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R&D Investments in Plant Breeding under Changing Intellectual Property Rights

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ABSTRACT

In a Cournot duopoly model, we examine three policy regimes relevant to current international plant breeding: patents alone, patents with a farmer exemption to use saved seed, and patents with research collaboration. In the symmetric version of the model where firms are identical, we show that the social planner prefers patents with research collaboration over patents alone and prefers the patents alone to patents with a farmer exemption. We examine two variations of the model where firms are asymmetric i. due to cost differences and ii. due to the different endowments of germplasm. Situations develop where the research collaboration resolves the common pool problem and increases R&D investment and where it creates free riding problem and decreases R&D investment. We show that the lower cost (more endowed) breeder invests more in R&D under the research collaboration than patents if variety differentiation is high and cost (knowledge endowment) dispersion is low. On the other hand, the higher cost (less endowed) breeder, generally, invests less in R&D under a research collaboration if variety differentiation or cost (knowledge endowment) dispersion is low. These findings suggest new gains are likely from the adoption of international conventions of plant breeders' rights.

Keywords: Plant Breeding, Farmer Exemption, Research Collaboration, Intellectual Property Rights, Product Differentiation, Cournot Oligopoly
JEL Classifications: D21, D43, D60, D82, L13, L24, O34, O38, Q16, Q18.

1. INTRODUCTION

The self-pollinating nature of some crops makes crop research output non-excludable and thus R&D investment in plant breeding industry considerably different from other sectors. In normal self-pollinating grain production, a portion of the crop can be saved and used again for seed without significant yield losses. This farmer saved seed, can present a serious problem for the economics of plant breeding. The development of a new variety can take up to ten years and cost "several million dollars (Acquaah, 2012)." Without some form of intellectual property right (IPR), the private sector has no incentive to invest in R&D in plant breeding (Galushko, 2008).

Most countries have some form of public investment in seed breeding or regulation to help create incentives in the private sector. International agreements on plant breeders' rights (PBRs) and IPRs have attempted to address the problems faced by trading nations as they try to change the nature of seed research from non-rival to rival and provide some return to breeding investment.

The International Union for the Protection of New Varieties of Plants (UPOV) was initiated to protect IPR in plant breeding. Seventy seven countries have joined the UPOV convention as of February 2021 (UPOV, 2021). Intellectual property laws, however, are not harmonized and there remain differences in the regimes of protection which are adopted by different members of UPOV. Some countries follow the 1978 version of the convention (e.g. Argentina, Norway, Brazil, and New Zealand). In other countries, the 1991 version of the UPOV is implemented (e.g. U.S., Canada, France, and Australia). The two versions of the convention are similar in the way that both regimes provide the owner with exclusive commercial rights for a limited period. The differences arise from various exemptions that different member states impose to the exclusive commercial rights of the owner.

The first common exemption to IPRs, namely the farmer exemption, gives farmers the right to save the seed they have grown for subsequent reproduction. Some empirical studies suggest that this system is less effective than patents (IPRs with no exemptions) in creating incentives to innovate for breeders e.g. Carew and Devadoss (2003), Alston and Venner (2002), and Perrin et al. (1983). Under UPOV-78, saving and replanting seeds was an automatic right for farmers; whereas under UPOV-91, this automatic right is eliminated, but can be granted by the member states (GRAIN, 1996). In the U.S., patents provide plant breeders with the power to prevent farmers from self-production of seeds with certain traits. In some countries, taxes or royalties are used to compensate plant breeders for the loss incurred as a result of farmers saving seeds.

Another important exemption to IPRs is the experimental use of registered varieties a.k.a. the researcher exemption. Unlike UPOV-78, under UPOV-91 the researcher exemption does not include the "essentially derived" varieties or the varieties which carry the essential characteristics of the initial protected varieties. The researcher exemption has been introduced to avoid limiting innovators access to the stock of knowledge while they are developing other new varieties (Moschini and Yerokhin, 2007). Due to the cumulative nature of innovation in the seed breeding industry, Scotchmer (1991) suggests that excessively strong IPRs can limit access to knowledge in research leading to "the tragedy of the anticommons" (Heller and Eisenberg, 1998). Lindner (1999) indicates that developing a specific new transgenic plant requires fifteen to fifty identifiable tangible components as research inputs. These components can be the property of different breeding firms. On the other hand, while the researcher exemption may solve "the tragedy of the anticommons" in some scenarios by connecting the building blocks of research, it might create a free riding problem when firms try to benefit from the R&D efforts of others. (Moschini and Yerokhin, 2007) show that a researcher exemption generally reduces the plant breeding firms' incentive to invest in R&D.

An alternative to the researcher exemption is a form of research collaboration where two or more plant breeding firms voluntarily join forces to develop new varieties when it is beneficial to all firms involved in the development of the new variety. This may eliminate the problem of limited access of breeders to propriety inputs in developing new varieties while mitigating the free riding problem. When such opportunities and synergies arise, more R&D investment and new varieties with better characteristics can benefit farmers as well.

1.1. Objectives

To explore the implications of the current policy options related to PBRs and IPRs, we develop a duopolistic model of product competition to study the effect of different IPRs on firm and industry level R&D investment as well as on farmer and breeder surplus. The model focuses on a game of three different IPRs that roughly resemble patents alone, patents with farmer exemption, and patents with research collaboration.

Our general model is characterized by many homogenous farmers who buy the breeders' varieties and two breeders who invest in product R&D, which increases the varieties' productivity, and sell their varieties to the farmers assuming Cournot competition. In the benchmark game, a symmetric duopoly is modelled where breeders have an identical initial endowment of knowledge and identical cost structures but produce differentiated products. Here the focus is to investigate how the industry-level R&D is affected by the choice of IPRs, and how IPRs rank in terms of their impact on farmer surplus and breeder surplus in the short run and long run.

This variation includes three stages as follows. In stage zero of this game, a social planner decides on the choice of IPR regime to maximize the summation of farmer surplus and breeder surplus. In stage one, breeders produce new varieties, given their initial stock of knowledge, and sell them to the farmers in a Cournot style duopoly market. In the same stage, breeders invest in R&D which increases the yield of varieties and consequently the derived demand for the new varieties by the farmers. If the IPR adopted by the social planner is research collaboration, breeders can contemporaneously utilize one another's product of R&D subject to a spillover parameter. If the IPR is a farmer exemption, farmers who purchased a new variety from either breeder, save the variety for replanting in stage two. In stage two, breeders compete in the Cournot competition style and sell their new varieties to the farmers. If the IPR regime is a farmer exemption, the portion of the farmers who did not purchase a variety from the breeders in stage one can buy the new varieties in stage two.

The breeders' profit is calculated for the two plant breeding firms to reflect the breeder surplus. The surplus for farmers buying the new varieties in different stages is calculated separately. The results show that the farmer exemption can decrease farmer surplus in stage two by deteriorating the breeders' incentive to invest in R&D. Furthermore, research collaboration addition to patent may solve the common pool problem when varieties are not close substitutes. On the other hand, it might create a free riding problem and lower the breeders' incentive to undertake R&D when varieties are not differentiated enough.

In the second and third variations of the game, we focus on patent and research collaboration. Breeders are assumed to be asymmetric either in cost structure or in initial stock of knowledge. The game is, again, in three stages in these variations. In stage zero, asymmetric firms decide whether a patent or a research collaboration is in place. The set of equilibrium IPRs constitutes the IPRs under which both breeders have higher or equal profits compared to the alternative IPR. In stage one, breeders invest in demand-increasing R&D. In stage two, breeders sell their new varieties to the farmers assuming Cournot competition. In the first asymmetric variation of the model, firms are assumed to have different efficiency in conducting R&D and one firm incurs lower R&D unit cost. In the second asymmetric variation, firms are similarly efficient but one firm benefits from a larger starting stock of knowledge. We show that research collaboration vis-à-vis stand-alone patents can be either increasing or decreasing the firm- and industry-level R&D for both asymmetric variations depending on the spillover and differentiation degrees. One of our most important findings, perhaps, is that where the research collaboration *is* encouraging higher R&D, asymmetric firms voluntarily cooperate in conducting research and a research collaboration policy may not need to be enforced by the social planner.

1.2. This Study in the Context of Previous Work

One of the first theoretical studies to examine the effect of plant breeding R&D on welfare when IPRs are enacted, was conducted by Moschini and Lapan (1997). They modeled plant breeding R&D as a "drastic" or "non-drastic" innovation for seed sold to competitive farmers based on the ability to price a new product. Patents, in their model, enable the breeder to charge farmers a price above the breeder's marginal cost. They conclude that when the innovation is non-drastic (the firm cannot capture full monopolistic rents), farmer and consumer surpluses are unaffected by R&D. On the other hand, when the innovation is drastic (full rents can be charged), the combination of larger agricultural output and lower prices results in an unambiguous increase in consumer surplus. The effect of a drastic innovation on farmer surplus is dependent on the elasticity of demand. Moschini et al. (2000) extended this model to an open economy and applied the model to the case of Roundup Ready (RR) soybeans. They found that the breeder realized the largest portion of benefit or about 44 to 75 percent. Farmers and consumers share from the benefit were 10-16 and 15-40 percent, respectively. Falck-Zepeda et al. (2000) used a similar approach to study the benefits of Bt cotton and Herbicide-Tolerant (HT) soybeans. Unlike, Moschini et al. (2000), they found a higher share of the surplus going to the farmers and consumers. Malla and Brewin (2015) also showed considerable gains to producers when two drastic innovations (RR and Liberty Link) were developed under more competition. These papers mainly focus on the distributional effect of patents and R&D as opposed to the differences in regimes of intellectual property protection.

