalty fee level might result in a decrease in welfare and lead to an inefficient investment level. Furthermore, each IPR system seems

<sup>7</sup> In France, an interprofessional agreement established in 2001 between farmers and seed companies led to the creation of a fee paid by a farmer when he sells his output. If he buys the seed from the seed producer (and does not self-produce), the fee is refunded. In Australia, the seed producer can choose the royalties on FSS (based on the farmers' production) at the same level as the royalties on commercialized seed varieties.

<sup>8</sup> We assume that the seed producer commits on prices. When the time lag between the harvest and the planting is short, farmers can save seed and decide whether to use it after observing prices. This would be the case for winter wheat in France: Harvest occurs in summer and the sowing occurs during the fall (Ambec, Langinier, and Lemarié, 2008).

to play a specific role: Large (small) innovations are more likely to be protected with patents (PBRs), consistent with Moschini and Yerokhin's (2008) findings while considering the research exemption.

Within the abundant literature on PBRs, empirical contributions find that introducing PBRs has a small positive impact on agricultural productivity growth (Naseem, Oehmke, and Schimmelpfennig, 2005; Carew, Smith, and Grant, 2009) and only a few PBRs are valuable (Srinivasan, 2012).<sup>9</sup> It is, however, not clear who benefits the most from PBRs and whether PBRs enhance or reduce incentives to innovate.<sup>10</sup>

Theoretical contributions study the impact of the two exemptions. Due to the research exemption, a PBR can be preferred to a patent for low research costs (Moschini and Yerokhin, 2008; Lence et al., 2015; Baudry and Hervouet, 2016), even though the research exemption tends to decrease the incentive of the first innovators to innovate (Nagaoka and Aoki, 2009).<sup>11</sup>

Our contribution is related to the stream of literature on the farmers' exemption. In a theoretical model of intertemporal pricing with different farmers' characteristics (myopic or not) and producers' pricing decisions (commitment or not), Perrin and Fulginiti (2008) compare different IPR systems and find that producers prefer the patent system to avoid the Coase conjecture (they will exhaust their rent as prices decline over time), whereas society and farmers prefer the PBR system. Moreover, due to the durable-good nature of seeds, producers might prefer to introduce hybrid seed (nondurable goods) even if it is less efficient.<sup>12</sup> If they can *ex ante* commit on prices, they adopt different pricing strategies to sell their seed as a durable good or not (Ambec, Langinier, and Lemarié, 2008). Consistent with this, Hansen and Knudson (1996) find statistically significant evidence that producers capture some of the benefits from FSS by pricing accordingly. Hence, the farmers' exemption does not necessarily decrease the incentive to innovate. The innovation stage has been introduced in Galushko (2008), who finds that a patent system seems preferable to a PBR system, unless the seed producer's marginal cost exceeds the farmers' reproduction cost (i.e., it is more efficient to let farmers self-produce). This latter contribution does not account for royalty fees on self-production, which we also analyze.

### The Model

We consider a three-period model ( $t = 0, 1, 2$ ) with two types of agents: a seed producer and risk-neutral farmers. In period zero, the seed producer invests  $I$  to discover a seed innovation that will increase farmers' productivity. The innovation is either large,  $\bar{\theta}$ , with probability  $\mu(I)$  or small,  $\underline{\theta}$ , with probability  $(1 - \mu(I))$ , where  $\mu'(I) > 0$ ,  $\mu''(I) < 0$  and  $\mu(0) = 0$ .<sup>13</sup>

Once the innovation has been discovered, the seed producer decides how to protect it: with a PBR or a patent (if it is available). With a patent, farmers are prohibited from self-producing, whereas with a PBR, they are allowed to re-use the seed as they see it fit. Thus, depending on the IPR method used, farmers can self-produce or not. Furthermore, patenting and PBR costs differ: The patenting cost is  $c_P > 0$ , whereas it is normalized to 0 for a PBR.

Once the seed producer introduces his protected innovation on the market, he produces it at zero marginal cost and faces a continuum of farmers of mass 1. Each farmer buys 0 or 1 units of seed

<sup>9</sup> This is consistent with findings about patent values in the patent literature (Schankerman and Pakes, 1986). See Wright et al. (2007) for an overview about agricultural innovations.

<sup>10</sup> According to Moschini, Lapan, and Sobolevsky (2000), innovators benefit from these innovations, while Falck-Zepeda, Traxler, and Nelson (2000) and Qaim and Traxler (2005) find that farmers might benefit. A few empirical U.S. studies on the impact of PBRs on investment do not find strong evidence. Only for wheat and soybeans, Butler and Marion (1985) find that PBRs have an impact on private investments, while Alston and Venner (2002) do not find any evidence in the wheat market.

<sup>11</sup> Problems due to the research exemption are similar to problems of protection of cumulative innovations (Scotchmer, 1991), which has been analyzed in Moschini and Yerokhin (2008).

<sup>12</sup> To prevent farmers from saving seed, contracts such as technology use agreements (TUAs) can also be used instead of "terminator" varieties (Yiannaka, 2014).

<sup>13</sup> If he does not invest, the seed producer finds a small innovation. By investing  $I > 0$ , he increases his chances of obtaining a large innovation.

during the first and second periods. In the first period, each farmer chooses to buy either the old seed, which generates a payoff,  $\pi$ , or the new seed, which generates a payoff,  $\theta\pi$ , where  $\theta \in \{\underline{\theta}, \bar{\theta}\}$  is the increase in productivity due to the investment  $I$ , with  $1 < \underline{\theta} < \bar{\theta}$ .

In the second period, each farmer chooses to buy either the old seed or the new one. If the new seed is protected with a PBR, each farmer can self-produce by saving part of the first-period harvest and replant it in the second period, which generates a payoff,  $\phi\theta\pi$ , with  $\phi < 1$ .<sup>14</sup> Self-producing farmers incur a loss in productivity due to the cost of saving part of the harvest and of the yield loss. We assume that farmers are homogeneous and  $\phi$  represents the productivity of self-producing farmers with  $\phi \in [0, 1]$ .<sup>15</sup> If a farmer decides to self-produce, he must pay a royalty fee,  $\tau$ , to the government, which will be paid back to the seed producer, if such a royalty fee system exists.<sup>16</sup>

To simplify, we consider that the old seed variety has been on the market for some time and is sold at a perfectly competitive price normalized to 0. Therefore, none of the farmers have an incentive to self-produce the old seed, as  $\pi > \phi\pi$ . Given the royalty fee level and the investment decision, the seed producer chooses the new seed prices  $p_1$  and  $p_2$  for the two periods. We assume that the seed producer commits to these prices, which seems realistic if the time lapse between saving and planting is short, as it is likely that the second-period price is determined before the replanting decision.<sup>17</sup> We normalize the discount factor to 1. We further assume that the patenting cost,  $c_P$ , is such that

$$(1) \quad \pi(\bar{\theta} - \underline{\theta}) < c_P < \pi \frac{\bar{\theta} - 1}{2}$$

and that the large innovation is not too large compared to the small one:<sup>18</sup>

$$(2) \quad \bar{\theta} < \frac{3\bar{\theta} - 1}{2}.$$

The timing of decisions is as follows: At period zero, the producer chooses his investment  $I$ ; once he has discovered a seed innovation, he chooses how to protect it (PBR or patent, if available). In the first period, he chooses seed prices for the first and second periods,  $\{p_1, p_2\}$ . The farmers observe these prices. If the innovation is protected with a PBR, each farmer decides whether to buy the old seed at price zero or the new seed at price  $p_1$  and then decides whether to save some seed to self-produce during the next period. In the second period, those who did not save part of their first-period harvest decide whether to buy the old seed or the new seed at price  $p_2$ , and those who self-produce might pay a royalty fee,  $\tau$ . If the innovation is patented, each farmer decides to buy either the old seed or the new one during both periods. Table 2 summarizes the parameters of the model.

### Plant Breeders' Right Regime

To answer the first set of questions, we first analyze the seed producer's behavior when only the PBR system is available. Using a backward induction argument, we first determine the equilibrium prices and then analyze the optimal level of investment.

<sup>14</sup> We assume that self-production proportionally reduces the farmer's payoff. The results are qualitatively similar if we consider that a self-producing farmer incurs a fixed cost,  $\phi$ , and gets a payoff,  $\theta\pi - \phi$ .

<sup>15</sup> This assumption can be justified when farmers form a cooperative, as is the case in Canada, for instance.

<sup>16</sup> In France, only 85% of the royalty fee is transferred to the seed producer (see Groupement National Interprofessionnel des Semences et Plants, n.d.). In a previous version of the paper, a fraction,  $\lambda$ , of the fee was paid back to the seed producer. However, assuming that  $\lambda = 1$  does not qualitatively change our results.

<sup>17</sup> However, if the period is long, it seems realistic that the producer will not commit to a second-period price and will set its price in the second period. See Ambec, Langinier, and Lemarié (2008) for a discussion of commitment and noncommitment cases.

<sup>18</sup> assumption (2) is necessary to have  $\pi(\bar{\theta} - \underline{\theta}) < \pi(\underline{\theta} - 1)/2$ , which ensures that (1) can be satisfied.

**Table 2. Parameters of the Model**

| Exogenous              |                                       | Endogenous |   |
|------------------------|---------------------------------------|------------|---|
| $\theta, \bar{\theta}$ | Small, large innovation               | $I$        | Investment in innovation                    |
| $\phi$                 | Productivity of self-producing farmer | $\mu(I)$   | Probability of obtaining a large innovation |
| $\pi$                  | Farmer’s payoff from old variety      | $p_t$      | Price of seed at date $t = 1, 2$            |
| $\theta\pi$            | Farmer’s payoff from new variety      |            |   |
| $\phi\theta\pi$        | Farmer’s payoff from self-production  |            |   |
| $\tau$                 | Self-production royalty fee           |            |   |
| $c_P$                  | Patenting cost                        |            |   |

*Price Equilibrium*

If the seed innovation is protected with a PBR, the seed producer cannot prevent farmers from self-producing during the second period. However, he can adopt either a “durable good” strategy—in which he sells seeds only during the first period (and let farmers self-produce in the second period)—or a “nondurable” good strategy—in which he sells seeds during the two periods. In this section, we assume that self-producing farmers pay a royalty fee,  $\tau$ .<sup>19</sup>

We first analyze whether the “durable good” strategy can be an equilibrium. At the beginning of the first period, the present value of the payoff of a farmer who decides to buy the seed in the first period at price  $p_1$  and self-produce during the next period and pay the royalty fee  $\tau$  is  $\theta\pi - p_1 + \phi\theta\pi - \tau$ . This payoff must be compared with the payoffs that the farmer could obtain by choosing alternative buying strategies. He could decide to buy the old (new) seeds during both periods and would get  $2\pi (\theta\pi - p_1 + \theta\pi - p_2)$  or to buy the old (new) seed during the first period and the new (old) seed during the second period, obtaining  $\pi + \theta\pi - p_2 (\theta\pi - p_1 + \pi)$ .

The present value of the seed producer’s payoff if he adopts this “durable good” strategy is  $p_1 + \tau$  because he sells the seed to all farmers in the first period and gets back the royalty fee paid by self-producing farmers in the second period. For  $\phi \geq \phi_1$  (which guarantees that replanting in the second period is more profitable than buying the old seed), with

$$(3) \quad \phi_1 \equiv \frac{\pi + \tau}{\theta\pi},$$

this “durable good” strategy is an equilibrium in which the producer chooses  $\{p_1^D, p_2^D\}$  such that

$$(4) \quad \begin{aligned} p_1^D &= \pi(\theta - 2) + \phi\theta\pi - \tau, \\ p_2^D &\gg \pi(\theta - 1). \end{aligned}$$

By choosing these prices, the seed producer ensures that none of the farmers find it worthwhile to buy during the second period as  $p_2^D$  is too high. Thus, the seed producer sells his new seed at price  $p_1^D$  to all farmers in the first period and to none of them in the second period, but he still gets back the royalty fee  $\tau$  and his payoff is

$$(5) \quad \Pi^D = \theta\pi(1 + \phi) - 2\pi.$$

The farmers get  $\theta\pi - p_1^D + \phi\theta\pi - \tau = 2\pi$ , and the total welfare (which is the sum of the present value of both payoffs) is thus

$$(6) \quad W^D = \theta\pi(1 + \phi).$$

The seed producer can however choose a “nondurable good” strategy in which he sells during both periods and obtains the present value  $p_1 + p_2$ . This “nondurable good” strategy can also be an

<sup>19</sup> The case without royalty fee is simply derived from setting  $\tau = 0$ .

**Table 3. Optimal Prices and Payoffs**

|                        | PBR                                  |                                      |  | Patent (P)               |
|------------------------|--------------------------------------|--------------------------------------|--|--------------------------|
|                        | Nondurable Good 1 (ND <sub>1</sub> ) | Nondurable Good 2 (ND <sub>2</sub> ) | Durable Good (D)                         |                          |
| Optimal Prices         |                                      |                                      |  |                          |
| $p_1$                  | $\pi(\theta - 1)$                    | $\pi(\theta - 1)$                    | $\pi(\theta - 2) + \phi\theta\pi - \tau$ | $\pi(\theta - 1)$        |
| $p_2$                  | $\pi(\theta - 1)$                    | $\theta\pi(1 - \phi) + \tau$         | $\gg \pi(\theta - 1)$                    | $\pi(\theta - 1)$        |
| Payoffs                |                                      |                                      |  |                          |
| Farmers' payoff        | $2\pi$                               | $\pi + \phi\theta\pi - \tau$         | $2\pi$                                   | $2\pi$                   |
| Seed producer's payoff | $2\pi(\theta - 1)$                   | $\theta\pi(2 - \phi) - \pi + \tau$   | $\theta\pi(1 + \phi) - 2\pi$             | $2\pi(\theta - 1) - c_P$ |
| Total welfare          | $2\pi\theta$                         | $2\pi\theta$                         | $\theta\pi(1 + \phi)$                    | $2\pi\theta - c_P$       |

equilibrium where he chooses the prices  $\{p_1^{ND}, p_2^{ND1}\}$  or  $\{p_1^{ND}, p_2^{ND2}\}$  such that

$$(7) \quad \begin{aligned} p_1^{ND} &= \pi(\theta - 1), \\ p_2^{ND1} &= \pi(\theta - 1) \text{ for } \phi < \phi_1, \text{ and } p_2^{ND2} = \theta\pi(1 - \phi) + \tau \text{ for } \phi \geq \phi_1. \end{aligned}$$

The seed producer sets a second-period price such that all farmers buy the new seed instead of self-producing. By setting both prices at  $\pi(\theta - 1)$ , as is the case for  $\phi < \phi_1$ , he guarantees that the farmers will not buy the old seed instead of the new one. At the same time he must ensure that the farmers will not self-produce by setting  $p_2^{ND1}$ . For  $\phi \geq \phi_1$ , this latter price is too high and, thus, the seed producer sets a lower price,  $p_2^{ND2}$ . Therefore, for  $\phi < \phi_1$ , the seed producer adopts nondurable good strategy 1 with prices  $\{p_1^{ND}, p_2^{ND1}\}$ , and his payoff is

$$(8) \quad \Pi^{ND1} = 2\pi(\theta - 1),$$

the farmers get  $2\pi$ , and the total welfare is  $2\theta\pi$ . For  $\phi \geq \phi_1$ , the seed producer adopts nondurable good strategy 2 with prices  $\{p_1^{ND}, p_2^{ND2}\}$ . His payoff is therefore

$$(9) \quad \Pi^{ND2} = \theta\pi(2 - \phi) - \pi + \tau,$$

the farmers get  $\pi + \phi\theta\pi - \tau$ , and the total welfare is also

$$(10) \quad W^{ND} = 2\theta\pi.$$

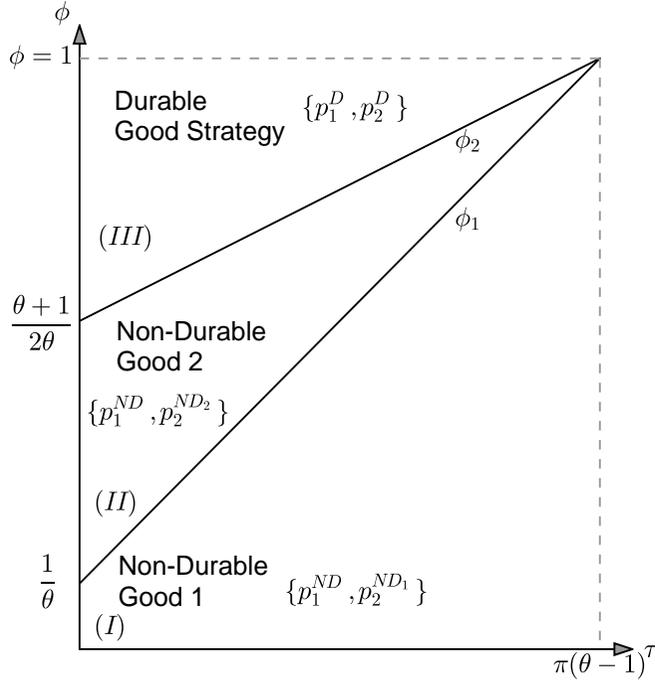
We summarize these different pricing strategies and associated payoffs in table 3.<sup>20</sup>

Given these equilibrium pricing strategies, the seed producer chooses nondurable good strategy 1 with prices  $\{p_1^{ND}, p_2^{ND1}\}$  for  $\phi < \phi_1$ , nondurable good strategy 2 with prices  $\{p_1^{ND}, p_2^{ND2}\}$  for  $\phi \in [\phi_1, \phi_2]$ , and the durable good strategy with prices  $\{p_1^D, p_2^D\}$  for  $\phi \geq \phi_2$ , where

$$(11) \quad \phi_2 = \frac{\pi(\theta + 1) + \tau}{2\theta\pi}.$$

When self-producing farmers are not productive ( $\phi < \phi_1$ ), the producer adopts a nondurable good strategy in which he sells the new seed at the same price during both periods. As farmers become more productive ( $\phi > \phi_1$ ), he reduces his second-period price to ensure that they do not self-produce. However, when they are very productive ( $\phi > \phi_2$ ), the producer adopts a durable good strategy in which he does not have to ensure that farmers do not self-produce anymore. In fact, he raises his second-period price to make sure that they will self-produce, and he increases his first-period price to capture the entire farmers' surplus. We summarize these findings in the following Lemma (all proofs are provided in Appendix B):

<sup>20</sup> The last column represents the patenting strategy presented in the section on plant breeders' rights and patent regime.



**Figure 1. Pricing Strategies under a PBR Regime**

LEMMA 1. Under a PBR regime, in equilibrium the producer adopts different pricing strategies:

- when  $\phi \geq \phi_2$ , a durable good strategy with prices  $\{p_1^D, p_2^D\}$ , as defined by equation (4).
- when  $\phi < \phi_2$ , nondurable good strategy 1 with prices  $\{p_1^{ND}, p_2^{ND_1}\}$  for  $\phi \geq \phi_1$  and nondurable good strategy 2 with prices  $\{p_1^{ND}, p_2^{ND_2}\}$  for  $\phi < \phi_1$ , as defined by equation (7).

We represent these findings in figure 1, where the axes are  $(\tau, \phi)$  for a given investment  $I$ . There are three different areas in figure 1. In area (I), for relatively low values of  $\phi$ , the seed producer adopts nondurable good strategy 1 with prices  $\{p_1^{ND}, p_2^{ND_1}\}$ . In area (II), for higher values of  $\phi$ , he adopts nondurable good strategy 2 with prices  $\{p_1^{ND}, p_2^{ND_2}\}$ . In area (III), for high values of  $\phi$ , he adopts a durable good strategy with prices  $\{p_1^D, p_2^D\}$ .

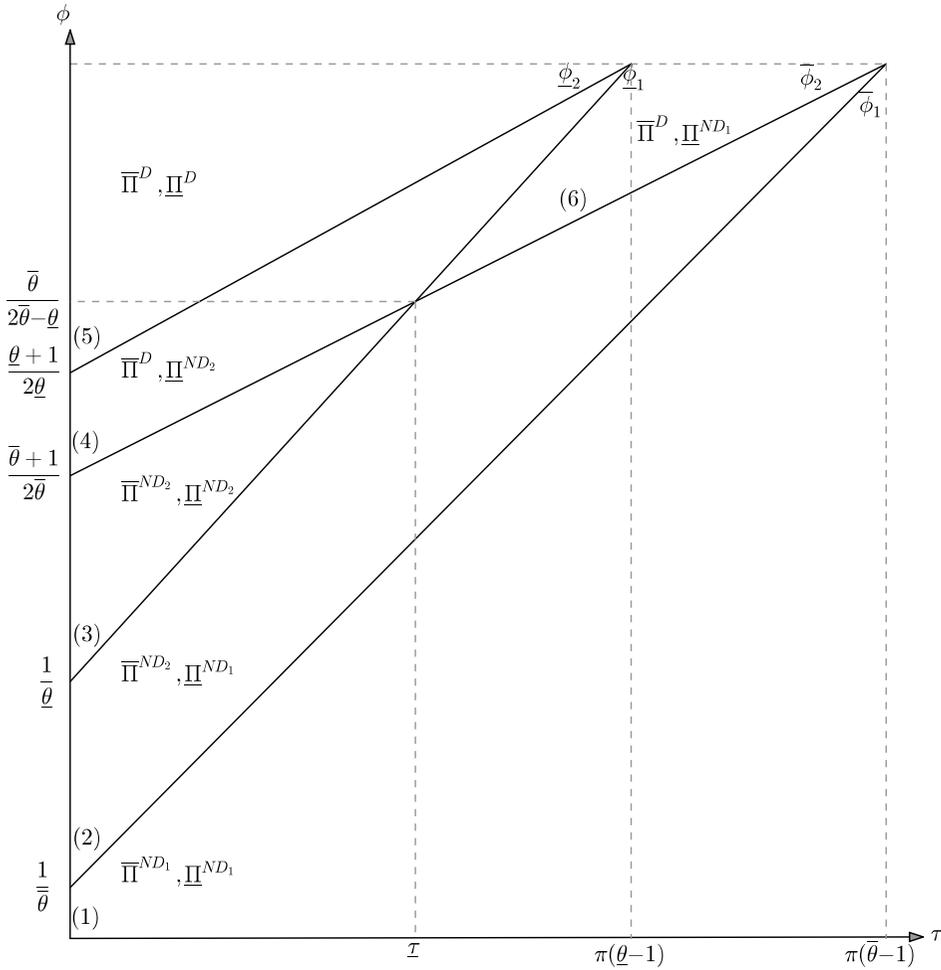
*Research Investment Decision*

At the outset of the game, the seed producer makes an investment decision that occurs before the realization of the increase in productivity is known. Therefore, based on the findings of the previous section, for each increase in productivity  $\underline{\theta}$  and  $\bar{\theta}$ , we define the pricing strategies and the corresponding payoffs for any  $\phi$  and  $\tau$ . It also implies that the cut-off values  $\phi_1$  and  $\phi_2$  as defined by equations (3) and (11) depend on  $\underline{\theta}$  and  $\bar{\theta}$  such that there are now four cut-off values:  $\bar{\phi}_1, \bar{\phi}_2, \underline{\phi}_1$ , and  $\underline{\phi}_2$ , as illustrated in figure 2, which is similar to figure 1.

As  $\underline{\theta} < \bar{\theta}$ ,  $\underline{\phi}_1 > \bar{\phi}_1$  and  $\underline{\phi}_2 > \bar{\phi}_2$ . The functions  $\bar{\phi}_2$  and  $\underline{\phi}_1$  intersect at  $\underline{\tau} \equiv \pi(\bar{\theta}(\underline{\theta} - 1) - (\bar{\theta} - \underline{\theta})) / (2\bar{\theta} - \underline{\theta}) < \pi(\bar{\theta} - 1)$  which is positive as  $\bar{\theta}(\underline{\theta} - 2) + \underline{\theta} > 0$  under assumption (2).<sup>21</sup>

We determine the benefit functions for the six different areas in figure 2 (see Appendix C). For instance, in area (1), for any value of  $\theta$ , the seed producer adopts nondurable good strategy 1

<sup>21</sup> With this assumption, there are six areas in figure 2. If we relax it, and  $\underline{\tau} < 0$ , area (3) disappears as  $\underline{\phi}_1 > \bar{\phi}_2$  for all  $\tau$  and, thus, there would be only four areas in figure 2.



**Figure 2. Seed Producer Equilibrium Payoffs under a PBR Regime for  $\theta \in \{\underline{\theta}, \bar{\theta}\}$**

with prices  $\{\bar{p}_1^{ND}, \bar{p}_2^{ND1}\}$ , and  $\{p_1^{ND}, p_2^{ND1}\}$ . For a small innovation,  $\underline{\theta}$ , the seed producer obtains  $\underline{\Pi}^{ND1} = 2\pi(\underline{\theta} - 1)$ , whereas he gets  $\bar{\Pi}^{ND1} = 2\pi(\bar{\theta} - 1)$  for a large innovation  $\bar{\theta}$ . In area (2), for a small (large) innovation he adopts nondurable good strategy 1 with associated prices  $\{p_1^{ND}, p_2^{ND1}\}$  (nondurable good strategy 2 with prices  $\{\bar{p}_1^{ND}, \bar{p}_2^{ND2}\}$ ) that generates a payoff  $\underline{\Pi}^{ND1}$  ( $\bar{\Pi}^{ND2} = \bar{\theta}\pi(2 - \phi) - \pi + \tau$ ).

Starting from a small value of  $\tau$  (or even  $\tau = 0$ ), for low self-producing farmers' productivity  $\phi$ , both small and large innovations induce nondurable good strategy 1. As  $\phi$  increases, the seed producer still adopts a nondurable good strategy for both types of innovation, except that now if a large innovation has been discovered he must reduce his second-period price in order to prevent self-production. Indeed, a large innovation generates a higher benefit to farmers who have more incentives to self-produce. As some point, as  $\phi$  keeps increasing, the seed producer with the large innovation switches to a durable good strategy as it is not worth trying to prevent self-production, while a small innovation still generates a nondurable good strategy. Eventually, when  $\phi$  is very large, only a durable good strategy is adopted.

As different strategies are adopted depending on the innovation size, the investment decisions are different in each area defined in figure 2. In area (1), the seed producer chooses  $I$  that solves

$$(12) \quad \max_I \{ \mu(I) \bar{\Pi}^{ND1} + (1 - \mu(I)) \underline{\Pi}^{ND1} - I \},$$

which gives the first-order condition  $\mu'(I)2(\bar{\theta} - \theta)\pi - 1 = 0$ . We denote  $I^{\overline{ND}_1, ND_1}$  the optimal investment when nondurable strategy 1 is adopted, which does not depend on  $\tau$  or  $\phi$ .

In area (2), he still adopts nondurable good strategy 1 for a small innovation, but he now adopts nondurable good strategy 2 for a large innovation. Hence, he chooses  $I$  that solves

$$(13) \quad \max_I \{ \mu(I)\overline{\Pi}^{ND_2} + (1 - \mu(I))\underline{\Pi}^{ND_1} - I \},$$

which gives the first-order condition  $\mu'(I)[2(\bar{\theta} - \theta)\pi + \pi + \tau - \bar{\theta}\phi\pi] - 1 = 0$ . We denote  $I^{\overline{ND}_2, ND_1}$  the optimal investment, which is now increasing with  $\tau$  but decreasing with  $\phi$ .