Galushko (2008) developed a model that compares the incentive for innovation and the distribution of benefits from research under protection of patent or PBRs with a farmer exemption. In that study, the research industry is modeled as a monopolistic seed company investing in R&D. The company develops a new variety and sells it to heterogeneous farmers. The results show that, under certain conditions, PBRs are as effective as patents in creating incentives for the breeder to invest in R&D activity. In addition, the share of farmers in total benefits is generally smaller under patents than under PBRs. In a second model, Galushko (2008) examines the effect of IPRs on the incentive of private and public researchers to share their research input. She finds that private firms and public researchers tend to maintain their exclusive rights and that knowledge sharing or cross licensing in the breeding industry is undermined under patents. She suggests that patents have generally reduced germplasm and have limited the flow of information to downstream research in the wheat and canola breeding industries and thus they can be a policy concern.

Another theoretical paper was developed by Moschini and Yerokhin (2007) to examine the impact of a researcher exemption to patent on the incentive of plant breeders to innovate. In their Bertrand model, there exist two firms that initially have access to the same germplasm or stock of knowledge. Each firm then engages in R&D activity and innovates a new seed with some probability. Only the best product is sold in the market. If a firm does not improve its product, it cannot proceed to the next innovation stage under a patent. It can only participate in the next innovation stage if the rival firm's innovation succeeds and the researcher exemption policy is in place. Their results suggest that the researcher exemption inevitably weakens the *ex-ante* incentive for private firms to innovate, especially when there is high cost and risk related to this research. On the other hand, when the costs and risks of research are low, a researcher exemption may be optimal in creating innovation incentives for private firms as it provides a larger pool of innovations for the subsequent inventions.

A more recent study by Hervouet and Langinier (2015) examines the effect of a farmer exemption on the price of new varieties and on the breeders' incentive for varietal development. They model the breeding industry as a monopolistic firm. They also assume that when farmers save seed, they pay a tax to the breeder to compensate her for the loss. They consider different scenarios where only the patent or farmer exemption is enacted or where a mix of the two policies is implemented. They find that a relatively high tax can eliminate self-production by farmers when only farmer exemption is enacted. Moreover, when farmer exemption and patents coexist, the self-production is not fully prevented. However, the breeder's incentive to innovate is increased. They conclude that the monopolist has the highest incentive to innovate if the IPR regime is either patent or farmer exemption with a prohibitive tax level.

Our paper contributes to the current literature in several ways. First, we extend the studies by Galushko (2008) and Hervouet and Langinier (2015) by distinguishing between the initial effect of a farmer exemption on farmer surplus and the effect in subsequent periods. This enables us to show if the farmers' initial optimal choice of IPR is different from the choice in subsequent periods. Second, we incorporate the effect of a research collaboration to be able to compare it with a farmer exemption and when the policy regime is pure patents. This helps assess whether farmer surplus can be greater under a research collaboration than that under a farmer exemption. This also helps us, ultimately, derive the social planner's optimal IPR.

Third, the models in the literature take breeding firms as either identical entities or a monopolist. This seems to be a strong assumption in the imperfectly oligopolistic agricultural biotechnology industry. Firms can be asymmetric in different aspects. One source of difference can arise from the production cost of firms especially if they engage in private cost-reducing R&D activities. Some firms, perhaps, incur lower costs in their varietal development process than others. Another important source of asymmetry in the plant breeding industry is the quality of germplasm that each firm possesses. At any point in time, firms can have access to significantly different stocks of knowledge; especially if the information is kept private and the leakage is small. Previous studies have not accounted for the effect of IPR protection regimes on the plant breeding industry when firms are asymmetric. When asymmetries exist in the industry at the time of policy implementation, each policy can have a considerably different impact on the performance of different firms. Specifically, different policies can give advantages to some firms and disadvantages to others.

We show that relaxing the previous assumptions can have important implications regarding the breeders' incentive to innovate and their surplus as well as their incentive to share their knowledge. The asymmetry incorporated into our model is the main driving force of the difference between our findings and the previous papers. We derive the conditions necessary for competing asymmetric breeders to cooperatively conduct R&D research even when one breeder is more efficient or has access to a greater stock of knowledge. Together with the symmetric variation of our model, we conclude that breeders' and society's interest are aligned for a wide range of our model parameters and that when a research collaboration successfully functions as an effective mechanism to encourage R&D investment, breeders may voluntarily cross license their varieties or share their knowledge and the social planner's prevention of such collaboration may lower firm- and industry-level R&D. We also show that under certain conditions, the research collaboration can lower the breeders' incentive to innovate and cause free riding. If so, the enforcement of a research collaboration by social planner can result in lower firm- and industry-level R&D. Table 1 describes how we introduce the effect of IPRs protection regimes on the demand for new varieties and on varietal development.

As shown in Table 1, under farmer exemption (case FE), if farmers buy the newly developed seed, they save it and use it in the subsequent period. Therefore, the seed purchased in stage one is deducted from the demand of period two. Under research collaboration (case RC), farmers are not allowed to save seed. However, researchers can use one another's technological information in order to develop new varieties. Under patent with no exemption (case NE), neither farmers nor researchers are given the exemptions.

Table 1: Three IPR policy regimes

Policy	Demand in Period 2	R&D Investment
Farmer Exemption (case FE)	Firms lose the part of the market demand which was fulfilled in period 1 by either firms	Firms conduct research independently; R&D spillover is zero
Patent with No Exemption (case NE)	No loss in demand; buyers who purchased seed in period 1 must buy seed in period 2	Firms conduct research independently; R&D spillover is zero
Research Collaboration (case RC)	No loss in demand; buyers who purchased seed in period 1 must buy seed in period 2	Firms share their stock of knowledge to develop new varieties; R&D spillover exists and can go up to a maximum level

The table describes the R&D investments and demand for firms' varieties following different regimes of IPRs. In the table FE, NE, and RC stand for patent with farmer exemption, patent with no exemption, and patent with research collaboration

The rest of the paper is organized as follows. We first develop our general model in section 2. Then we develop three variations to this benchmark model in section 3. In subsection 3.1, we assume breeders are symmetric and we compare three different IPR regimes, namely patents, patents with farmer exemption, and patents with research collaboration. In subsection 3.2 and 3.3 we focus on patents and research collaboration regimes. In subsection 3.2, we assume cost dispersion exists between the breeding firms and in subsection 3.3 it is assumed that one firm starts the game with a higher stock of knowledge. Finally, in section 4, we present our discussion and concluding remarks.

2. BENCHMARK MODEL

Consider an industry with two firms that produce differentiated varieties and sell them to many perfectly competitive homogeneous farmers. We denote the firms h and l and assume that firm h has some advantage over firm l: firms are cost identical but firm h has access to a larger stock of knowledge or a higher quality germplasm at the beginning of the game compared to firm l; alternatively, the initial stock of knowledge is the same but firm h is more efficient in conducting R&D or has a lower unit cost than firm l.

The IPR is determined in period zero. Observing the regime of IPR, in period one, breeders produce new varieties using their privately owned stock of knowledge and sell them in the market under Cournot competition. Over the same period, breeders conduct research to improve the productivity of their varieties which are sold in the subsequent period. In period two, firms supply the improved varieties in the market and compete again à la Cournot. Farmers choose between the seeds based on their productivity and price. The choice of farmers and breeders is different under different IPRs. Under a protection policy with farmer exemption, denoted FE hereafter, farmers who buy a variety from either breeding firm are assumed to save the seed for replanting it in period two. Thus, the breeders lose the portion of demand which was met in period one by either of them. It is assumed that the improvement of the varieties from period one to period two is incremental and the increase in the seed productivity is not large enough relative to the price to justify purchasing the improved seed in period two by the farmers who already bought a breeder's seed in period one. This assumption holds in equilibrium for the range of variety differentiation which will be introduced shortly. In addition, costs related to storing and cleaning the varieties for subsequent production under FE are assumed to be zero, for simplicity.[1]

When the protection policy with research collaboration, hereafter denoted RC, is enacted, breeders must share their innovation product when trying to introduce a new variety for period two. Therefore, spillover of knowledge is assumed to happen in this case (and only this case). Farmers must buy the varieties from the

1 Costs related to storing and cleaning the varieties for subsequent production can range from zero to a prohibitive level where FE and NE become identical policies. For simplicity, we assume these costs are zero. However, small enough amounts for these costs do not change the results qualitatively due to continuity of the profit functions.

breeders in each period and seed saving by farmers is not allowed. Finally, under patents with no exemption (hereafter denoted NE), farmers are not allowed to save seed for replanting and breeders do not share their knowledge and thus own it privately in period two as well as in period one.

The comparative static analysis for a general demand function for breeders proved to be intractable. We assume the following linear demand functions for breeders that allow for a partial equilibrium analysis. Assume the derived inverse demand functions for the breeders' varieties in period one and two are, respectively, given by:

$$w_{i,1}=A(G_i)-x_{i,1}-\theta x_{j,1} \quad ;i, j\in\{h, l\}, i\neq j \quad (1)$$

$$w_{i,2}=A(G_i, e_i, e_j)-x_{i,2}-\theta x_{j,2}-\Psi (x_{i,1}+x_{j,1}) \; ; i, j\in\{h, l\}, i\neq j \quad (2)$$

where Ψ is equal to one when the protection policy is FE and zero otherwise, G_i denotes the initial stock of knowledge owned by firm i, $w_{i,1}$ and $w_{i,2}$ stand for the price that firm i charges farmers for its variety in periods 1 and 2 (i.e. $x_{i,1}$ and $x_{i,2}$), respectively.[2] e_i is the R&D expenditure undertaken by firm i and $A(G_i)$ and $A(G_i, e_i, e_j)$ are the product of breeders' R&D expenditure in the previous periods. Moreover, in firm i's demand equation in period two, e_j is a determining factor only when the regime of protection is RC. Finally, θ denotes the degree of differentiation between varieties x_l and x_h and, to assure an interior solution, $0<\theta<1$ is assumed, that is we exclude the possibility of production of either perfect substitute varieties or non-substitutable varieties by the two breeders. A firms' initial stock of knowledge and their investments in R&D activity is assumed to shift the farmers demand for varieties. A similar approach was applied previously by Kabiraj and Roy (2004). They modeled the effect of R&D investments on consumers demand and assumed firms' R&D investments increase the quality of goods, captured by an outward shift in the demand curve.

In equations 1 and 2, R&D investment by breeding firms is assumed to increase the variety productivity and accordingly the farmers' demand for the variety. The magnitude of the increase in the productivity of firm i's variety (i.e. A_i) is a function of the initial stock of knowledge (G_i) and firm i's R&D investment (e_i) which is assumed to be in linear form for simplicity. If the protection regime is RC, firm i's effective R&D investment is also a function of firm j's R&D investment (e_j) subject to a spillover parameter, $0\leq\beta\leq1$, and period one and two stock functions, respectively, are:

$$A_{i,1}=G_i \; ; i\in\{h, l\} \quad (3)$$

$$A_{i,2}=e_i+G_i+\beta e_j \; ; i, j\in\{h, l\}, i\neq j \quad (4)$$

The spillover parameter, β, is equal to *zero* for protection regimes other than RC. In this study, spillover refers to the voluntary exchange of useful technological information rather than an involuntary leakage. The degree of spillover regulates the impact that new R&D efforts can be useful to the competing firm under research collaboration regime. Equation (4) is similar to how the R&D spillover is formulated in the study by Kamien et al. (1992). In their paper, however, the R&D investment is undertaken to decrease the firms' unit cost of production.[3] They argue that the R&D process is modeled this way to describe the type of R&D process which involves many possible paths and trial and error. If the firms share information completely, they can avoid duplication of efforts whereas when information is kept and used privately each firm has to try the same trial and error process[4]. On the other hand, with high spillover, when varieties are not sufficiently differentiated, each firm has a lower incentive to invest in costly R&D which strengthens the competitor and firms try to free ride instead.

Let the cost function for firm i's varietal improvement be given by:

$$E_i=k_i e_i^2 \; ; i \in \{h, l\} \quad (5)$$

where E_i is the cost associated with varietal development incurred by firm i, e_i is how much firm i spends on R&D projects, and k_i is a positive scalar that captures a breeder's efficiency in conducting R&D.[5] Costs other than R&D associated with producing the seed are assumed to be zero.

Finally, breeder surplus is assumed to be captured by the summation of breeder profits. And farmer surplus in each period is defined as summation of the areas under farmers demand for each variety and above the variety's price and is given by:

$$FS_{i,1} = \sum_i \frac{1}{2}((1+\Psi)A(G_i) - w_{i,1}))x_{i,1} \qquad ;i, j \in \{h,l\}, i \neq j \quad (6)$$

$$FS_{i,2} = \sum_i \frac{1}{2}(A(G_i,e_j,e_i) - w_{i,2}))x_{i,2} \qquad ;i, j \in \{h,l\}, i \neq j \quad (7)$$

where FS stands for farmer surplus.

We can now have a complete description of the game. Our game is set as follows. In period zero, the IPR is determined. In period one, given the IPR set in period zero, firms produce a new variety using their available stock of knowledge or germplasm. Assume

2 Unlike Moschini and Yerokhin (2007), we assume both verities are bought by farmers. The intuition behind this assumption is that because the varieties are differentiated and each variety has its strengths and weaknesses, by applying variety complementation, farmers plant multiple varieties (in larger fields) or a rotation of various varieties (in smaller fields) to obtain consistent performance (Klein et al., 2012).

3 Spence (1984) modeled knowledge accumulation resulted from cost reducing R&D investments, by a firm itself as well as by other firms through spillover, using a similar approach.

4 The trial and error process to develop improved varieties seems to be a reasonable description of R&D conducted in the agricultural biotechnology industry. Malla and Gray (2005) describe a R&D process in plant breeding as firms using research trials to search for the highest yielding off-spring. This results in developing an improved variety with higher expected yield.

5 The cost function assumed in equation (5) implies decreasing return to scale. This property is also implied in the cost function (Eq. 16) assumed in Kabiraj and Roy (2004) for R&D production (Eq. 15). With a more general specification such as $E_i=k_0+k_{1i} e_i^2$; $i\in\{h, l\}$, if the scalar $k_0>0$ is small enough, it does not change our results qualitatively.

this privately owned germplasm is the results of each firm's R&D activity before implementing a new intellectual property protection policy. Firms can be, therefore, asymmetric in terms of the stock of knowledge or the quality of germplasm they have access to in period one. They can also be asymmetric in terms of the cost of undertaking R&D due to one firm having a proprietary knowledge that makes it more efficient in conducting further R&D. Farmers buy the new varieties from the breeding firms and their demand for the new varieties depends on the productivity of firms' innovated varieties and their prices. Different levels of productivity for the varieties are represented in different intercepts of the demand curves which are endogenously determined in the model. In period one, breeding firms also engage in a costly R&D activity and invest in product innovation. These decisions determine the demand for each firm's product in period two. The model is solved in the standard Cournot style and by means of backward induction.

The amount the breeding firms invest in R&D activity and how much they produce differ under different types of protection regimes. Based on the inverse demand equations described above for the breeders and their cost functions, the intertemporal profit maximization problem for breeders can be written as:

$$\max_{x_{i,t}\geq 0, e_i\geq 0} \pi_i = \sum_{t=1,2} w_{i,t}x_{i,t} - k_i e_i^2 \qquad ;i\in\{h,l\} \qquad (8)$$

Where t refers to periods one and two when breeders sell their varieties to the farmers. Discount rate is assumed to be zero.[6] A Subgame Perfect Nash Equilibrium is determined by simultaneously solving the profit maximization problems for firms for each period and under each policy. Given the above specification of the functions, optimal levels of R&D investment, price charged and quantity produced by each firm, and farmer and breeder surplus under different types of protection regimes are derived. We show the detailed derivation process for this general model under NE in the appendix. The variations of the general model can be thought of as special cases of the general model and can be solved with a similar approach and thus are not shown.

3. DERIVATION OF EQUILIBRIA

In subsection 3.1 through 3.3, we characterize the optimal levels of the amount spent on R&D and the quantity of varieties produced by breeders. We solve the model using backward induction. We solve the level of production in period two for the firms given their level of R&D and quantity produced in period one. Then we use these values to find the optimal levels of R&D investment and quantities produced in period one. Finally, we plug the optimal values found for period one back into the optimal equations of period two to derive the endogenous variables in terms of the model's parameters.

3.1. The Symmetric Model

We start with a symmetric model where breeders are assumed to have the same cost function and initial endowment of knowledge.

For simplicity, we make the following assumptions:

Assumption 3.1.1. Breeders R&D cost function is given by $E_i=e_i^2$, $i\in\{h, l\}$; that is $k=1$

Assumption 3.1.2. Breeders initial stock of knowledge is $G_i=1$, $i\in\{h, l\}$

In addition, a social planner decides the IPR in the symmetric model. In period zero, the social planner chooses an IPR to maximize the summation of breeder and farmer surplus. In period one, breeders produce new varieties and sell them to farmers based on their initial stock of knowledge and compete à la Cournot. Breeders also conduct R&D in period one to stimulate their variety demand in period two. In period two, breeders sell their new varieties to farmers, again, assuming Cournot competition. The game ends in period two.[7]

With symmetric breeders, we can simplify the inverse demand, $w_{i,t}$, for new varieties to

$$w_{i,1}=1-x_{i,1}-\theta x_{j,1} \;;i, j\in\{h, l\},i\neq j \qquad (9)$$

$$w_{i,2}=1+\beta e_j+e_i-x_{i,2}-\theta x_{j,2}-\Psi(x_{i,1}+x_{j,1}) \;;i, j\in\{h, l\},i\neq j \qquad (10)$$

In addition, profits can be written as

$$\max_{x\geq 0,e\geq 0} \pi_i = \sum_{t=1,2} w_{i,t}x_{i,t} - e_i^2 \qquad ;i,j\in\{h,l\},i\neq j \qquad (11)$$