For the six areas in figure 2 we determine the optimal investment levels (see Appendix C). Even without further specification on  $\mu(I)$ , in the next subsections we analyze and compare the privately optimal investment levels. These investment levels will also be compared to the socially optimal investment levels that maximize the total expected welfare and are solutions of

$$(14) \quad \max_I \{ \mu(I)\overline{W} + (1 - \mu(I))\underline{W} - I \},$$

where  $\overline{W}$  and  $\underline{W}$  are determined in function of the pricing strategies chosen for large and small innovations. For each of the six areas in figure 2, we calculate the different levels of socially optimal investments. For instance, in area (1), the socially optimal investment is the solution of

$$(15) \quad \max_I \{ \mu(I)\overline{W}^{ND} + (1 - \mu(I))\underline{W}^{ND} - I \},$$

where  $W^{ND} = 2\theta\pi$  for  $\theta \in \{\underline{\theta}, \bar{\theta}\}$  and the first-order condition is  $\mu'(I)[2\pi(\bar{\theta} - \theta)] - 1 = 0$ . We denote  $I_W^{\overline{ND}, ND}$  the solution of this maximizing program, which does not depend on  $\tau$  or  $\phi$ .

To compare and contrast privately optimal investments with socially optimal investments, we first consider a situation in which there is no royalty fee ( $\tau = 0$ ), as in Canada. Then we analyze a situation in which a positive royalty fee can be levied (as in France).

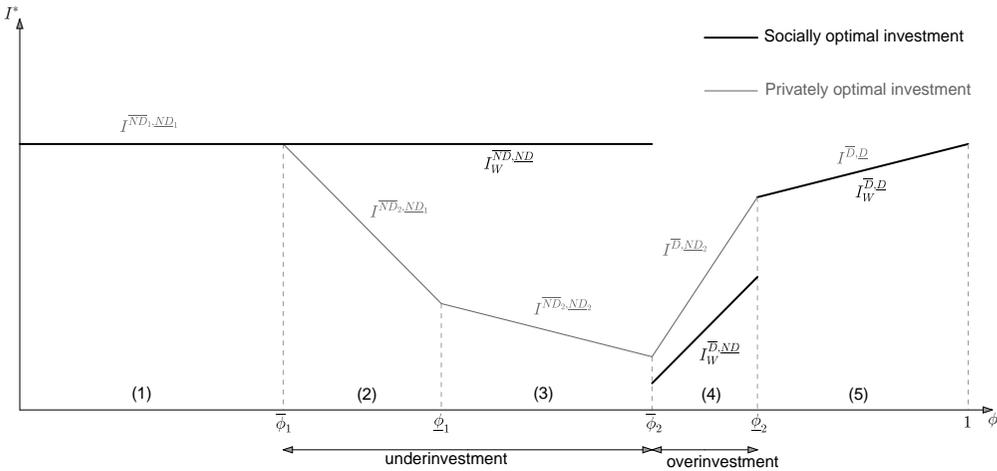
### No Royalty Fee on Self-Production

We first consider the case in which farmers do not pay a royalty fee on self-production. In figure 2, we consider the y-axis. Figure 3 represents both privately and socially optimal investments as a function of  $\phi$  (see Appendix C).

The privately optimal investment has some kind of U-shape. For  $\phi < \bar{\phi}_1$ , the producer adopts nondurable good strategy 1 for both innovations, and his investment is constant at a high level. As self-producing farmers are more efficient ( $\phi \in [\bar{\phi}_1, \bar{\phi}_2]$ ), he chooses nondurable good strategy 2 for a large innovation, which forces him to reduce his second-period price (to prevent self-production), so that he is less eager to obtain a large innovation and his optimal investment is decreasing with  $\phi$ . As self-producing farmers are even more efficient ( $\phi \in [\bar{\phi}_2, \phi_2]$ ), the investment increases with  $\phi$  when a durable good strategy is used for a large innovation; the producer gets an extra gain from having a large innovation. For  $\phi \in [\phi_2, 1]$ , he uses a durable good for both innovations, and his optimal investment is still increasing at a slower rate, as he gets an extra gain from a large innovation, but the magnitude is smaller.

This finding is consistent with observations of investment in the seed industry. Very productive self-producing farmers (high  $\phi$ ) can be found in the wheat market, where there is less private investment compared to other U.S. seed markets. One explanation could be that it is optimal for the seed producer to let farmers self-produce if they have high productivity. On the other hand, corn (maize) varieties are mainly hybrid, which makes self-production not attractive for farmers (low  $\phi$ ), and there is more private investment in that market (Fuglie et al., 2011).

The socially optimal investment is a nonmonotonic function of  $\phi$ . For low values of  $\phi$  ( $\phi < \bar{\phi}_2$ ), as the seed producer uses nondurable good strategies, investment is constant at its maximum level.

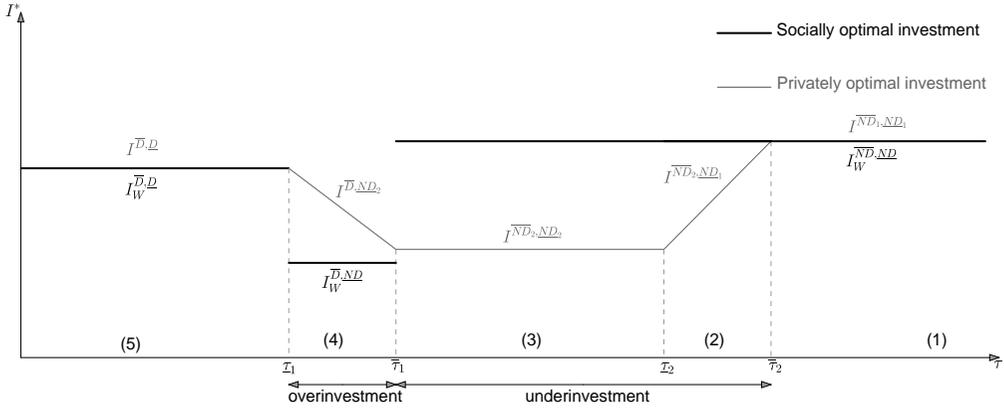


**Figure 3. Privately and Socially Optimal Investments under a PBR Regime without Royalty Fee ( $\tau = 0$ )**

Initially, for  $\phi < \bar{\phi}_1$  the seed producer chooses nondurable good strategy 1 for both innovation sizes and he benefits from a large innovation, as do farmers: The level of investment is at its highest. Then, as  $\phi$  increases ( $\phi \in [\bar{\phi}_1, \bar{\phi}_2]$ ), the seed producer must reduce his second-period price and use nondurable good strategy 2; farmers (but not the seed producer) benefit from a large innovation as  $\phi$  increases. In fact, these two effects offset each other: The marginal gain for farmers is equal to the marginal loss for the seed producer. As  $\phi$  increases even more ( $\phi > \bar{\phi}_2$ ), the seed producer switches to a durable good strategy for a large innovation and still adopts nondurable good strategy 2 for a small innovation. This switch creates a sharp jump downward in the socially optimal investment. With these new strategies, farmers are worse off with a large innovation, thus the decrease in socially optimal investment. However, as  $\phi$  increases, the extra loss of farmers is smaller than the extra gain of the seed producer and, thus, the socially optimal investment increases. The introduction of the durable good strategy does not benefit farmers, as the seed producer captures their entire surplus.

Lastly, we compare the privately and socially optimal investments, which coincide for small and large values of  $\phi$ , when the seed producer chooses nondurable good strategy 1 or a durable good strategy for both innovations. However, for intermediate values of  $\phi$ , as  $\phi$  increases, the seed producer first under-invests and then over-invests. For  $\phi \in [\bar{\phi}_1, \bar{\phi}_2]$ , a large innovation would make farmers better off when the seed producer uses nondurable good strategies. However, as he must reduce the second-period price with nondurable good strategy 2, he has less incentive to invest. Therefore, he under-invests, as he has less to gain from a large innovation than farmers do. As  $\phi$  increases ( $\phi \in [\bar{\phi}_2, \phi_2]$ ), it becomes more profitable to let farmers self-produce in the case of a large innovation, and thus the seed producer uses a durable good (nondurable good) strategy for a large (small) innovation. He has now more to gain from a large innovation than do farmers, and thus he over-invests. We summarize these findings in the following Lemma:

LEMMA 2. *Under a PBR regime without royalty fee ( $\tau = 0$ ), the privately optimal research investment is first constant, then decreases, increases, and reaches its maximum level as  $\phi$  increases. Compared to the socially optimal investment, the seed producer under-invests (over-invests) for  $\phi \in [\bar{\phi}_1, \bar{\phi}_2]$  ( $\phi \in [\bar{\phi}_2, \phi_2]$ ).*



**Figure 4. Privately and Socially Optimal Investments under a PBR Regime with Royalty Fee**

**Royalty Fee on Self-Production**

We now consider the case in which self-producing farmers must pay a positive exogenous royalty fee. We assume that self-producing is relatively efficient such that<sup>22</sup>

$$(16) \quad \phi \text{ is slightly above } \frac{\theta + 1}{2\theta}.$$

We now represent the optimal levels of investment as a function of  $\tau$  in figure 4.

The privately optimal investment function has also some kind of U-shape. For  $\tau < \tau_1 \equiv \pi(2\phi\theta - \theta - 1)$  (area (5) in figures 2 and 4), as the durable good strategy is adopted for any innovation size, there is no extra gain in having a large innovation as  $d(\bar{\Pi}^D - \underline{\Pi}^D)/d\tau = 0$ . The optimal investment is independent of  $\tau$ , so the producer does not have to intensify or reduce his investment as  $\tau$  increases. As  $\tau$  increases,  $\tau_1 \leq \tau < \bar{\tau}_1 \equiv \pi(2\phi\bar{\theta} - \bar{\theta} - 1)$  (area (4)), nondurable good strategy 2 (durable good strategy) is adopted for a small (large) innovation. The extra gain from having a large innovation decreases with  $\tau$  as  $d(\bar{\Pi}^D - \underline{\Pi}^{ND_2})/d\tau < 0$  and, therefore, the seed producer reduces his investment.

We then reach area (3) ( $\bar{\tau}_1 \leq \tau < \tau_2 \equiv \pi(\phi\theta - 1)$ ), where the producer adopts nondurable good strategy 2 for all innovation sizes. There is no gain from having a large innovation, and the optimal investment is independent of  $\tau$ . As nondurable good strategy 1 becomes more attractive with a small innovation (area (2)) ( $\tau_2 \leq \tau < \bar{\tau}_2 \equiv \pi(\phi\bar{\theta} - 1)$ ), the extra gain from having a large innovation increases with  $\tau$  as  $d(\bar{\Pi}^{ND_2} - \underline{\Pi}^{ND_1})/d\tau > 0$ . Finally, for  $\tau \geq \bar{\tau}_2$  (area (1)), nondurable good strategy 1 is adopted for both innovation sizes and the investment is constant at its maximum level.

We then compare these privately optimal investments to the socially optimal investments that maximize total welfare. When  $\tau$  is small (area (5) in figures 2 and 4) or very large (area (1)), both privately and socially optimal investments coincide. The maximum investment is reached for high values of  $\tau$ . For  $\tau \in [\bar{\tau}_1, \bar{\tau}_2]$  (areas (2) and (3)), the producer under-invests. When he adopts nondurable good strategy 2 for any innovation size (area (3)), or nondurable good strategy 2 for a large innovation (area (2)), he benefits less than farmers from a large innovation. From a social viewpoint, it would be better to discover a large innovation, but the producer is less eager to do so. For  $\tau \in [\tau_1, \bar{\tau}_1]$  (area (4)), the producer over-invests. He uses a durable good strategy (nondurable good strategy 2) for a large (small) innovation. The farmers' benefit is smaller under the durable

<sup>22</sup> For different values of  $\phi$ , the figure would be similar to figure 4. For  $\phi \in [\frac{\theta + 1}{2\theta}, \frac{\bar{\theta}}{2\bar{\theta} - \theta}]$ , the figure will be the same. For  $\phi \in [\frac{\bar{\theta}}{2\bar{\theta} - \theta}, 1]$ , there will be five investment levels in areas (5), (4), (6), (2) and (1). For  $\phi \in [(\frac{\theta + 1}{2\theta}, \frac{\theta + 1}{2\theta})]$ , there will be four investment levels in areas (4), (3), (2) and (1).

good strategy than under the nondurable good strategy, as  $2\pi < \pi + \phi\theta\pi - \tau$ . The welfare gain from a large innovation is smaller than the gain of the producer. We summarize these findings in the following Lemma:

LEMMA 3. *Under a PBR regime with royalty fee, if assumption (16) is satisfied, the privately optimal research investment is first constant, then decreases, increases, and reaches its maximum level as  $\tau$  increases. Compared to the socially optimal investment, the seed producer over-invests (under-invests) for  $\tau \in [\underline{\tau}_1, \bar{\tau}_1]$  ( $\tau \in [\bar{\tau}_1, \bar{\tau}_2]$ ).*

When farmers do (do not) benefit from a large innovation, the seed producer does not (does), and thus he under-invests (over-invests).

### Plant Breeders' Right and Patent Regime

In order to answer the second set of questions, we now consider a situation in which both PBRs and patents are available, so that the seed producer can now decide to patent his innovation or use a PBR. By backward induction, we first determine the equilibrium prices and then analyze the choice of protection (PBR or patent). Lastly, we determine the optimal level of investment.