With the above demand and profit functions, optimal quantities and R&D investments by firms are given by

$$x_{i,1}^{FE} = \frac{\theta^6+4\theta^5-6\theta^4-28\theta^3+8\theta^2+48\theta+12}{\theta^7+6\theta^6+4\theta^5-40\theta^4-64\theta^3+64\theta^2+132\theta+24} \;;i,j\in\{h,l\},i\neq j \qquad (12)$$

$$x_{i,1}^{z} = \frac{1}{\theta+2} \qquad ;i,j\in\{h,l\},i\neq j, z\in\{NE,RC\} \qquad (13)$$

$$x_{i,2}^{FE} = \frac{\theta(\theta-2)(\theta+2)(\theta^3+2\theta^2-4\theta-6)}{\theta^7+6\theta^6+4\theta^5-40\theta^4-64\theta^3+64\theta^2+132\theta+24} \;;i,j\in\{h,l\},i\neq j \qquad (14)$$

$$x_{i,2}^{NE} = \frac{(\theta-2)(\theta+2)}{\theta^3+2\theta^2-4\theta-6} \qquad ;i,j\in\{h,l\},i\neq j \qquad (15)$$

$$x_{i,2}^{RC} = \frac{-(\theta-2)(\theta+2)}{\beta\theta(\beta+1)-2\beta-\theta^3-2\theta^2+4\theta+6} \qquad ;i,j\in\{h,l\},i\neq j \qquad (16)$$

$$e_i^{FE} = \frac{-2\theta(\theta^3+2\theta^2-4\theta-6)}{\theta^7+6\theta^6+4\theta^5-40\theta^4-64\theta^3+64\theta^2+132\theta+24} \;;i,j\in\{h,l\},i\neq j \qquad (17)$$

6 A positive discount rate will change the threshold values in propositions without changing the qualitative results. Therefore, the discount rate is assumed to be zero for clarity of disposition.

7 Under a more complex game where farmers who buy a new seed in period one can replant it in both periods two and three for free and famers who buy a new seed in period two can replant it in period three under FE, the main conclusions derived in this model remain the same.

$$e_i^{FE} = \frac{-2\theta(\theta^3 + 2\theta^2 - 4\theta - 6)}{\theta^7 + 6\theta^6 + 4\theta^5 - 40\theta^4 - 64\theta^3 + 64\theta^2 + 132\theta + 24} \quad ; i, j \in \{h, l\}, i \neq j \tag{18}$$

$$e_i^{RC} = \frac{2 - \beta\theta}{\beta\theta(\beta + 1) - 2\beta - \theta^3 - 2\theta^2 + 4\theta + 6} \quad ; i, j \in \{h, l\}, i \neq j \tag{19}$$

The above equations give rise to the following propositions. Farmer and breeder surplus as well as all proofs of the propositions are detailed in the mathematical appendix.

Proposition 1 – When firms are symmetric, R&D investment under the IPRs can be characterized as:

i. Breeders tend to invest less in R&D under RC than NE when variety differentiation is low or knowledge spillover is high
ii. Firms undertake less R&D under FE than NE or RC for all levels of variety differentiation and knowledge spillover.

Part i of proposition 1 points at two potential disadvantages of RC: firstly, when varieties produced are not very different, breeders are less willing to share knowledge since it generates a stronger competitor; secondly, when knowledge spillover is high, along with the first disadvantage, firms try to reduce costly R&D and free ride on other firms' R&D investment. Part ii refers to the intuitive problem with FE that reduced demand for new variety as a result of farmers' saved seeds decreases the breeders' incentive to undertake R&D.

The next step is to examine how IPRs rank in terms of farmer surplus. Farmer surplus is calculated by the standard approach with one exception: under FE, buyers of the new varieties in period one benefit from the varieties for two periods, the surplus net of price for period one plus the surplus without payment in period two. Moreover, we examine the farmer surplus obtained from varieties purchased in period one separately from that gained by buying the varieties in period two. The reason for this is that R&D investment undertaken in period one only affects the varieties produced in period two. Therefore, FE in period one does not negatively affect the farmer surplus by lowering the R&D investment in the same period. This can be viewed as the short run effect. The FE regime, however, lowers the R&D investment undertaken in period one used in the production of new varieties in period two. This negatively affects farmer surplus gained by using the new varieties in period two and can be thought of as the long run effect.

From binary comparisons of farmer surplus (FS) under different IPRs, in the short run (SR) and in the long run (LR), we can prove proposition 2 (see appendix).

Proposition 2 – When breeding firms are symmetric, farmer surplus under IPRs has the following ranking:

i. In period one, $FS_{SR}^{NE} = FS_{SR}^{RC} < FS_{SR}^{FE}$
ii. In period two, $FS_{LR}^{FE} < FS_{LR}^{NE} \leq FS_{LR}^{RC}$.

Proposition 2 shows that, even though farmers might enjoy a higher surplus in period one under FE, in period two and through decreases in R&D investment by breeders, this policy results in the lowest farmer surplus. The proposition also shows that, in the long run, farmer surplus under RC is at least as high as that under NE, making RC a more favourable regime for farmers. Figure 1 depicts the farmers all-time optimal IPR. It shows that if knowledge spillover is relatively high and varieties are differentiated enough, the positive effect of increases in R&D in period two under RC can overcome the loss in the farmer surplus in period one, making RC the farmers preferred policy in both periods one and two.

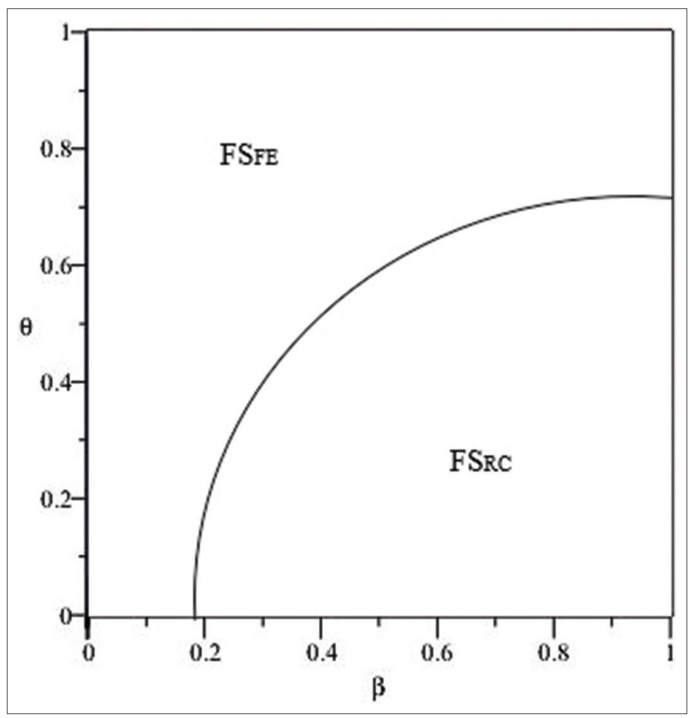
We now consider breeders surplus (BS). Binary comparisons of the breeders' profits under different IPRs result in the following proposition:

Proposition 3 – when firms are symmetric, IPRs in terms of the breeders' profit are ranked as

$BS^{FE} < BS^{NE} \leq BS^{RC}$

Note in proposition 3 that symmetric breeders are better off on aggregate under RC than NE for all range of the model parameters. This shows than even when R&D investment is lower under RC than under NE, (when varieties are similar and knowledge spillover is high) the increase in breeders overall profit due to knowledge sharing overcomes the loss of lower R&D investment by each firm.

Figure 1: Farmers all-time optimal IPR



θ represents variety differentiation and β stands for knowledge spillover in Figure 1. In addition, the areas in Figure 1 show which policy dominates the other policies in terms of all-time farmers surplus. For similar varieties or when varieties are differentiated and knowledge spillover is low, farmer exemption is the dominant policy. On the other hand, when variety differentiation is high (θ is low) and knowledge spillover is high, research collaboration dominates pure patents and farmer exemption in generating the highest farmers surplus

The social planner chooses the IPR which maximizes the total surplus: the sum of farmers and breeders surpluses in both periods. The social planner prefers RC to NE and NE to FE for all range of the model parameters. Proofs for proposition 3 and the following proposition are detailed in the appendix.

Proposition 4 – under FE, breeders charge a lower price in period two than period one.

Proposition 4 indicates that, under FE, the increase in demand that results from R&D investment does not overcome the loss in demand for the breeders. This finding is related to the literature of durable goods, pioneered by Coase (1972). Under FE, the saved seed presents a durable feature to the developed variety. Using the durable goods theory, Perrin and Fulginity (2004) compared the monopolist's pricing of a non-durable crop trait such as hybrid or a variety protected by patent and a durable crop trait such as the case of varieties protected by FE. They find that the price which the monopolist can charge under FE is about a quarter of that under a patent. This is in line with Coase's conjecture where the monopolistic firm inevitably charges a lower price or the competitive price in the absence of a credible commitment. We incorporate the effect of R&D in varietal development in our study. Proposition 4 shows that even in the presence of demand-increasing R&D, in equilibrium, the breeders have to charge a lower price for their varieties than in the first period, under FE. This is clear in wheat market in Canada, where seed is saved without penalty. There is a drastic fall in price from certified seed to commodity wheat which has virtually the same yield potential.