#### Price Equilibrium and Intellectual Property Right Choice

If the seed producer chooses a PBR, the pricing strategies are those defined in the section on price equilibrium in a PBR regime. If he patents his innovation, the durable good strategy is ruled out, as farmers cannot self-produce, and the only possible pricing strategy is thus a nondurable strategy,  $\{p_1^P, p_2^P\}$ , such that

$$(17) \quad p_1^P = p_2^P = \pi(\theta - 1).$$

The seed producer's payoff is

$$(18) \quad \Pi^P = 2\pi(\theta - 1) - c_P,$$

the farmers get  $2\pi$ , and the total welfare is thus

$$(19) \quad W^P = 2\theta\pi - c_P.$$

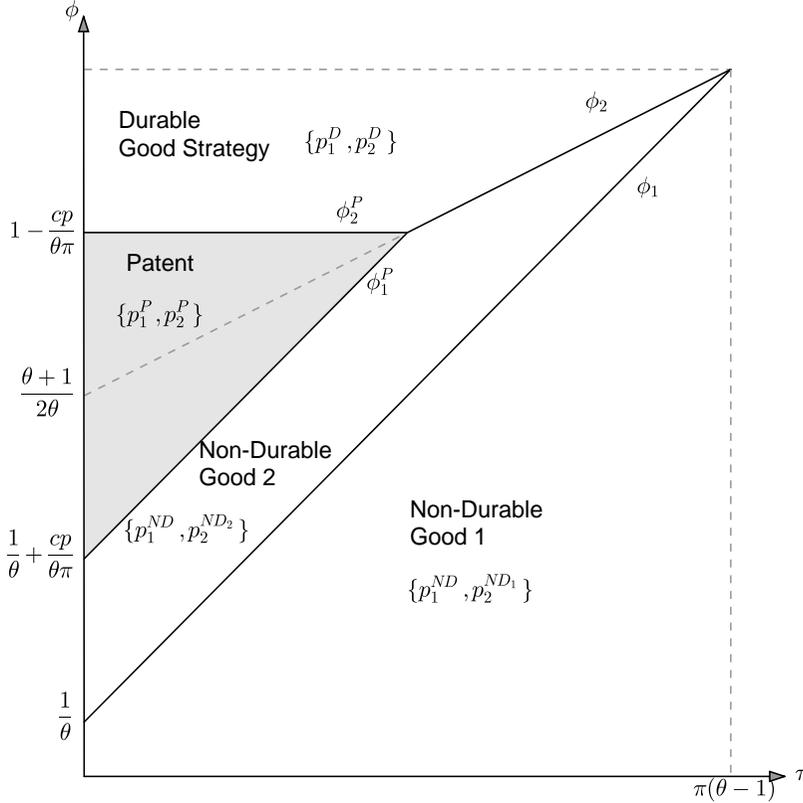
This case is similar to the case of nondurable good strategy 1. Prices and payoffs are summarized in the last column of table 3. We summarize this pricing strategy in the following Lemma:

LEMMA 4. *Under a patent system, a unique pricing strategy,  $\{p_1^P, p_2^P\}$ , as defined by equation (17), is adopted in equilibrium by the seed producer.*

If both PBRs and patents are available, once the innovation has been discovered and  $\theta$  has been realized ( $\underline{\theta}$  or  $\bar{\theta}$ ), the seed producer must decide whether to patent it or to use a PBR. In the former case, he pays a patenting cost,  $c_P$ , and his patenting payoff is equation (18), which must be compared with the payoff he would get from getting a PBR:  $\Pi^D$ , as defined by equation (5), if a durable good strategy is adopted, and  $\Pi^{ND_1}$  or  $\Pi^{ND_2}$ , as defined by equations (8) and (9), if a nondurable good strategy is adopted.

Not surprisingly, patenting depends on the patenting cost. For a high patenting cost,  $c_P \geq 2\pi(\theta - 1)$ , the seed producer never patents, as it is too costly. However, for lower values,  $c_P < 2\pi(\theta - 1)$ , which is always satisfied under assumption (1), he might decide to patent.

When self-producing farmers are not productive (i.e.,  $\phi < \phi_1$ ; (area I) in figure 1), the producer never patents because patenting and using a PBR generate the same gross payoff. Indeed, he sells his



**Figure 5. Pricing Strategies under a PBR and Patent Regime**

seed as a nondurable good even in the case of a PBR because farmers have a high loss in productivity if they self-produce. When they are more productive, for  $\phi_1 < \phi < \phi_2$  (area (II) in figure 1), he prefers to patent if  $\Pi^P > \Pi^{ND_2}$  or, equivalently, for  $\phi > \phi_1^P$ , where

$$(20) \quad \phi_1^P \equiv \frac{\pi + c_P + \tau}{\theta\pi}.$$

The seed producer who adopts a nondurable good strategy with a PBR must reduce his second-period price to make sure farmers do not self-produce, which makes this strategy less attractive than patenting. However, because patenting is costly, there is an area in which he is better off using a PBR, for  $\phi_1 < \phi < \phi_1^P$ . Finally, for  $\phi_2 < \phi < 1$ , (area (III) in figure 1), the seed producer prefers to patent if  $\Pi^P > \Pi^D$  or, equivalently, for  $\phi < \phi_2^P$ , where

$$(21) \quad \phi_2^P \equiv \frac{\theta\pi - c_P}{\theta\pi}.$$

The durable good strategy adopted when the seed producer chooses a PBR is more profitable than patenting if self-producing farmers have a high productivity. This allows him to increase his first-period price. If patenting is too costly, the area where the seed producer patents will shrink as patenting becomes less attractive. Figure 5 illustrates these findings.

We summarize these findings in the following Proposition:

**PROPOSITION 1.** *When PBRs and patents are available, the producer prefers a patent over a PBR*

- when  $\phi > \phi_1^P$  if a nondurable good strategy is adopted under the PBR regime;

- when  $\phi < \phi_2^P$  if a durable good strategy is adopted under the PBR regime.

Even for a relatively low patenting cost, the seed producer might prefer to let farmers self-produce. From these findings, we derive the following Corollary:

**COROLLARY 1.** *When PBRs and patents are available, self-production cannot be completely eliminated.*

When he can choose between a patent and a PBR, the seed producer might still prefer to protect his invention with a PBR. Therefore, the patenting option reduces the likelihood of adopting a durable good strategy even if it does not fully prevent self-production by farmers.

*Research Investment Decision*

To study the investment decision of the seed producer when he can either patent or use a PBR, we first identify his IPR decision for any innovation size. Then, we calculate the optimal investment decisions. We have already determined his payoffs when he protects his innovation with a PBR in the section on the research investment decision in a PBR regime. We now define his payoffs if he patents. If he has discovered a small (large) innovation, his payoff from patenting is  $\underline{\Pi}^P = 2\pi(\underline{\theta} - 1) - c_P$  ( $\overline{\Pi}^P = 2\pi(\overline{\theta} - 1) - c_P$ ).

In the six areas defined in figure 2, we compare the benefit of the producer if he protects his innovation with a patent or with a PBR. In area (1), where nondurable good strategy 1 is always adopted under a PBR regime whatever the innovation size, the patenting strategy is never preferred to a PBR because, for any  $\theta$ ,  $2\pi(\theta - 1) - c_P < 2\pi(\theta - 1)$  is always satisfied as  $c_P > 0$ . In other words, patenting or choosing a PBR lead to identical gross payoffs, but patenting is costlier. In area (2), the producer prefers to use a PBR if  $c_P > \pi(\overline{\theta} - \underline{\theta})/\underline{\theta}$ , which is always satisfied under assumption (1) because  $\pi(\overline{\theta} - \underline{\theta})/\underline{\theta} < \pi(\overline{\theta} - \underline{\theta})$ . In area (3), when the innovation is small (large), a PBR is always preferred to a patent if  $\phi < \phi_1^P$  ( $\phi < \overline{\phi}_1^P$ ). In areas (4) and (5), the producer patents his small (large) innovation if  $\phi < \phi_2^P$  ( $\phi < \overline{\phi}_2^P$ ). In area (6), he never patents, because  $\phi > \overline{\phi}_2^P > \phi_2^P$ . We represent these areas in figure 6.<sup>23</sup>

There are now nine different areas: depending on the innovation size, the seed producer might choose different property rights. Indeed, in areas (7) and (9) of figure 6, a large innovation is protected with a patent, whereas a small one is protected with a PBR. The innovation size thus affects the patenting decision. We summarize this finding in the following Proposition:

**PROPOSITION 2.** *The seed producer has a tendency to patent large innovations and to use PBRs for small innovations.*

For productive self-producing farmers ( $\phi \in [\phi_2^P, \overline{\phi}_2^P]$ , area (9) in figure 6), the producer prefers to patent a large innovation for low levels of  $\tau$ . However, he prefers to use a durable good strategy with a PBR for a small innovation. In area (7), he patents a large innovation but uses a PBR with nondurable good strategy 2 for a small innovation. Overall, he patents a large innovation more often than a small one.

For each area in figure 6, we determine the privately and socially optimal investments. For instance, in area (7), the seed producer chooses  $I$  that solves

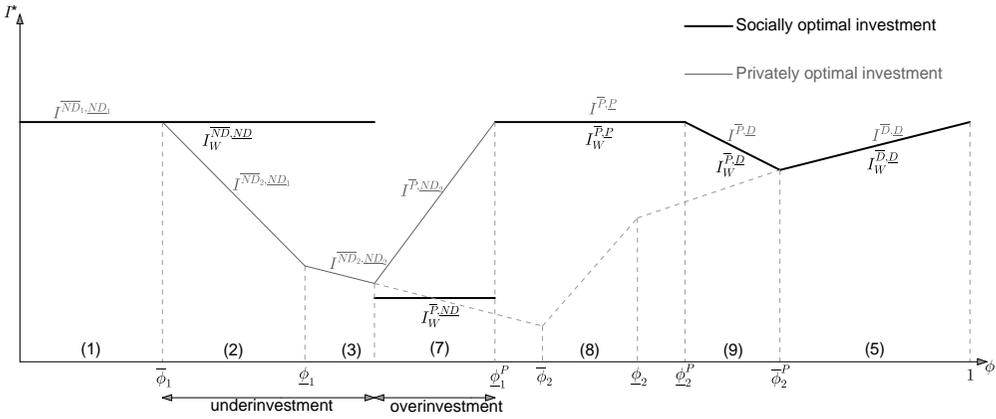
$$(22) \quad \max_I \{ \mu(I)\overline{\Pi}^P + (1 - \mu(I))\underline{\Pi}^{ND_2} - I \}.$$

We denote  $I^{\overline{P}, ND_2}$  the optimal investment level. The socially optimal investment is the solution of

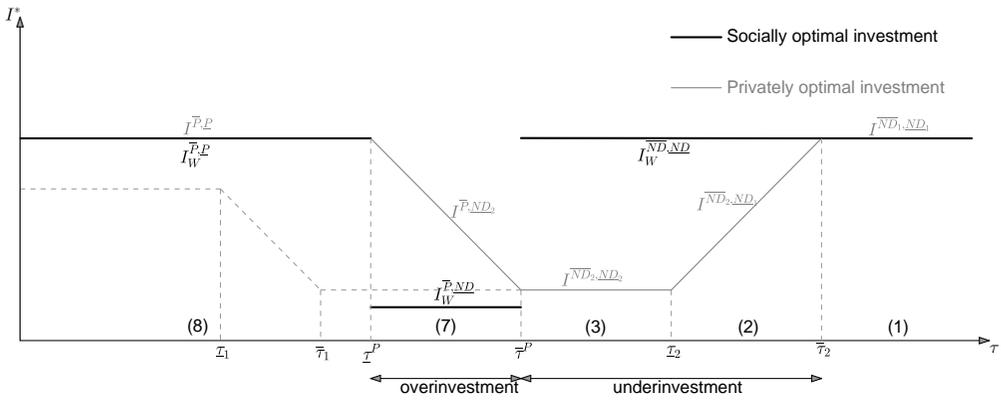
$$(23) \quad \max_I \{ \mu(I)\overline{W}^P + (1 - \mu(I))\underline{W}^{ND} - I \},$$

<sup>23</sup> Contrary to figures 1, 2, and 5, the expressions along the vertical axis are not the intercepts but functions  $\phi$ .





**Figure 7. Privately and Socially Optimal Investments under a PBR and Patent Regime without Royalty Fee ( $\tau = 0$ )**



**Figure 8. Privately and Socially Optimal Investments under a PBR and Patent Regime with Royalty Fee**

initially under-invests and then over-invests. As soon as he uses nondurable good strategy 2, he has less incentive to obtain a large innovation and, thus, he reduces his investment. However, when the seed producer patents a large innovation, he is more eager to find a large innovation and, thus, he over-invests. We summarize these findings in the following Lemma:

LEMMA 5. *Under a PBR and patent regime without royalty fee ( $\tau = 0$ ), the privately optimal research investment is a nonmonotonic function of  $\phi$ . Compared to the socially optimal investment, the seed producer under-invests (over-invests) for  $\phi \in [\bar{\phi}_1, \bar{\phi}_1^P]$  ( $\phi \in [\bar{\phi}_1^P, \underline{\phi}_1^P]$ ).*

Royalty Fee on Self-Production

We now consider that self-producing farmers pay a royalty fee and assumption (16) is satisfied. We represent the privately and socially optimal investments as functions of  $\tau$  in figure 8 (similar to figure 3).

When the producer patents both innovations (for very low  $\tau$ ), his investment level is at its highest, the same as under a PBR regime with nondurable good strategy 1. However, when he patents (uses PBR with nondurable good strategy 2) his large (small) innovation (for higher  $\tau$ ), his investment decision is decreasing with  $\tau$ . The gain from using nondurable good strategy 2 with a small innovation is positive because the second-period price increases with  $\tau$ , so that the producer

is less eager to obtain a large innovation. Then, when he uses nondurable good strategy 2 for both innovations, his investment is independent of  $\tau$  at its lowest level. It increases with  $\tau$  when he uses nondurable good strategy 1 for the small innovation: His gain from obtaining a large innovation is positive. For high values of  $\tau$ , he uses nondurable good strategy 1 for both innovations, and his investment level is at its highest.