So far it is assumed that firms are symmetric. This helped answer the important question of how IPRs affect breeder and farmer surplus. We now relax this assumption to examine how breeders are affected by research collaborations when they are asymmetric. Two important forces are at play. On the one hand, research collaboration may eliminate the tragedy of the anticommons and increase R&D investment and welfare of breeders and farmers. On the other hand, it may reduce a firm's incentive to invest in R&D due to the free-riding effect. We examine this issue in the next subsections.

3.2. The Asymmetric Model

It may seem intuitive that in an oligopoly market structure with product competition with identical products, firms that are more efficient or enjoy a head start prefer no knowledge sharing or research collaboration. However, with product differentiation which naturally emerges in the plant breeding industry, the choice of IPR might not be straightforward. That is, if varieties' characteristics are different enough, breeders have higher market power over their product and, in the presence of a knowledge spillover, even larger and more efficient firms may prefer RC over NE. In this subsection and next, we derive the conditions that can give rise to this phenomenon. In addition, proposition 1 showed that symmetric firms tend to free ride on other firms R&D investment when knowledge spillover is high and as a result they invest less under RC. We assume knowledge spillover is maximum i.e. β=1 and investigate whether there is a possibility where asymmetric firms invest more under RC than NE.

The focus in subsection 3.2.1 and 3.2.2 is on the effect of the research collaboration on breeders' R&D investment. Thus, the two policies of NE and RC are examined. The game in this case has three periods similar to the symmetric model. However, unlike the symmetric case, in the asymmetric model firms decide whether to participate in a RC policy or choose NE, in period zero. In period one, breeders invest in R&D to improve the quality of their varieties that they sell in period two to farmers under Cournot competition. In subsection 3.2.1, we assume that firms benefit from an equal stock of knowledge (or germplasm) but are asymmetric in terms of their efficiency in conducting R&D investments. In subsection 3.2.2, on the other hand, we assume firms have the same R&D cost structure, but one firm enjoys a head start or enters the game with a greater stock of knowledge. Games are solved by backward induction.

3.2.1 Firms Are Asymmetric in Costs

Costs in undertaking R&D is assumed to be the source of asymmetry between the firms while it is assumed that G_i=1 for $i\in\{h, l\}$. Let firm h's unit cost of conducting R&D be the same as before, i.e., 1, however, let firm l incur a k unit cost when investing in each unit of R&D where k is a scalar and is greater than 1. This means that firm h is more efficient in undertaking R&D than firm l. Under this assumption, our general model of breeders' inverse demand and profit changes to:

$$w_i=1+\beta e_j+e_i-x_i-\theta x_j \;;i,j\in\{h, l\},i\neq j \tag{20}$$

$$\max_{x\geq 0,e\geq 0} \pi_h = w_h x_h - e_h^2 \tag{21}$$

$$\max_{x\geq 0,e\geq 0} \pi_l = w_l x_l - k e_l^2 \tag{22}$$

β is zero for the NE case and it is equal to one for RC. With the above inverse demand and profit functions, optimal quantities and R&D investments by firms are given by:

$$x_h^{NE} = \frac{(\theta-2)(\theta+2)(k\theta^3-2k\theta^2-4k\theta+8k-2)}{k\theta^6-12k\theta^4+44k\theta^2-4\theta^2-48k+12} \tag{23}$$

$$x_l^{NE} = \frac{k(\theta-2)(\theta+2)(\theta^3-2\theta^2-4\theta+6)}{k\theta^6-12k\theta^4+44k\theta^2-4\theta^2-48k+12} \tag{24}$$

$$x_i^{RC} = \frac{k(\theta+2)}{k\theta^2+4k\theta+3k-1} \qquad ;i,j\in\{h,l\} \tag{25}$$

$$e_h^{NE} = \frac{-2(k\theta^3-2k\theta^2-4k\theta+8k-2)}{k\theta^6-12k\theta^4+44k\theta^2-4\theta^2-48k+12} \tag{26}$$

$$e_l^{NE} = \frac{-2(\theta^3-2\theta^2-4\theta+6)}{k\theta^6-12k\theta^4+44k\theta^2-4\theta^2-48k+12} \tag{27}$$

$$e_h^{RC} = \frac{k}{k\theta^2+4k\theta+3k-1} \tag{28}$$

$$e_l^{RC} = \frac{1}{k\theta^2+4k\theta+3k-1} \tag{29}$$

Breeder profits are given by:

$$BS_h^{NE} = \frac{(\theta^2-2)(\theta^2-6)\left(k\theta^3-2k\theta^2-4k\theta+8k-2\right)^2}{\left(k\theta^6-12k\theta^4+44k\theta^2-4\theta^2-48k+12\right)^2} \quad (30)$$

$$BS_l^{NE} = \frac{k\left(\theta^3-2\theta^2-4\theta+6\right)^2(k\theta^4-8k\theta^2+16k-4)}{\left(k\theta^6-12k\theta^4+44k\theta^2-4\theta^2-48k+12\right)^2} \quad (31)$$

$$BS_h^{RC} = \frac{k^2(\theta+1)(\theta+3)}{\left(k\theta^2+4k\theta+3k-1\right)^2} \quad (32)$$

$$BS_l^{RC} = \frac{k(k\theta^2+4k\theta+4k-1)}{\left(k\theta^2+4k\theta+3k-1\right)^2} \quad (33)$$

Proposition 5 –

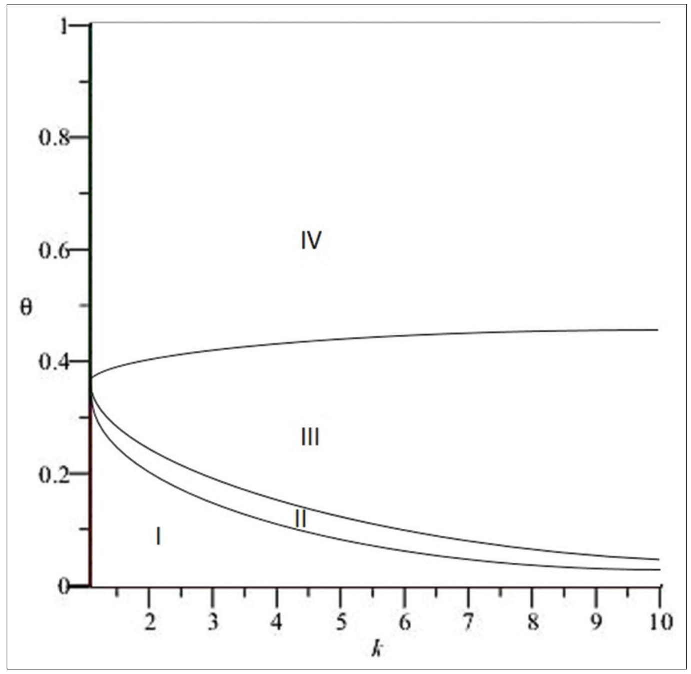
i. The lower cost firm invests more in R&D under RC than NE if variety differentiation is high and cost dispersion is low
ii. The higher cost firm invests less in R&D under RC than NE if variety differentiation is low or if variety differentiation is moderate and cost dispersion is low.

Part i of proposition 5 depicts the situation where RC can overcome the tragedy of the anticommons. When varieties are highly differentiated, each breeder has a high market power or is nearly a monopolist in her respective market. At the same time, when breeders are not quite different in terms of efficiency in conducting R&D, the more efficient breeders can benefit from the knowledge product of less efficient breeders. These two forces together make RC preferable by breeders over NE in equilibrium.

The opposite is true in part ii of proposition 5 where RC not only does not eliminate the tragedy of the anticommons, but it creates the common pool problem and lowers R&D investment by breeders. When variety differentiation is low, each breeder has a lower market power. With low cost dispersion, the less efficient breeder has an incentive to free ride on the more efficient breeder's R&D investment under RC.

Figure 2 illustrates proposition 5 and it shows some important features of the difference between NE and RC in terms of firm level as well as industry level R&D. The figure is divided into four areas. Part *I* and *II* show the range of the parameters for which industry-level R&D is higher under RC than NE. Part *III* and *IV* are the opposite. Area *I* represents the region where firm *h* invests more under RC than NE. This means that not only can RC increase the less efficient firm's R&D investment but also encourage the more efficient firm to undertake more R&D investment when varieties are highly differentiated. Firm *h* loses its incentive as the cost differences (i.e. *k*) increases. Part *II* shows the level of the parameters where firm *h* invests less under RC than NE, however, this decrease is overcome by the increase in R&D by firm *l*, resulting in a higher industry-level R&D under RC than NE. Part *I* and *II* can be considered as the range of the parameters for which RC can eliminate the tragedy of the anticommons effect of RC. Part *III* and *IV* refer to the range of the parameters for which