Compared to the socially optimal investments, the producer over- or under-invests (see Appendix D) as illustrated in figure 8. For low and high values of  $\tau$  (areas (1) and (8) in figure 8), the privately and socially optimal investments coincide. In areas (2) and (3) ( $\tau \in [\underline{\tau}_P, \bar{\tau}_2]$ ) with  $\tau_P \equiv \pi(\phi\theta - 1) - c_p$ , he uses nondurable good strategies and under-invests. In area (3), he has less to gain from a large innovation than society does. In fact, farmers benefit from nondurable good strategy 2 more than the producer does. In area (2), even though he uses nondurable good strategy 1 for a small innovation, society still gains more from a large innovation than the producer does. In area (7) ( $\tau \in [\underline{\tau}_P, \bar{\tau}_P]$ ), the producer uses a patent (PBR with nondurable good strategy 2) for a large (small) innovation. From a society viewpoint, he should not invest too much because, for a small innovation, he reduces his second-period price to prevent farmers from self-producing, which makes them better off. Thus, farmers gain less from a patented large innovation than from a small one with nondurable good strategy 2. Overall, society does not benefit from a large innovation. Even though his investment is decreasing with  $\tau$ , the producer over-invests. We summarize these findings in the following Lemma:

LEMMA 6. *Under a PBR and patent regime with a royalty fee, if assumption (16) is satisfied, the privately optimal research investment is a nonmonotonic function of  $\tau$ . Compared to the socially optimal investment, the seed producer over-invests (under-invests) for  $\tau \in [\underline{\tau}_P, \bar{\tau}_P]$  ( $\tau \in [\bar{\tau}_P, \bar{\tau}_2]$ ).*

### Comparison of the PBR Regime and the PBR and Patent Regime

#### No Royalty Fee on Self-Production

In absence of royalty fee, depending on the productivity of self-producing farmers, the seed producer under-invests or over-invests as stated in the following Lemma:

LEMMA 7. *Without royalty fee, the seed producer*

- *under-invests under a PBR regime and a PBR and patent regime for  $\phi \in [\bar{\phi}_1, \bar{\phi}_1^P]$ ;*
- *under-invests (over-invests) under a PBR regime (PBR and patent regime) for  $\phi \in [\bar{\phi}_1, \phi_1^P]$ ;*
- *under-invests (over-invests) under a PBR regime while he invests at the socially optimal level under a PBR and patent regime for  $\phi \in [\underline{\phi}_1^P, \bar{\phi}_2]$  (for  $\phi \in [\bar{\phi}_2, \underline{\phi}_2]$ ).*

As a result, the seed producer under and over-invests less frequently under a PBR and patent regime. Indeed, under a PBR regime, he under-invests when  $\phi \in [\bar{\phi}_1, \bar{\phi}_2]$  while under a PBR and patent regime he under-invests when  $\phi \in [\bar{\phi}_1, \bar{\phi}_1^P]$ , where  $\bar{\phi}_1^P < \bar{\phi}_2$ . Under a PBR regime, he over-invests when  $\phi \in [\bar{\phi}_2, \underline{\phi}_2]$  while under a PBR and patent regime he over-invests when  $\phi \in [\bar{\phi}_1^P, \phi_1^P]$ , where  $\underline{\phi}_2 - \bar{\phi}_2 > \phi_1^P - \bar{\phi}_1^P < \bar{\phi}_2 - \bar{\phi}_1^P$ . We state this finding in the following Proposition:

PROPOSITION 3. *Without royalty fee, under a PBR and patent regime, the seed producer under and over-invests less frequently than under a PBR regime.*

The producer chooses the socially optimal investment more often under a PBR and patent regime.

#### Royalty Fee on Self-Producing

With a royalty fee, the results are summarized in the following Lemma:

LEMMA 8. *With a royalty fee and if assumption (16) is satisfied, the seed producer*

- *over-invests (under-invests) under a PBR regime but invests at the socially optimal level under a PBR and patent regime for  $\tau \in [\underline{\tau}_1, \bar{\tau}_1]$  (for  $\tau \in [\bar{\tau}_1, \underline{\tau}^P]$ );*
- *under-invests (over-invests) under a PBR regime (PBR and patent regime) for  $\tau \in [\underline{\tau}^P, \bar{\tau}^P]$ ;*
- *under-invests under a PBR regime and a PBR and patent regime for  $\tau \in [\bar{\tau}^P, \bar{\tau}_2]$ .*

If only the PBR regime is available (as in Europe), the optimal investment levels are lower than under a PBR and patent regime. Thus, having a PBR and patent regime allows to intensify the research investment. We state this finding in the following Proposition:

PROPOSITION 4. *With a royalty fee and if assumption (16) is satisfied, the investment level is higher under a PBR and patent regime than under a PBR regime.*

If we start from a situation in which the seed producer patents both innovations (area (8) in figure 8), as the royalty fee  $\tau$  increases we switch to area (7), where he still patents a large innovation but uses nondurable good strategy 2 with a PBR for a small one. With this pricing strategy, the second-period price decreases for a small innovation, which benefits farmers. Thus, from a social viewpoint, it is better to have a small innovation: the seed producer over-invests. As  $\tau$  increases further (area (3)), he uses a nondurable good strategy with a PBR for both innovations and, thus, he has less to gain from a large innovation: he under-invests.

Under a PBR and patent regime, the seed producer is less likely to under-invest compared to the case with only a PBR regime as he under-invests under a PBR regime (under a PBR and patent regime), for  $\tau \in [\bar{\tau}_1, \bar{\tau}_2]$  ( $\tau \in [\bar{\tau}_P, \bar{\tau}_2]$ ), where  $\bar{\tau}_P > \bar{\tau}_1$ . However, he over-invests more often as he over-invests under a PBR regime (under a PBR and patent regime), for  $\tau \in [\underline{\tau}_1, \bar{\tau}_1]$  ( $\tau \in [\underline{\tau}_P, \bar{\tau}_P]$ ), where  $\bar{\tau}_1 - \underline{\tau}_1 < \bar{\tau}_P - \underline{\tau}_P$ . We summarize these findings in the following Proposition:

PROPOSITION 5. *With a royalty fee and if assumption (16) is satisfied, the seed producer under-invests less often under a PBR and patent regime rather than under a PBR regime, but he over-invests more often.*

Introducing the patent system provides more options to the seed producer, and thus patenting boosts the investment in innovation. Overall, the seed producer under-invests less often when he has the choice of property rights.

### Incentive to Innovate and Welfare

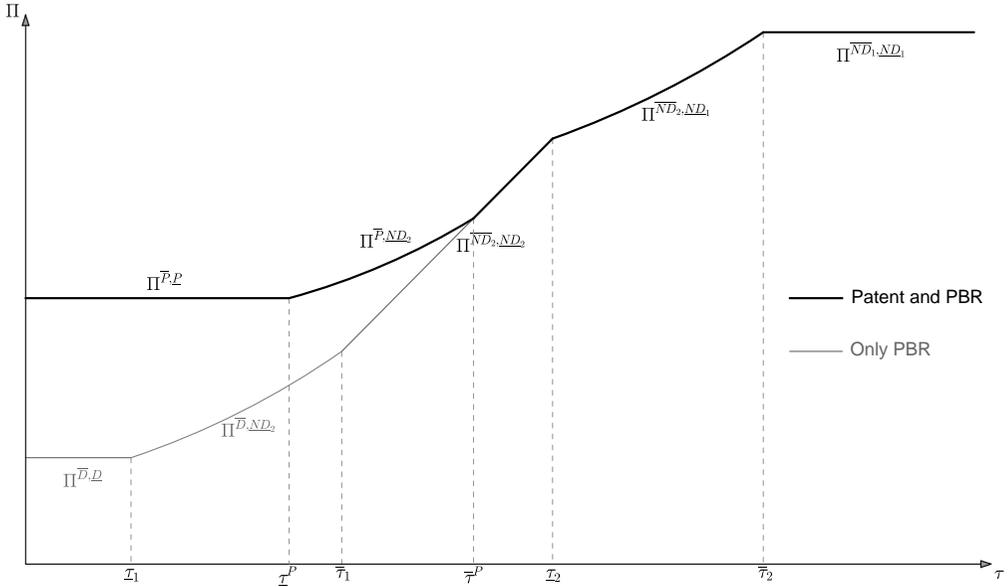
We now turn to the third set of questions related to policy issues. We first characterize the incentive to innovate of the seed producer and then analyze the impact of the privately optimal investments on total welfare. In order to calculate both profit and welfare functions evaluated at the optimal investment levels, we consider the following functional form<sup>24</sup>:

$$(24) \quad \mu(I) = 1 - \exp^{-I}.$$

#### *Incentives to Innovate*

We use the traditional definition of “pure” incentive to innovate (Arrow, 1962): the difference between the profit that the seed producer would earn from investing and the profit he would earn if he did not invest. In our setting, not investing is equivalent to selling the old seed in a perfectly

<sup>24</sup> It satisfies the conditions  $\mu'(I) > 0$ ,  $\mu''(I) < 0$  and  $\mu(0) = 0$ . As a robustness check, we used a different functional form,  $\mu(I) = \arctan I/1.58$ , that led to similar findings.



**Figure 9. Incentives to Innovate under a PBR and Patent Regime with Royalty Fee**

competitive market and obtaining a null payoff. Therefore, the incentive to innovate is represented by the *ex ante* expected profit of the seed producer,  $\mu(I)\bar{\Pi} + (1 - \mu(I))\underline{\Pi} - I$ , evaluated at each optimal investment level and corresponding profit  $\bar{\Pi}$  and  $\underline{\Pi}$ .

Under a PBR regime, in area (1) in figure 2, the seed producer’s *ex ante* expected profit is

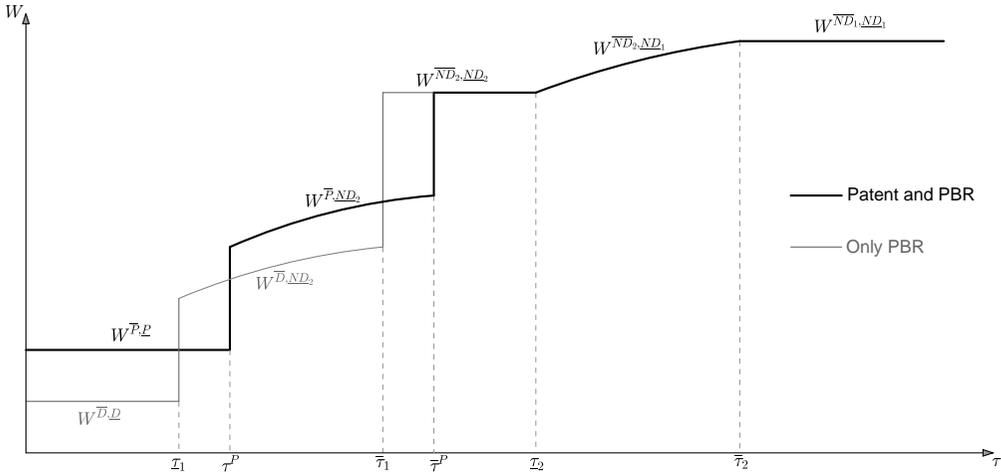
$$(25) \quad \Pi^{\overline{ND}_1, \underline{ND}_1} = \mu(I^{\overline{ND}_1, \underline{ND}_1})\bar{\Pi}^{ND_1} + (1 - \mu(I^{\overline{ND}_1, \underline{ND}_1}))\underline{\Pi}^{ND_1} - I^{\overline{ND}_1, \underline{ND}_1},$$

which is independent of  $\tau$ , since  $I^{\overline{ND}_1, \underline{ND}_1}$  does not depend on  $\tau$ . For each of the six areas in figure 2, we calculate the levels of *ex ante* expected profit, which we represent in a graph  $(\tau, \Pi)$  in figure 9. We also assume that assumption (16) is satisfied.

As  $\tau$  increases, the incentive to innovate is first constant before it increases. The strongest incentive to innovate is reached when the producer uses nondurable good strategy 1 for both innovations (high  $\tau$ ). Initially, for  $\tau < \tau_1$ , as  $\tau$  increases, the *ex ante* expected profit is low and constant when the producer uses a durable good strategy for both innovations. As  $\tau$  increases ( $\tau_1 < \tau < \tau_1\text{-bar}$ ), the producer uses nondurable good strategy 2 (durable good strategy) for a small (large) innovation. As  $\tau$  increases, the profit from a large innovation is reduced through a reduction of  $p_1^D$ , while the profit from a small innovation increases. However, the negative impact due to the large innovation outweighs the positive impact of the small one. In other words, the loss associated with a large innovation is larger than the gain associated with a small innovation.

As  $\tau$  increases further ( $\tau_1\text{-bar} < \tau < \tau_2$ ), the producer uses nondurable good strategy 2 for both innovations, and his profit increases due to an increase in the profit from a small innovation. When the producer uses nondurable good strategy 1 for a small innovation (for  $\tau_2 < \tau < \tau_2\text{-bar}$ ), the incentive to innovate still increases but at a smaller rate as only the profit from a large innovation increases with  $\tau$ . For  $\tau > \tau_2\text{-bar}$ , the producer always uses nondurable good strategy 1 for both innovations and, thus, his *ex ante* expected profit is no longer affected by  $\tau$ . Due to the different pricing strategies adopted depending on the royalty fee, a PBR regime with a low level of royalty fee does not boost innovation. However, an increase in the royalty fee has a positive effect on the incentive to innovate.

Under a PBR and patent regime, we calculate the *ex ante* expected profit for the nine areas in figure 6 that we graphically illustrate in figure 9. The incentive to innovate is also first constant and then increasing, but at a higher level than under the PBR regime. The incentives are similar for high level of  $\tau$  ( $\tau > \tau^P$ ) when the producer uses nondurable good strategies. However, for lower value



**Figure 10. Welfare under a PBR and Patent Regime with Royalty Fee**

of  $\tau$ , the two cases differ. For  $\tau < \tau^P$ , the producer always patents both innovations, which makes the expected profit independent of  $\tau$  at a higher level than under a PBR regime. However, because of the patenting cost, this is not the highest incentive level. For  $\tau \geq \tau^P$ , the producer patents (uses nondurable good strategy 2) his large (small) innovation, which increases his incentive to innovate as  $\tau$  increases. This increase is entirely due to the small innovation profit. However, this increase is smaller than when the seed producer uses nondurable good strategy 2 for both innovations.

Allowing the seed producer to choose between a patent and a PBR boosts the incentive to innovate compared to the case where he can only use a PBR. The patent system restores some of the lack of incentive to innovate. We summarize these results in the following Proposition:

**PROPOSITION 6.** *If assumption (16) is satisfied, the incentive to innovate increases with  $\tau$ . The highest incentive to innovate is reached for high levels of the royalty fee. Under a PBR and patent regime, the incentive to innovate is higher than under a PBR regime.*

An inappropriate level of royalty fee  $\tau$  does not boost innovation. When choosing a royalty fee, the public authority should consider its impact on the seed producer’s pricing and protection strategies.

*Welfare Analysis*

Lastly, we plot the total welfare evaluated at the privately optimal investments defined previously with the functional form (24) under a PBR regime and a PBR and patent regime in figure 10.

Under a PBR regime, if  $\tau < \tau_1$ , the producer chooses a durable good strategy for both innovations, which generates a relatively low social welfare. As  $\tau$  increases ( $\tau \geq \tau_1$ ), initially as he uses nondurable good strategy 2 for a small innovation, welfare increases. It keeps increasing in a nonmonotonic way until it reaches its maximum, when he uses nondurable good 1 for both innovations ( $\tau > \tau_2$ ). In fact, welfare reaches its maximum level when there is no self-producing (large values of  $\tau$ ).

Having a choice of IPRs does not always enhance welfare. It is enhanced if the patenting strategy prevents self-production (for  $\tau \in [0, \tau_1]$ ). Farmers obtain the same surplus ( $2\pi$ ), whereas the producer gains from patenting. Welfare is also enhanced when the producer uses nondurable good strategy 2 with a PBR (patents) for a small (large) innovation under a PBR and patent regime instead of using a durable good strategy for a large innovation under the PBR regime. However, when the patenting strategy replaces nondurable good strategy 2, farmers are worse off and welfare is reduced. This occurs if the producer patents both innovations under a PBR and patent regime,

whereas he uses a durable good strategy (nondurable good strategy 2) for large (small) innovation under the PBR regime (for  $\tau \in [\underline{\tau}_1, \underline{\tau}^P]$ ). This also happens if he uses a patent (PBR with nondurable good strategy 2) for large (small) innovation under a PBR and patent regime instead of nondurable good strategy 2 under the PBR regime (for  $\tau \in [\bar{\tau}_1, \bar{\tau}^P]$ ). An increase of  $\tau$  implies a decrease in investment and welfare as the probability of obtaining a small innovation increases. We state these findings in the following Proposition:

**PROPOSITION 7.** *If assumption (16) is satisfied, even though the total welfare is increasing with  $\tau$ , it is not always enhanced under a PBR and patent regime.*

For  $\tau > \bar{\tau}^P$ , having a PBR regime or a PBR and patent regime leads to the same welfare because the producer prefers to use a PBR without allowing farmers to self-produce. In fact, choosing nondurable good strategy 1 with a PBR is equivalent to a patenting strategy, but it is less costly. For  $\tau \leq \bar{\tau}^P$ , having a PBR and patent regime has an ambiguous effect on welfare. Indeed, an inappropriate level of royalty fee can reduce welfare. Thus, starting from a European system (only PBRs) and allowing producers to patent might reduce welfare for inappropriate values of the royalty fee. If  $\tau = 0$ , as in the United States, having a PBR and patent regime enhances welfare because it prevents self-production.

### Example of Parameterization of the Model

In order to better relate our model with a real-life environment, we provide some parametrization of the model with a discussion of the results obtained with these specific parameters. As an example, we focus on the case of wheat in France. The moving average yield over 5 years was 6.663 tons per hectare (t/ha) in 1993 and 7.357 t/ha in 2013.<sup>25</sup> As we are interested in looking at the hypothetical effect of a patent, we consider a gap of 20 years to account for the maximum lifetime of a patent, if the crop was protected with a patent. This gives us an approximate rise of 10% of wheat yield so that  $\theta = 1.1$ . We will then consider  $\underline{\theta} = 1.1$  and  $\bar{\theta} = 1.11$ . On average, French farmers cultivate 16.5ha of wheat,<sup>26</sup> so if we assume a net gain of €15/t (€30/t), then the profit would be  $\pi = 6.663 \text{ t/ha} \times 16.5 \text{ ha} \times €15/\text{t} = 1,649$  ( $\pi = 6.663 \text{ t/ha} \times 16.5 \text{ ha} \times €30/\text{t} = 3,298$ ). Based on this back-of-the-envelope calculation, we consider two different levels for  $\pi$ : 1,500 and 3,000. We then calibrate  $cp$ . In our theoretical model, there is a representative farmer and only one firm; the reality is more complex. In 2013 there were 298,820 French farmers and 20 different wheat varieties that represented 67% of the market share.<sup>27</sup> As we consider a monopolist, we assume that his demand represents approximately 3% of the market share (1 variety out of 20), so that the firm supplies approximately 9,000 farmers. As the lower bound of the difference between patenting and PBR costs is approximately €20,000 in Europe, we divide it by the number of farmers supplied by the firm and obtain a rough approximation of  $cp = 2.2$ .<sup>28</sup>

To summarize, we use the following parameters for French wheat:  $\pi = 1,500$  and 3,000,  $\underline{\theta} = 1.1$ ,  $\bar{\theta} = 1.11$ , and  $cp = 2.2$ . We also consider  $cp = 22$  because  $cp = 2.2$  corresponds to a lower bound.

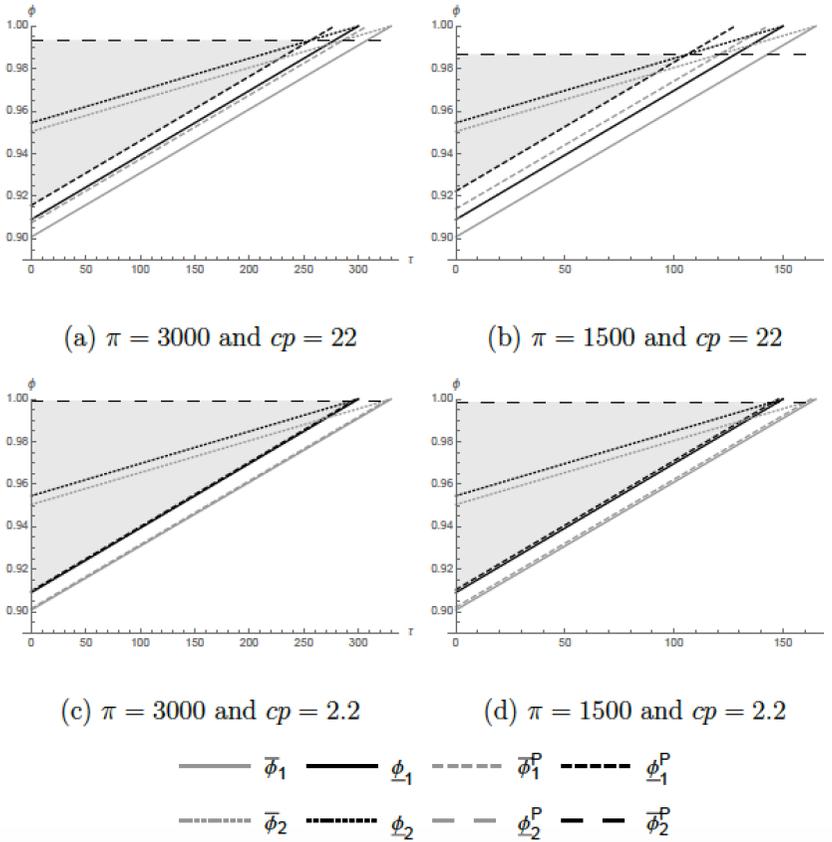
Figures 11a–d are equivalent to figure 6 with different parameter values. As in figure 6, the gray area represents patenting small and large innovations. Figure 11b is similar to figure 6, whereas in figures 11a, c, and d strategies  $\{\underline{ND}_2, \underline{ND}_2\}$  are replaced by strategies  $\{\bar{P}, \underline{ND}_1\}$ . However, the flavor of the results is similar. In fact, one can verify that assumptions (1) and (2) are satisfied under the parameters of figure 11b. If we relax one of these assumptions, we obtain one of the other figures.

<sup>25</sup> Farm Accountancy Data Network (FADN) database provides wheat yield for European countries (variable SE110).

<sup>26</sup> In 2013, according to the FADN, variable SE110D.

<sup>27</sup> From the FADN database and “Groupement National Interprofessionnel des Semences et Plantes” (GNIS).

<sup>28</sup> Moreover, we also can assume that the patent cost is higher because firms develop many varieties for only few commercial successes, and some costs of the patent system are not included in appendix table A1.



**Figure 11. Parameterization**

In these figures, we now wonder where we can expect to obtain the most likely results. In order to answer that question, we need to calibrate  $\phi$  and  $\tau$ . The loss of productivity from using FSS has been assessed to be between 0.2 t/ha and 0.3 t/ha.<sup>29</sup> Based on the moving average wheat yield in 2013, a loss of 0.2 t/ha (0.3 t/ha) gives approximately a loss of 2.7% (4.07%) so that  $\phi = 0.973$  ( $\phi = 0.959$ ). Therefore,  $\phi$  is very large: between 0.959 and 0.973. The royalty fee on FSS is about 0.7 /t of produced wheat, for a yield at  $7.3 \times 57$  t/ha, then the fee is €5.15/ha.<sup>30</sup> Farmers are cultivating 16.5ha such that  $\tau = 85$  ( $= €5.15/\text{ha} \times 16.5$  ha).

In figure 11b, at  $\tau = 85$  and  $\phi \in [0.959, 0.973]$ , the producer would patent a large innovation and use a PBR with a nondurable good strategy for a small innovation. In France, a producer cannot use a patent to protect his innovation, and thus he uses a nondurable good strategy with a PBR. If the producer could patent his innovation, he would patent a large innovation. In absence of patent, these calibrated parameters will correspond to area (3) in figure 2. As we can see in figure 4, this will lead to under-investment. However, if the producer could patent, it would be area (7) in figure 6, which will lead to over-investment. So, the absence of patent could lead to under-investment, but introducing a patent could lead to over-investment. Furthermore, in order to completely prevent farmers from using FFS, the royalty fee should be increased by 41.2% to €120.

<sup>29</sup> Estimations are from GNIS.

<sup>30</sup> In France, the royalty fee on FSS has been established by an interprofessional agreement between farmers and breeders. In the United Kingdom, farmers have two choices to pay the royalty fee: They can either pay when there FSS are treated at £47.17/t of FSS treated or they can pay £8.44/ha of cultivated wheat (British Society of Plant Breeders, n.d.). In Australia, each breeder chooses the level of its royalty fee from a range of \$0.95/t–\$4.25/t of produced wheat (Australian dollars) (Variety Central, n.d.).

In the four figures, for smaller values of  $\phi$ , the producer will choose nondurable good strategies, which could be the case of hybrid maize if we assumed that the parameters defined above are similar for wheat and maize.

### Conclusion

We focus on the problem of incentives to innovate due to seed saving by self-producing farmers that decreases the seed producer's profit. The loss incurred may decrease private investments. In many countries, to correct the incentive problem, self-producing farmers must pay a royalty fee to seed producers. We provide a theoretical model to analyze the effects of the farmers' exemption and its royalty fee on the producer's behavior (pricing and investment decisions) in two regimes: a PBR regime and a PBR and patent regime. In the PBR regime, we first analyze the equilibrium seed prices depending on the seed saving productivity and the royalty fee. For a high (low) productivity and a low (high) royalty fee, the producer chooses a durable good strategy (nondurable good strategy). The investment decision is affected by the pricing strategies adopted; it can be suboptimal compared to the socially optimal investments. Under a PBR and patent regime, large (small) innovations tend to be protected with patents (PBRs) so that self-production is not completely eliminated. Additionally, the producer does not always invest at the socially optimal level. However, he tends to invest more often at a suboptimal investment level when he can only use a PBR. Under a PBR and patent regime, the seed producer has a higher incentive to innovate, even though the impact of having a PBR and patent regime on the total welfare is ambiguous.

We have analyzed the farmers' exemption in a very simple setting, accounting only for competition from farmers. Introducing both exemptions and analyzing their impact in a more dynamic setting, is part of our future research agenda.

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### Appendix A: Patents and PBR Costs

Patenting <sup>31</sup> and PBR costs are divided among different fees. Information about these costs are gathered from the U.S. Patent and Trademark Office (2018), the European Patent Office (2018), the U.S. Department of Agriculture, Agricultural Marketing Service (2018), and the EU Community Plant Variety Office (2018).

Table A1 lists the minimum costs to obtain a patent and a PBR in the United States and in Europe (several fees are not included in this table). For example, there are extra fees if the number of claims or pages reaches a maximum, fees that are different depending on the patent system. Moreover, patenting costs in Europe depend on the number of countries where the innovation will be protected. Maintenance fees for each country have to be paid, and translation fees increase patenting cost in Europe. Table A1 shows that the costs of a U.S. utility patent is approximately three times higher than a U.S. PBR, and a European patent is four times more expensive than a European PBR. In estimating the cost of U.S., European, and Japanese patents for 2003, van Pottelsberghe de la Potterie and François (2009) find that a European patent protected in 13 countries costs approximately \$129,183. Furthermore, to comply with all the patent requirements, firms seeking patent protection usually hire lawyers, as the drafting of patents is complex, which increases the total patenting cost even more.

**Table A1. Comparison between Patent and PBR Costs (2017)**

|                    | Patent     |            | PBR       |               |
|--------------------|------------|------------|-----------|---------------|
|                    | USPTO (\$) | EPO (€)    | USDA (\$) | CPOV (€)      |
| Application fee    | 280        | 210        | 518       | 650           |
| Search fee         | 600        | 1,360      | -         | -             |
| Examination fee    | 720        | 1,620      | 3,864     | 1,530–3,050   |
| Grant/issue fee    | 960        | 915        | 768       | -             |
| Designated states  | -          | 580        | -         | -             |
| Maintenance Fees   | 3.5 years  | 0–5 years  | -         | 0–10 years    |
|                    | 1,600      | 1,855      | -         | 2,500         |
|                    | 7.5 years  | 0–10 years | -         | 0–20 years    |
|                    | 3,600      | 8,255      | -         | 5,000         |
|                    | 11.5 years | 0–20 years | -         | 0–25 years    |
|                    | 7,400      | 23,855     | -         | 6,250         |
| Total for 20 years | 15,160     | 28,540     | 5,150     | 7,180 (wheat) |

<sup>31</sup> In the United States, only some species (e.g., ornamental varieties, like roses) can be protected with a plant patent. Agricultural varieties (e.g., wheat or maize) are protected with utility patents.