Figure 2: R&D comparison under NE and RC



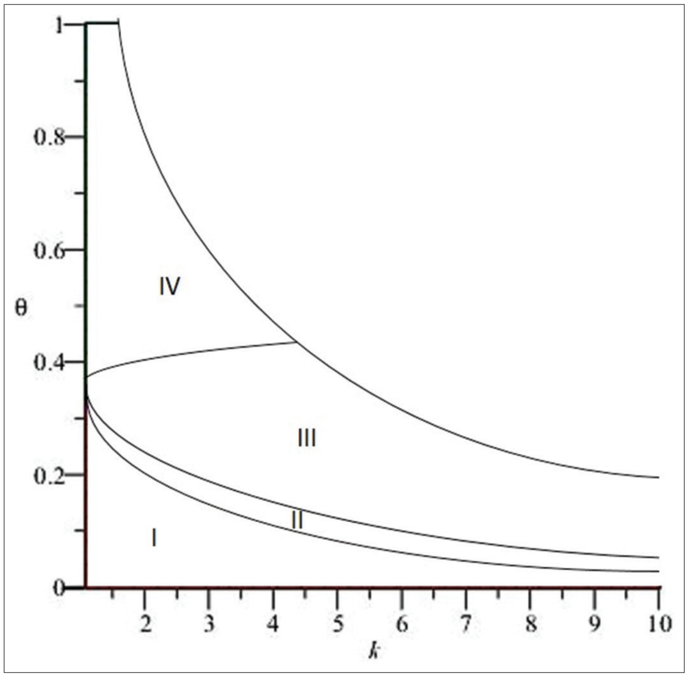
θ represents variety differentiation and k captures breeders' efficiency asymmetry in conducting R&D in Figure 2. In the figure, areas *I* and *II* show the range of the parameters for which industry-level R&D is higher under RC than NE. Part Area *III* and *IV* are the opposite

RC would decrease the incentive to invest in industry-level R&D. More importantly, part *IV* is where R&D investment by firm *l* is higher under NE than under RC which reflects the free-riding effect or the tragedy of the commons.

We observed that for a range of the model parameters, RC can increase firm- and industry-level R&D. To determine if, in the absence of a social planner, firms agree to follow a research collaboration policy, we compare their profit under each case. It is assumed that a firm will voluntarily accept a policy if its profit is greater under that policy than under the alternative. It is easy to show that firm *l* prefers RC for the total range of the model parameters. A possible agreement, therefore, depends on the profit of firm under the two policies. If the range of parameters where RC overcomes the tragedy of the anticommons coincides with that of the firms' interest, RC need not necessarily be enforced by a social planner since firms cooperate in conducting R&D to increase their profits. Figure 3 emphasizes this point. It is basically Figure 2 but with the area where firm prefers RC over NE. It shows that firm *h* prefers RC to NE if variety differentiation is high or cost dispersion is low.

Figure 3 shows that where RC can help increase R&D, asymmetric firms voluntarily adopt it. This suggests that if anything, the policy concerned with RC may be towards approving it where it is not deteriorating R&D activity. For example, in Figure 3, firms agree on collaborating in R&D in area *IV*. However, the form of this collaboration is two firms with highly similar varieties and with less overall R&D investment collude where the more efficient firm does the main

Figure 3: R&D levels and firms selected IPR



θ represents variety differentiation and k captures breeders' efficiency asymmetry in conducting R&D in Figure 3. In the figure, areas are constrained by the conditions under which breeders voluntarily adopt an RC policy. In addition, areas *I* and *II* show the range of the parameters for which industry-level R&D is higher under RC than NE. Part Area *III* and *IV* are the opposite

R&D activity and the less efficient firm free rides. Even this case can be beneficial to the society if it prevents unfruitful and repeated R&D investments. Here R&D is mainly undertaken by the more efficient firm and yet farmers benefit from two different varieties. This result may be controversial in the sense that it shows a research collaboration need not necessarily be enforced where firms' interest and that of the society are aligned. In subsection 3.2.2, we check whether these results hold when firms are similarly efficient in conducting R&D, however one firm has a larger starting stock of knowledge.

3.2.2. Firms are asymmetric in their stock of knowledge

In this subsection, we assume that firm h starts the game with a greater stock of knowledge (e.g. higher quality germplasm), and investigate how RC compares to NE in terms of firm- and industry-level R&D. The firms' cost structures in this variation of the model are assumed to be identical (k_i=1, $i\in\{h,l\}$) and the only source of asymmetry is the stock of knowledge. We assume that the firms' stock of knowledge has the following relationship.

$$G_h=\tau . G_l \tag{34}$$

where τ is a scalar which represents the asymmetry in the firms' initial stock of knowledge. We set G_l equal to one in eq. (34) and thus τ is assumed to be greater than one and it is the stock of knowledge of firm h at the beginning of the game. We also assume that τ is less than the level of asymmetry for which quantity produced by the less endowed firm drops to zero, denoted by $\breve{\tau}$, as indicated in the following assumption.

Assumption 3.3. Breeders asymmetry in stocks for all $0<\theta<1$ is below the level which creates a monopoly market structure given by:

$$\breve{\tau} = \frac{2(\theta^2-3)}{\theta(\theta^2-4)} \tag{35}$$

With the above assumptions, our general model of breeders' inverse demand and profit changes to:

$$w_l=1+\beta e_h+e_l-x_l-\theta x_h \tag{36}$$

$$w_h=\tau+\beta e_l+e_h-x_h-\theta x_l \tag{37}$$

$$\max_{x\geq 0, e\geq 0} \pi_i = w_i x_i - e_i^2 \qquad ;i,j\in\{h,l\} \tag{38}$$

Similar to the previous case, β is zero for the NE case and it is equal to one for RC. With the above inverse demand and profit functions, optimal quantities and R&D investments by firms are given by

$$x_h^{NE} = -\frac{(\theta-2)(\theta+2)(2\tau\theta^2-\theta^3-6\tau+4\theta)}{(\theta^3-2\theta^2-4\theta+6)(\theta^3+2\theta^2-4\theta-6)} \tag{39}$$

$$x_l^{NE} = \frac{(\theta-2)(\theta+2)(\tau\theta^3-4\tau\theta-2\theta^2+6)}{(\theta^3-2\theta^2-4\theta+6)(\theta^3+2\theta^2-4\theta-6)} \tag{40}$$

$$x_h^{RC} = -\frac{2\tau\theta-\theta^2+3\tau-2\theta+1}{(\theta-2)(\theta^2+4\theta+2)} \tag{41}$$

$$x_l^{RC} = \frac{\tau\theta^2+2\tau\theta-\tau-2\theta-3}{(\theta-2)(\theta^2+4\theta+2)} \tag{42}$$

$$e_h^{NE} = \frac{2(2\tau\theta^2-\theta^3-6\tau+4\theta)}{(\theta^3-2\theta^2-4\theta+6)(\theta^3+2\theta^2-4\theta-6)} \tag{43}$$

$$e_l^{NE} = -\frac{2(\tau\theta^3-4\tau\theta-2\theta^2+6)}{(\theta^3-2\theta^2-4\theta+6)(\theta^3+2\theta^2-4\theta-6)} \tag{44}$$

$$e_h^{RC} = -\frac{2\tau\theta-\theta^2+3\tau-2\theta+1}{(\theta-2)(\theta+2)(\theta^2+4\theta+2)} \tag{45}$$

$$e_l^{RC} = \frac{\tau\theta^2+2\tau\theta-\tau-2\theta-3}{(\theta-2)(\theta+2)(\theta^2+4\theta+2)} \tag{46}$$

Breeder profits are given by:

$$BS_h^{NE} = \frac{(\theta^2-2)(\theta^2-6)\left(2\tau\theta^2-\theta^3-6\tau+4\theta\right)^2}{\left(\theta^3-2\theta^2-4\theta+6\right)^2\left(\theta^3+2\theta^2-4\theta-6\right)^2} \tag{47}$$

$$BS_l^{NE} = \frac{(\theta^2-2)(\theta^2-6)\left(\tau\theta^3-4\tau\theta-2\theta^2+6\right)^2}{\left(\theta^3-2\theta^2-4\theta+6\right)^2\left(\theta^3+2\theta^2-4\theta-6\right)^2} \tag{48}$$

$$BS_h^{RC} = \frac{(\theta+1)(\theta+3)(2\tau\theta-\theta^2+3\tau-2\theta+1)^2}{\left(\theta-2\right)^2\left(\theta+2\right)^2\left(\theta^2+4\theta+2\right)^2} \tag{49}$$

$$BS_l^{RC} = \frac{(\theta+1)(\theta+3)(\tau\theta^2+2\tau\theta-\tau-2\theta-3)^2}{(\theta-2)^2(\theta+2)^2(\theta^2+4\theta+2)^2} \quad (50)$$

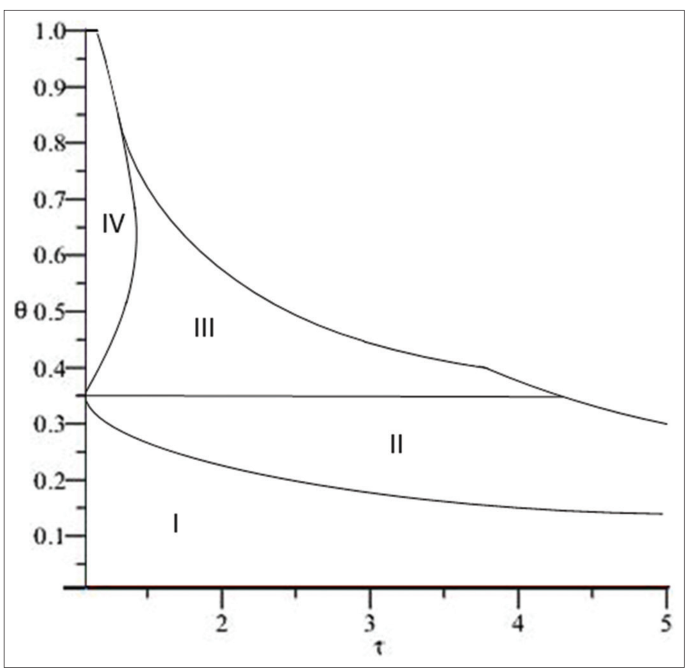
The above functions give rise to proposition 6.

Proposition 6 –

i. The firm with a larger stock of knowledge invests more in R&D under RC than NE if variety differentiation is high and head-start dispersion is low
ii. The firm with a smaller stock of knowledge invests less in R&D under RC than NE if variety differentiation and head-start dispersion are low.

Proposition 6 draws a similar conclusion to proposition 5. Part i derives the range of the model parameters for which firm invests more in R&D under RC than NE or the possibility that RC increases the incentive of the firm with the larger stock of knowledge to invest in R&D. This result arises since with high variety differentiation, each breeder has a strong market power in her variety market and thus a research collaboration benefits the breeders by increasing their demand more than it harms them by creating a stronger competitor. Part ii of the proposition, however, refers to the range of the parameters for which firm invests less under RC than NE and free rides. Different cases of proposition 6 are presented in Figure 4. Apart from the constraint, the area of the figure is restricted to the part for which firm 's profit is higher under RC than NE that is where firm volunteers to share knowledge with firm .

Figure 4: R&D comparison under NE and RC and firms selected IPR



θ represents variety differentiation and τ reflects breeders' asymmetry in the initial stock of knowledge in Figure 4. In the figure, areas are constrained by the conditions under which breeders voluntarily adopt an RC policy. In addition, areas *I* and *II* show the range of the parameters for which industry-level R&D is higher under RC than NE. Part Area *III* and *IV* are the opposite

Similar to the previous subsection, Figure 4 is divided into four areas. *I* and *II* are the areas for which industry-level R&D is higher under RC than NE. Parts *III* and *IV* show the opposite. Area *I* shows the range of the model parameters for which RC increases firm *h*'s incentive to invest in R&D. Area *IV* shows the range for which firm *l* invests less in R&D under RC than NE. In other words, firm *l* free rides on firm *h*'s R&D investment in the presence of a research collaboration. The graph, however, shows that when RC increases the industry-level and to some extent the firm-level R&D, firms voluntarily cooperate in research even when firm *l* free rides on firm *h*'s R&D investment. Outside this area, RC may result in a reduction in the firm- and industry-level R&D.

4. CONCLUSION

The durability and non-excludability features of breeders' research products make appropriability a challenge in plant breeding industry and undermine breeders' incentive to innovate. Different policies have been introduced to solve this problem. Previous researchers have examined the effect of these policies on plant breeders' incentive to innovate and based on different objectives have drawn different policy implications. In the previous studies, the industry was modeled as either a monopolist or a few identical firms. This overlooks the impact of these policies on different types of firms when there are some levels of asymmetry among them. With the presence of asymmetry, some policies might be favourable to a group of firms and harmful to other firms. Asymmetry is introduced to the analysis in this paper to examine how IPRs affect breeders' incentive to innovate and surplus when they are not identical entities.

Another controversial aspect of IPRs is the farmer exemption provision. If farmer surplus is modeled in the short run and long run separately, one might explain how farmers may favour a farmer exemption in the short run. However, using a reasonable range of starting conditions, we find that farmers prefer a different IPR in the later periods due to the undermining effect of farmer exemption on the incentive of breeders for varietal improvement. We assumed linear factor demands for varieties since a general model proved untraceable. However, even with this setting, we believe we obtain novel results in understanding the effect of IPRs on the breeder's incentive to innovate, breeder and farmer surpluses, and especially on the effectiveness of research collaboration in creating higher incentive to invest in R&D by asymmetric firms.

Considering the ongoing debate on the effect of IPRs on farmer surplus and the fact that many countries are still skeptical about joining the UPOV convention or in upgrading to the UPOV-91 version, this study sheds more light on the issue and expands the analysis to some aspects of IPRs which were not deeply examined previously. Our results agree with the critics of farmer exemption in that farmer saved-seeds undermine the incentive to innovate by breeders to the extent that farmers can be worse off in the long run. We also found that the free-riding effect seems to be a greater problem concerning research collaboration than the tragedy of the anticommons. Our analysis shows that when research collaboration *is* effective in encouraging higher R&D investment, it could be voluntarily practiced by asymmetric breeders. Under UPOV-91, breeders can choose if they want to share their knowledge or cross license their innovation products and it is up to the member states whether a farmer exemption is granted to farmers or not. Overall, our results suggest possible gains from the UPOV-91 convention that were not discussed in the previous studies. We also shed light on concerns about a concentrated sector with asymmetries in costs or stocks of knowledge that are relevant to the current plant breeding industry in a number of countries.

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MATHEMATICAL APPENDIX

The benchmark model derivation -

With the farmers' demand for the new varieties, breeders face a maximization problem given by

$$max_{x\geq 0,\, e\geq 0}\pi_i = \sum_{t=1,2} w_{i,t}\, x_{i,t} - k_i\, e_i^2\,;\; i\in\{h, l\} \quad (51)$$

The first order conditions for the breeders' problem in period two, given their R&D investment in period one, is as follows:

$$FOCs: G_i + e_i - 2x_{i,2} - \theta x_{j,2} = 0\,;\; i, j\in \{h, l\},\, i\neq j \quad (52)$$

By solving the above FOCs simultaneously, we get the quantities of period two as functions of R&D of period one, given by:

$$x_{i,2} = -\frac{2\left(G_i + e_i\right) - \theta\left(G_j + e_j\right)}{(\theta-2)(\theta+2)} \quad ;i, j\in\{h,l\}, i\neq j \quad (53)$$

The next step is to plug the above optimal quantities into the breeders profit function and derive FOCs for R&D investments:

$$FOCs := \frac{2\left(4(G_i + e_i) - k_i e_i\left(\theta^4 - 8\theta^2 + 16\right) - 2\theta(G_j + e_j)\right)}{(\theta-2)^2(\theta+2)^2} = 0$$
$$;i, j\in\{h,l\}, i\neq j \quad (54)$$

By solving the above FOCs simultaneously, we get the optimal level of R&D investments by breeders given by

$$e_i = \frac{2\left(2G_i(1+k_j(\theta^2-4)) - \theta k_j G_j\left(\theta^2-4\right)\right)}{k_i k_j\left(\theta^6 - 12\theta^4 + 48\theta^2 - 64\right) - 4\left(\left(k_i + k_j\right)\left(\theta^2-4\right)+1\right)}$$
$$;i, j\in\{h,l\}, i\neq j \quad (55)$$

Moreover, FOCs for $x_{i,1}$ are

$$FOCs:\; G_i - 2x_{i,1} - \theta x_{j,1} = 0\;;i,j\in\{h,l\}, i\neq j \quad (56)$$

And the optimal quantities of breeders' varieties in period one can be derived by solving the above FOCs simultaneously:

$$x_{i,1} = \frac{\theta G_j - 2G_i}{(\theta-2)(\theta+2)} \quad ;i, j\in\{h,l\}, i\neq j \quad (57)$$

Finally, the optimal levels of quantities produced by the breeders in period two can be obtained by plugging the optimal R&D into their equations:

$$x_{i,2} = -\frac{k_i(\theta-2)(\theta+2)\left(2G_i(1+k_j(\theta^2-4)) - \theta k_j G_j\left(\theta^2-4\right)\right)}{k_i k_j\left(\theta^6 - 12\theta^4 + 48\theta^2 - 64\right) - 4\left(\left(k_i + k_j\right)\left(\theta^2-4\right)+1\right)}$$
$$;i, j\in\{h,l\}, i\neq j \quad (58)$$

Thus, the optimal quantities are derived as functions of the model parameters. It can be easily shown that the second order conditions for the maximization problems above are satisfied. In addition, the non-negativity condition requires that if $G_i > G_j$, the following relation must hold

$$\frac{G_i}{G_j} < \breve{\tau} = \frac{2(k_i\left(\theta^2-4\right)+1)}{k_i\theta\left(\theta^2-4\right)} \quad (59)$$

Farmer and breeder surplus in the symmetric model

Farmer surplus of the farmers that buy the varieties in period 1, under various IPRs is given by:

$$FS_{SR}^{FE} = \frac{(\theta^6 + 4\theta^5 - 6\theta^4 - 28\theta^3 + 8\theta^2 + 48\theta + 12)(2\theta^7 + 11\theta^6 + 2\theta^5 - 74\theta^4 - 84\theta^3 + 120\theta^2 + 192\theta + 36)}{\left(\theta^7 + 6\theta^6 + 4\theta^5 - 40\theta^4 - 64\theta^3 + 64\theta^2 + 132\theta + 24\right)^2} \quad (60)$$

$$FS_{SR}^{z} = \frac{\theta+1}{\left(\theta^2+2\right)^2}, z\in\{NE, RC\} \quad (61)$$