### Appendix B: Price Equilibrium under a PBR regime

When  $\phi \geq \phi_1$ , the seed producer chooses between nondurable good strategy 2 with prices  $\{p_1^{ND}, p_2^{ND_2}\}$  which yields a payoff  $\Pi^{ND_2}$  and the durable good strategy with prices  $\{p_1^D, p_2^D\}$ , which yields  $\Pi^D$ . As long as  $\Pi^{ND_2} > \Pi^D$  ( $\Pi^{ND_2} \leq \Pi^D$ ), a nondurable good strategy (durable good strategy) will be adopted, which happens for  $\phi < \phi_2$  (for  $\phi \geq \phi_2$ ) with  $\phi_1$  and  $\phi_2$  defined by equations (2) and (9). In a graph  $(\tau, \phi)$  represented in figure 1 we find three distinct areas where  $\phi_2 > \phi_1$ .

### Appendix C: Optimal Investment Levels under a PBR Regime

Before calculating the optimal investment levels, we first define under what circumstances the producer chooses a pricing strategy for each innovation size. In figure 2, we represent the different areas where the producer chooses a durable good strategy and a nondurable good strategy for  $\underline{\theta}$  and  $\bar{\theta}$ .

In the text, we have calculated the benefit functions for areas (1) and (2). In area (3), the producer adopts nondurable good strategy 2 with prices  $\{\bar{p}_1^{ND}, \bar{p}_2^{ND_2}\}$  and  $\{\underline{p}_1^{ND}, \underline{p}_2^{ND_2}\}$ , and the benefits are  $\bar{\Pi}^{ND_2}$  and  $\underline{\Pi}^{ND_2} = \underline{\theta}\pi(2 - \phi) - \pi + \tau$ . In area (4), if he has discovered a large innovation, the seed producer adopts a durable good strategy with prices  $\{\bar{p}_1^D, \bar{p}_2^D\}$  and obtains  $\bar{\Pi}^D = \bar{\theta}\pi(1 + \phi) - 2\pi$ . If he has discovered a small innovation, he adopts nondurable good strategy 2 with prices  $\{\underline{p}_1^{ND}, \underline{p}_2^{ND_2}\}$  and gets  $\underline{\Pi}^{ND_2}$ . In area (5), the seed producer always adopts a durable good strategy and, thus, the benefit for a large innovation is  $\bar{\Pi}^D$  and  $\underline{\Pi}^D = \underline{\theta}\pi(1 + \phi) - 2\pi$  for a small one. Finally, in area (6), the seed producer adopts a durable good strategy for a large innovation and obtains  $\bar{\Pi}^D$  and nondurable good strategy 1 for a small innovation and obtains  $\underline{\Pi}^{ND_1}$ .

In each area defined in figure 2, we determine the investment decision of the seed producer. We first determine the privately optimal investment and then the socially optimal investment.

In area (1) in figure 2, the producer uses nondurable good strategy 1 for any innovation size, and thus he chooses  $I$  that solves

$$(C1) \quad \max_I \{ \mu(I)\bar{\Pi}^{ND_1} + (1 - \mu(I))\underline{\Pi}^{ND_1} - I \},$$

which gives the first-order condition (FOC)  $\mu'(I)[2(\bar{\theta} - \underline{\theta})\pi] - 1 = 0$ . We denote  $I^{\bar{ND}_1, \underline{ND}_1}$  the optimal investment level, which is independent of  $\tau$  and  $\phi$ .

In area (2), the seed producer uses nondurable good strategy 1 for a small innovation and nondurable good strategy 2 for a large innovation and then chooses  $I$  that solves

$$(C2) \quad \max_I \{ \mu(I)\bar{\Pi}^{ND_2} + (1 - \mu(I))\underline{\Pi}^{ND_1} - I \},$$

which gives the FOC  $\mu'(I)[2(\bar{\theta} - \underline{\theta})\pi - \pi(\bar{\theta}\phi - 1) + \tau] - 1 = 0$ . We denote  $I^{\bar{ND}_2, \underline{ND}_1}$  the optimal level of investment, which is increasing with  $\tau$  and decreasing with  $\phi$ . Indeed, if we totally differentiate the FOC and rearrange the terms, we find that  $sign(dI/d\tau) = sign(\mu'(I))$ , where  $\mu'(I) > 0$  and  $sign(dI/d\phi) = sign(-\mu'(I)\pi\bar{\theta})$ .

In area (3), when the seed producer uses nondurable good strategy 2 for any innovation size, he chooses  $I$  that solves

$$(C3) \quad \max_I \{ \mu(I)\bar{\Pi}^{ND_2} + (1 - \mu(I))\underline{\Pi}^{ND_2} - I \},$$

which gives the FOC  $\mu'(I)[(\bar{\theta} - \underline{\theta})\pi(2 - \phi)] - 1 = 0$ . We denote  $I^{\bar{ND}_2, \underline{ND}_2}$  the optimal investment level, which does not depend on  $\tau$  but is decreasing with  $\phi$  as  $sign(dI/d\phi) = sign(-\mu'(I)(\bar{\theta} - \underline{\theta})\pi)$ .

In area (4), the seed producer uses a durable good strategy for a large innovation and nondurable good strategy 2 for a small innovation and thus chooses  $I$  that solves

$$(C4) \quad \max_I \{ \mu(I) \bar{\Pi}^D + (1 - \mu(I)) \underline{\Pi}^{ND_2} - I \},$$

which gives the FOC  $\mu'(I)[2(\bar{\theta} - \underline{\theta})\pi - \pi\bar{\theta}(1 - \phi) + \underline{\theta}\pi\phi - \pi - \tau] - 1 = 0$ . We denote  $I^{\bar{D}, ND_2}$  the optimal investment level, which is decreasing in  $\tau$  and increasing with  $\phi$ .

In area (5), the seed producer uses the durable good strategy for any innovation size and chooses  $I$  that solves

$$(C5) \quad \max_I \{ \mu(I) \bar{\Pi}^D + (1 - \mu(I)) \underline{\Pi}^D - I \},$$

which gives the FOC  $\mu'(I)[(1 + \phi)(\bar{\theta} - \underline{\theta})\pi] - 1 = 0$ . We denote  $I^{\bar{D}, D}$  the optimal investment level, which does not depend on  $\tau$  or  $\phi$ .

In area (6), the seed producer uses the durable good strategy for a large innovation and nondurable good strategy 1 for a small innovation and thus chooses  $I$  that solves

$$(C6) \quad \max_I \{ \mu(I) \bar{\Pi}^D + (1 - \mu(I)) \underline{\Pi}^{ND_1} - I \},$$

which gives the FOC  $\mu'(I)[\pi(\bar{\theta} - \underline{\theta}) + \phi\bar{\theta}\pi - \underline{\theta}\pi] - 1 = 0$ . We denote  $I^{\bar{D}, ND_1}$  the optimal investment level, which does not depend on  $\tau$  but is increasing with  $\phi$ .

We then calculate the socially optimal investment levels that solve

$$(C7) \quad \max_I \{ \mu(I) \bar{W} + (1 - \mu(I)) \underline{W} - I \},$$

where  $\bar{W}$  and  $\underline{W}$  are determined in function of the pricing strategies chosen by the seed producer for large and small innovations. For each of the six areas in figure 2, we calculate the different levels of socially optimal investments. In area (1) in figure 2, the socially optimal level of investment is the solution of

$$(C8) \quad \max_I \{ \mu(I) \bar{W}^{ND} + (1 - \mu(I)) \underline{W}^{ND} - I \},$$

where  $W^{ND} = 2\theta\pi$ . Thus, the FOC is  $\mu'(I)[2\pi(\bar{\theta} - \underline{\theta})] - 1 = 0$ . We denote  $I_W^{\bar{ND}, ND}$  the solution of this maximizing program, which does not depend on  $\tau$  and  $\phi$ . The solution is the same in areas (2) and (3).

In area (4) the socially optimal level of investment is the solution of

$$(C9) \quad \max_I \{ \mu(I) \bar{W}^D + (1 - \mu(I)) \underline{W}^{ND} - I \},$$

where  $\bar{W}^D = \bar{\theta}\pi(1 + \phi)$ . Thus, the FOC is  $\mu'(I)[\pi(\bar{\theta} - \underline{\theta}) + \phi\bar{\theta}\pi - \underline{\theta}\pi] - 1 = 0$ . We denote  $I_W^{\bar{D}, ND}$  the solution, which does not depend on  $\tau$  but is increasing with  $\phi$ .

In area (5), the socially optimal level of investment is the solution of

$$(C10) \quad \max_I \{ \mu(I) \bar{W}^D + (1 - \mu(I)) \underline{W}^D - I \}.$$

Thus, the FOC is  $\mu'(I)[\pi(\bar{\theta} - \underline{\theta})(1 + \phi)] - 1 = 0$ . We denote  $I_W^{\bar{D}, D}$  the solution of this maximizing program, which is increasing with  $\tau$  and  $\phi$ . Lastly, in area (6), the socially optimal level of investment,  $I_W^{\bar{D}, ND}$ , is identical to the level of area (4).

We now compare the privately and socially optimal investment levels for  $\tau \geq 0$ . To obtain the case without royalty fee we set  $\tau = 0$  and the case with royalty fee is for  $\tau > 0$ .

In area (1),  $I_W^{\overline{ND},ND} = I^{\overline{ND}_1,ND_1}$  as both investments are solutions of  $\mu'(I)[2(\overline{\theta} - \underline{\theta})\pi] - 1 = 0$  or equivalently,  $\mu'(I) = 1/A$  where  $A = 2(\overline{\theta} - \underline{\theta})\pi$ . In area (2),  $I^{\overline{ND}_2,ND_1}$  is the solution of  $\mu'(I)[2(\overline{\theta} - \underline{\theta})\pi - \pi(\overline{\theta}\phi - 1) + \tau] - 1 = 0$  or  $\mu'(I) = 1/B$ , where  $B = 2(\overline{\theta} - \underline{\theta})\pi - \pi(\overline{\theta}\phi - 1) + \tau$  that we compare to  $\mu'(I) = 1/A$ . As  $B < A$  for  $\tau < \overline{\tau}_2$ , we thus show that  $I_W^{\overline{ND},ND} > I^{\overline{ND}_2,ND_1}$  in area (2). The same reasoning applies for all remaining areas. A comparison of all the investment levels in all the areas is summarized in table C1, as well as the profit and total welfare functions and the privately and socially optimal investment levels.

**Table C1. Results under a PBR regime**

| Figure 2 | Profit  | Privately Optimal Investment | Welfare                                 | Socially Optimal Investment  |
|----------|---|------------------------------|---|--|
| Area (1) | $\overline{\Pi}^{ND_1}, \underline{\Pi}^{ND_1}$ | $I^{\overline{ND}_1,ND_1}$   | $\overline{W}^{ND}, \underline{W}^{ND}$ | $I_W^{ND,ND} = I^{\overline{ND}_1,ND_1}$                                       |
| Area (2) | $\overline{\Pi}^{ND_2}, \underline{\Pi}^{ND_1}$ | $I^{\overline{ND}_2,ND_1}$   | $\overline{W}^{ND}, \underline{W}^{ND}$ | $I_W^{\overline{ND},ND} = I^{\overline{ND}_1,ND_1} > I^{\overline{ND}_2,ND_1}$ |
| Area (3) | $\overline{\Pi}^{ND_2}, \underline{\Pi}^{ND_2}$ | $I^{\overline{ND}_2,ND_2}$   | $\overline{W}^{ND}, \underline{W}^{ND}$ | $I_W^{\overline{ND},ND} = I^{\overline{ND}_1,ND_1} > I^{\overline{ND}_2,ND_2}$ |
| Area (4) | $\overline{\Pi}^D, \underline{\Pi}^{ND_2}$      | $I^{\overline{D},ND_2}$      | $\overline{W}^D, \underline{W}^{ND}$    | $I_W^{\overline{D},ND} < I^{\overline{D},ND_2}$                                |
| Area (5) | $\overline{\Pi}^D, \underline{\Pi}^D$           | $I^{\overline{D},D}$         | $\overline{W}^D, \underline{W}^D$       | $I_W^{\overline{D},D} = I^{\overline{D},D}$                                    |
| Area (6) | $\overline{\Pi}^D, \underline{\Pi}^{ND_1}$      | $I^{\overline{D},ND_1}$      | $\overline{W}^D, \underline{W}^{ND_1}$  | $I_W^{\overline{D},ND} = I^{\overline{D},ND_1}$                                |

**Appendix D: Optimal Investment Levels under a PBR and Patent Regime**

When the producer has the choice between a patent and a PBR, we represent the different areas in figure 6. For the nine different areas, we calculate the optimal investment levels chosen by the seed producer. In areas (1)–(6), the results are similar to those we found before, and the areas are similar to those of figure 2.

In area (7) in figure 6, the seed producer chooses a PBR for a small innovation and a patent for a large innovation. He then solves the following optimization program:

$$(D1) \quad \max_I \{ \mu(I)\bar{\Pi}^P + (1 - \mu(I))\underline{\Pi}^{ND_2} - I \},$$

which gives the FOC  $\mu'(I)[2(\bar{\theta} - \underline{\theta})\pi - \pi + \underline{\theta}\pi\phi - \tau - c_P] - 1 = 0$ . We denote  $I^{\bar{P},ND_2}$  the optimal level of investment, which is decreasing with  $\tau$  and increasing with  $\phi$ .

If the seed producer decides to patent both types of innovation, in area (8), he solves

$$(D2) \quad \max_I \{ \mu(I)\bar{\Pi}^P + (1 - \mu(I))\underline{\Pi}^P - I \},$$

which gives the FOC  $\mu'(I)[2(\bar{\theta} - \underline{\theta})\pi] - 1 = 0$ . We denote  $I^{\bar{P},P}$  the optimal level of investment, which does not depend on  $\tau$  or  $\phi$ .

In area (9), if the seed producer chooses a PBR for a small innovation and a patent for a large innovation, he chooses  $I$  that solves

$$(D3) \quad \max_I \{ \mu(I)\bar{\Pi}^P + (1 - \mu(I))\underline{\Pi}^D - I \},$$

which gives the FOC  $\mu'(I)[(2\bar{\theta} - \underline{\theta}(1 + \phi))\pi - c_P] - 1 = 0$ . We denote  $I^{\bar{P},D}$  the optimal level of investment, which does not depend on  $\tau$  but decreases with  $\phi$ .

We then calculate the socially optimal levels of investment that solve

$$(D4) \quad \max_I \{ \mu(I)\bar{W} + (1 - \mu(I))\underline{W} - I \},$$

as before. We find the different levels of socially optimal investment, one for each of the nine areas in figure 6. We also compare these different levels of investment. We summarize the profit and social welfare functions and the optimal investment levels in table D1.

**Table D1. Results under a PBR and Patent Regime**

| Figure 6 | Profit                                     | Privately optimal investment | Welfare                            | Socially optimal investment                                     |
|----------|--|------------------------------|------------------------------------|---|
| Area (1) | $\bar{\Pi}^{ND_1}, \underline{\Pi}^{ND_1}$ | $I^{\bar{ND}_1,ND_1}$        | $\bar{W}^{ND}, \underline{W}^{ND}$ | $I_W^{ND,ND} = I^{\bar{ND}_1,ND_1}$                             |
| Area (2) | $\bar{\Pi}^{ND_2}, \underline{\Pi}^{ND_1}$ | $I^{\bar{ND}_2,ND_1}$        | $\bar{W}^{ND}, \underline{W}^{ND}$ | $I_W^{\bar{ND},ND} = I^{\bar{ND}_1,ND_1} > I^{\bar{ND}_2,ND_1}$ |
| Area (3) | $\bar{\Pi}^{ND_2}, \underline{\Pi}^{ND_2}$ | $I^{\bar{ND}_2,ND_2}$        | $\bar{W}^{ND}, \underline{W}^{ND}$ | $I_W^{\bar{ND},ND} = I^{\bar{ND}_1,ND_1} > I^{\bar{ND}_2,ND_2}$ |
| Area (4) | $\bar{\Pi}^D, \underline{\Pi}^{ND_2}$      | $I^{\bar{D},ND_2}$           | $\bar{W}^D, \underline{W}^{ND}$    | $I_W^{\bar{D},ND} < I^{\bar{D},ND_2}$                           |
| Area (5) | $\bar{\Pi}^D, \underline{\Pi}^D$           | $I^{\bar{D},D}$              | $\bar{W}^P, \underline{W}^P$       | $I_W^{\bar{D},D} = I^{\bar{D},D} < I_W^{\bar{D},ND}$            |
| Area (6) | $\bar{\Pi}^D, \underline{\Pi}^{ND_1}$      | $I^{\bar{D},ND_1}$           | $\bar{W}^D, \underline{W}^{ND_1}$  | $I_W^{\bar{D},ND} < I^{\bar{D},ND_1}$                           |
| Area (7) | $\bar{\Pi}^P, \underline{\Pi}^{ND_2}$      | $I^{\bar{P},ND_2}$           | $\bar{W}^P, \underline{W}^{ND}$    | $I_W^{\bar{P},ND_2} < I^{\bar{P},ND_2}$                         |
| Area (8) | $\bar{\Pi}^P, \underline{\Pi}^P$           | $I^{\bar{P},P}$              | $\bar{W}^P, \underline{W}^P$       | $I_W^{\bar{P},P} = I_W^{\bar{D},ND}$                            |
| Area (9) | $\bar{\Pi}^P, \underline{\Pi}^D$           | $I^{\bar{P},D}$              | $\bar{W}^P, \underline{W}^D$       | $I_W^{\bar{P},D} = I^{\bar{P},D} < I_W^{\bar{D},ND}$            |

### Appendix E: Incentives to Innovate

We first consider the PBR regime and calculate the seed producer's *ex ante* expected profit for each of the six areas of figure 2. In area (1), given the optimal investment  $I^{\overline{ND}_1, \underline{ND}_1}$  that does not depend on  $\tau$ , the *ex ante* expected payoff is

$$(E1) \quad \Pi^{\overline{ND}_1, \underline{ND}_1}(I^{\overline{ND}_1, \underline{ND}_1}) = \mu(I^{\overline{ND}_1, \underline{ND}_1})2(\overline{\theta} - \underline{\theta})\pi + 2\pi(\underline{\theta} - 1) - I^{\overline{ND}_1, \underline{ND}_1},$$

which does not depend on  $\tau$ .

In area (2), given the optimal investment  $I^{\overline{ND}_2, \underline{ND}_1}$  that increases with  $\tau$ , the *ex ante* expected payoff is

$$(E2) \quad \begin{aligned} \Pi^{\overline{ND}_2, \underline{ND}_1}(I^{\overline{ND}_2, \underline{ND}_1}(\tau), \tau) &= \mu(I^{\overline{ND}_2, \underline{ND}_1})[\overline{\theta}\pi(2 - \phi) - \pi + \tau] \\ &+ (1 - \mu(I^{\overline{ND}_2, \underline{ND}_1}))2\pi(\underline{\theta} - 1) - I^{\overline{ND}_2, \underline{ND}_1}, \end{aligned}$$

which we differentiate with respect to  $\tau$

$$(E3) \quad \frac{d\Pi^{\overline{ND}_2, \underline{ND}_1}}{d\tau} = \frac{\partial \Pi^{\overline{ND}_2, \underline{ND}_1}}{\partial I} \frac{\partial I}{\partial \tau} + \frac{\partial \Pi^{\overline{ND}_2, \underline{ND}_1}}{\partial \tau}.$$

Using the envelope theorem, the first part is equal to 0 and thus

$$(E4) \quad \frac{\partial \Pi^{\overline{ND}_2, \underline{ND}_1}}{\partial \tau} = \mu(I^{\overline{ND}_2, \underline{ND}_1}) > 0.$$

In area (3), given the optimal investment  $I^{\overline{ND}_2, \underline{ND}_2}$  that does not depend on  $\tau$ , the *ex ante* expected payoff is

$$(E5) \quad \Pi^{\overline{ND}_2, \underline{ND}_2}(I^{\overline{ND}_2, \underline{ND}_2}) = \mu(I^{\overline{ND}_2, \underline{ND}_2})(\overline{\theta} - \underline{\theta})\pi(2 - \phi) + \underline{\theta}\pi(2 - \phi) - \pi + \tau - I^{\overline{ND}_2, \underline{ND}_2}.$$

Thus, by differentiating it we obtain  $\partial \Pi^{\overline{ND}_2, \underline{ND}_2} / \partial \tau = 1 > 0$ .

In area (4), given  $I^{\overline{D}, \underline{ND}_2}$  that decreases with  $\tau$ , the *ex ante* expected payoff is

$$(E6) \quad \begin{aligned} \Pi^{\overline{D}, \underline{ND}_2}(I^{\overline{D}, \underline{ND}_2}(\tau), \tau) &= \mu(\cdot)[\overline{\theta}\pi(1 + \phi) - 2\pi - \tau(1 - \lambda)] \\ &+ (1 - \mu(\cdot))[\underline{\theta}\pi(2 - \phi) - \pi + \tau] - I^{\overline{D}, \underline{ND}_2}. \end{aligned}$$

Thus, by differentiating the expected payoff function, we obtain

$$(E7) \quad \frac{d\Pi^{\overline{D}, \underline{ND}_2}}{d\tau} = \frac{\partial \Pi^{\overline{D}, \underline{ND}_2}}{\partial I} \frac{\partial I}{\partial \tau} + \frac{\partial \Pi^{\overline{D}, \underline{ND}_2}}{\partial \tau}.$$

Using the envelope theorem, the first part is equal to 0 and thus

$$(E8) \quad \frac{\partial \Pi^{\overline{D}, \underline{ND}_2}}{\partial \tau} = -\mu(\cdot)(1 - \lambda) + (1 - \mu(\cdot)) = 1 - \mu(\cdot)(2 - \lambda).$$

The sign of this derivative depends on the value of  $\mu(I^{\overline{D}, \underline{ND}_2})$ . Thus

$$(E9) \quad \begin{aligned} \frac{\partial \Pi^{\overline{D}, \underline{ND}_2}}{\partial \tau} &< 0 \text{ if } \mu(I^{\overline{D}, \underline{ND}_2}) < 1/(2 - \lambda), \\ \frac{\partial \Pi^{\overline{D}, \underline{ND}_2}}{\partial \tau} &\geq 0 \text{ if } \mu(I^{\overline{D}, \underline{ND}_2}) \geq 1/(2 - \lambda). \end{aligned}$$

In area (5), given  $I^{\overline{D}, \underline{D}}$  that does not depend on  $\tau$ , the *ex ante* expected profit is

$$(E10) \quad \Pi^{\overline{D}, \underline{D}}(I^{\overline{D}, \underline{D}}) = \mu(I^{\overline{D}, \underline{D}})(\overline{\theta} - \underline{\theta})\pi(1 + \phi) + \underline{\theta}\pi(1 + \phi) - 2\pi - \tau(1 - \lambda) - I^{\overline{D}, \underline{D}}.$$

Thus, by differentiating the expected payoff function, we obtain  $\partial \Pi^{\bar{D},D} / \partial \tau = -(1 - \lambda) < 0$ .

In area (6), given  $I^{\bar{D},ND_1}$  that does not depend on  $\tau$ , the *ex ante* expected profit is

$$(E11) \quad \Pi^{\bar{D},ND_1} = \mu(I^{\bar{D},ND_1})\pi[(\bar{\theta} - \underline{\theta}) + \bar{\theta}\phi - \underline{\theta}] - I^{\bar{D},ND_1},$$

which is independent of  $\tau$ .

If we consider the functional form  $\mu(I) = 1 - \exp^{-I}$ , in area (4), we find that  $\partial \Pi^{\bar{D},ND_2} / \partial \tau < 0$ . In order to represent these functions in a graph  $(\Pi, \tau)$ , we use this functional form. We represent these functions in figure 9.

We now consider the case where both patents and PBRs are available and calculate the *ex ante* expected profit for each of the nine areas of figure 6. In areas (1)–(6), the expected payoffs have been calculated above and are, respectively,  $\Pi^{\bar{ND}_1,ND_1}$ ,  $\Pi^{\bar{ND}_2,ND_1}$ ,  $\Pi^{\bar{ND}_2,ND_2}$ ,  $\Pi^{\bar{D},ND_2}$ ,  $\Pi^{\bar{D},D}$ , and  $\Pi^{\bar{D},ND_1}$ .

In area (7), the expected payoff evaluated at  $I^{\bar{P},ND_2}$  is

$$(E12) \quad \Pi^{\bar{P},ND_2} = \mu(I^{\bar{P},ND_2})\bar{\Pi}^P + (1 - \mu(I^{\bar{P},ND_2}))\underline{\Pi}^{ND_2} - I^{\bar{P},ND_2}.$$

Using the envelope theorem, we calculate the derivative of  $\Pi^{\bar{P},ND_2}$  with respect to  $\tau$ :

$$(E13) \quad \frac{\partial \Pi^{\bar{P},ND_2}}{\partial \tau} = (1 - \mu(I^{\bar{P},ND_2})) > 0.$$

In area (8), the expected payoff evaluated at  $I^{\bar{P},P}$  is

$$(E14) \quad \Pi^{\bar{P},P} = \mu(I^{\bar{P},P})\bar{\Pi}^P + (1 - \mu(I^{\bar{P},P}))\underline{\Pi}^P - I^{\bar{P},P},$$

which does not depend on  $\tau$ .

In area (9), the expected payoff evaluated at  $I^{\bar{P},D}$  is

$$(E15) \quad \Pi^{\bar{P},D} = \mu(I^{\bar{P},D})\bar{\Pi}^P + (1 - \mu(I^{\bar{P},D}))\underline{\Pi}^D - I^{\bar{P},D}.$$

Using the envelope theorem, we calculate the derivative of  $\Pi^{\bar{P},D}$  with respect to  $\tau$ :

$$(E16) \quad \frac{\partial \Pi^{\bar{P},D}}{\partial \tau} = -(1 - \mu(I^{\bar{P},D}))(1 - \lambda) < 0.$$

Using the same functional form for  $\mu(I)$ , we represent the different expected payoff functions in figure 9.

## Appendix F: Welfare Analysis

We calculate the total expected welfare evaluated at the private optimal levels of investment.

Under a PBR regime, we again use the six different areas in figure 2 and the corresponding private investment levels reported in table A1. For instance, in area (1), the total expected welfare is

$$(F1) \quad W^{\bar{ND}_1,ND_1} = \mu(I^{\bar{ND}_1,ND_1})2(\bar{\theta} - \underline{\theta})\pi + 2\underline{\theta}\pi - I^{\bar{ND}_1,ND_1}.$$

As  $I^{\bar{ND}_1,ND_1}$  does not depend on  $\tau$ ,  $\bar{W}^{\bar{ND}_1,ND_1}$  also does not depend on  $\tau$ .

In area (2), the total expected welfare is

$$(F2) \quad W^{\bar{ND}_2,ND_1} = \mu(I^{\bar{ND}_2,ND_1})2(\bar{\theta} - \underline{\theta})\pi + 2\underline{\theta}\pi - I^{\bar{ND}_2,ND_1}.$$

The optimal investment  $I^{\bar{ND}_2,ND_1}$  increases with  $\tau$ , and thus

$$(F3) \quad \frac{\partial W^{\bar{ND}_2,ND_1}}{\partial \tau} = \frac{\partial I^{\bar{ND}_2,ND_1}}{\partial \tau} (\mu'(I^{\bar{ND}_2,ND_1})2(\bar{\theta} - \underline{\theta})\pi - 1) > 0,$$

as  $\mu'(I^{\bar{ND}_2,ND_1})2(\bar{\theta} - \underline{\theta})\pi - 1 > 0$ .

For each area, we calculate the total expected welfare evaluated at the optimal investment levels. We use the functional form  $\mu(I) = 1 - \exp^{-I}$  to represent figure 10.