Farmer surplus of the farmers that buy the varieties in period 2, under various IPRs is given by:

$$FS_{LR}^{FE} = \frac{\theta(\theta-2)(\theta+2)(\theta^3 + 2\theta^2 - 4\theta - 6)(\theta^7 + 5\theta^6 + 2\theta^5 - 34\theta^4 - 54\theta^3 + 56\theta^2 + 120\theta + 24)}{\left(\theta^7 + 6\theta^6 + 4\theta^5 - 40\theta^4 - 64\theta^3 + 64\theta^2 + 132\theta + 24\right)^2} \quad (62)$$

$$FS_{LR}^{NE} = \frac{(\theta+1)(\theta-2)^2(\theta+2)^2}{\left(\theta^3 + 2\theta^2 - 4\theta - 6\right)^2} \quad (63)$$

$$FS_{LR}^{RC} = \frac{(\theta+1)(\theta-2)^2(\theta+2)^2}{\left(\beta\left(\beta\theta + \theta - 2\right) - \theta^3 - 2\theta^2 + 4\theta + 6\right)^2} \quad (64)$$

Breeders surplus under various IPRs is given by:

$$BS^{FE} = \frac{4(\theta^{12} + 7\theta^{11} - 96\theta^9 - 128\theta^8 + 476\theta^7 + 894\theta^6 - 948\theta^5 - 2296\theta^4 + 336\theta^3 + 2040\theta^2 + 720\theta + 72)}{\left(\theta^7 + 6\theta^6 + 4\theta^5 - 40\theta^4 - 64\theta^3 + 64\theta^2 + 132\theta + 24\right)^2} \quad (65)$$

$$BS^{NE} = \frac{4(\theta^6 + 4\theta^5 - 4\theta^4 - 30\theta^3 - 14\theta^2 + 48\theta + 42)}{(\theta+2)^2\left(\theta^3 + 2\theta^2 - 4\theta - 6\right)^2} \quad (66)$$

$$BS^{RC} = \frac{2(\beta^4\theta^2 + \beta^3\left(2\theta^2 - 4\theta\right) + \beta^2\left(-3\theta^4 - 8\theta^3 + 5\theta^2 + 8\theta + 4\right) - 2\beta\left(\theta^4 - 2\theta^3 - 16\theta^2 - 6\theta + 12\right) + 2\left(\theta^6 + 4\theta^5 - 4\theta^4 - 30\theta^3 - 14\theta^2 + 48\theta + 42\right))}{(\theta+2)^2\left(\beta\left(\beta\theta + \theta - 2\right) - \theta^3 - 2\theta^2 + 4\theta + 6\right)^2} \quad (67)$$

Proposition 1 Proof – first consider part i. The binary comparison of the equilibrium R&D under NE and RC results in

$$e_i^{NE}-e_i^{RC}=\frac{\beta(\theta^4+2\theta^3-4\theta^2-2\theta(\beta+4)+4)}{(\theta^3+2\theta^2-4\theta-6)(\beta\theta(\beta+1)-2\beta-\theta^3-2\theta^2+4\theta+6)}$$

(68); with the following conditions:

a. $e_i^{NE}-e_i^{RC}>0$ iff $\frac{\theta^4+2\theta^3-4\theta^2-8\theta+4}{2\theta}<\beta\le 1$ or $0.3593040860<\theta<1$

b. $e_i^{NE}-e_i^{RC}\le 0$ iff $0\le\beta\le\frac{\theta^4+2\theta^3-4\theta^2-8\theta+4}{2\theta}$ and $0\le\theta\le 0.3593040860$

Now consider part ii.

$$e_i^{FE}-e_i^{NE}=\frac{4(\theta^6+4\theta^5-6\theta^4-28\theta^3+8\theta^2+48\theta+12)}{(\theta^7+6\theta^6+4\theta^5-40\theta^4-64\theta^3+64\theta^2+132\theta+24)(\theta^3+2\theta^2-4\theta-6)}$$

(69);

a. this is negative for all $0<\theta<1$

b.

$$e_i^{FE}-e_i^{RC}=\frac{\beta\theta^8+6\beta\theta^7-4\theta^6(1-\beta)-2\theta^5(\beta^2+21\beta+8)-4\theta^4(\beta^2+16\beta-6)+8\theta^3(\beta^2+10\beta+14)+4\theta^2(3\beta^2+32\beta-8)-48(4\theta+1)}{(\theta^7+6\theta^6+4\theta^5-40\theta^4-64\theta^3+64\theta^2+132\theta+24)(\beta\theta(\beta+1)-2\beta-\theta^3-2\theta^2+4\theta+6)}$$

; this is negative for all $0\le\beta\le 1$ and $0<\theta<1$

Proposition 2 Proof – first consider part i.

$$FS_{SR}^{FE}-FS_{SR}^{NE}=\frac{\theta^{15}+14\theta^{14}+62\theta^{13}+12\theta^{12}-676\theta^{11}-1580\theta^{10}+1344\theta^9+9376\theta^8+7400\theta^7-17296\theta^6-33920\theta^5-5248\theta^4+34608\theta^3+33504\theta^2+10944\theta+1152}{(\theta^7+6\theta^6+4\theta^5-40\theta^4-64\theta^3+64\theta^2+132\theta+24)^2(\theta+2)^2}$$

(71); this is greater than zero for all $0<\theta<1$.

Now consider part ii.

$$FS_{LR}^{FE}-FS_{LR}^{NE}=[(\theta-2)(\theta+2)(\theta^{17}+10\theta^{16}+20\theta^{15}-116\theta^{14}-512\theta^{13}+192\theta^{12}+3864\theta^{11}+3104\theta^{10}-137728\theta^9-200096\theta^8+233328\theta^7+516488\theta^6-118824\theta^5-624432\theta^4-147784\theta^3+289992\theta^2+172800\theta+2304)]/[(\theta^7+6\theta^6+4\theta^5-40\theta^4-64\theta^3+64\theta^2+132\theta+24)^2(\theta^3+2\theta^2-4\theta-6)^2]$$

a. (72);

this is negative for all $0<\theta<1$.

b.

$$FS_{LR}^{FE}-FS_{LR}^{RC}=[(\theta-2)(\theta+2)(\beta^4\theta^3(2\theta^{10}+15\theta^9+20\theta^8-120\theta^7-364\theta^6+152\theta^5+1464\theta^4+796\theta^3-1728\theta^2-1776\theta-288)+\beta^3\theta^2(4\theta^{11}+22\theta^{10}-20\theta^9-320\theta^8-248\theta^7+1760\theta^6+2320\theta^5-4264\theta^4-6640\theta^3+3360\theta^2+6528\theta+1152)+\beta^2\theta(-4\theta^{14}-38\theta^{13}-82\theta^{12}+311\theta^{11}+1516\theta^{10}+292\theta^9-7692\theta^8-9472\theta^7+13208\theta^6+29948\theta^5+4352\theta^4-25472\theta^3-23712\theta^2-9408\theta-1152)+\beta\theta(-4\theta^{14}-30\theta^{13}-8\theta^{12}+472\theta^{11}+940\theta^{10}-2664\theta^9-8752\theta^8+5176\theta^7+35008\theta^6+6784\theta^5-65392\theta^4-40608\theta^3+43968\theta^2+43776\theta+6912)+\theta^{17}+10\theta^{16}+20\theta^{15}-116\theta^{14}-512\theta^{13}+192\theta^{12}+3864\theta^{11}+3104\theta^{10}-137728\theta^9-200096\theta^8+233328\theta^7+516488\theta^6-118828\theta^5-624432\theta^4-147784\theta^3+289992\theta^2+172800\theta+2304]/[(\theta^7+6\theta^6+4\theta^5-40\theta^4-64\theta^3+64\theta^2+132\theta+24)^2(\beta\theta(\beta+1)-2\beta-\theta^3-2\theta^2+4\theta+6)^2]$$

(73);

this is negative for all $0\le\beta\le 1$ and $0<\theta<1$.

c.

$$FS_{LR}^{NE}-FS_{LR}^{RC}=\frac{(\theta+1)(\theta+2)^2(\theta-2)^2\beta(\beta\theta+\theta-2)(\beta\theta(\beta+1)-2\beta-2\theta^3-4\theta^2+8\theta+12)}{(\theta^3+2\theta^2-4\theta-6)^2(\beta\theta(\beta+1)-2\beta-\theta^3-2\theta^2+4\theta+6)^2}$$

(74);

this is negative for all $0<\beta\le 1$ and $0<\theta<1$. ■

Proposition 3 Proof – First, consider breeders' industry profits under NE and RC. Their difference is given by:

$$BS^{NE}-BS^{RC}=2\beta[\beta^3\theta^2(\theta^4-8\theta^2+12)+\beta^2\theta(2\theta^5-4\theta^4-16\theta^3+32\theta^2+24\theta-48)+\beta(-\theta^8+21\theta^6+12\theta^5-100\theta^4-64\theta^3+112\theta^2+96\theta+48)-2\theta^8-4\theta^7+16\theta^6+12\theta^5-64\theta^4+64\theta^3+192\theta^2-192\theta-288]/[(\theta^3+2\theta^2-4\theta-6)^2(\beta\theta(\beta+1)-2\beta-\theta^3-2\theta^2+4\theta+6)^2]$$

(75);

this is negative for all $0<\beta\leq1$ and $0<\theta<1$.

Next, consider breeders' profits under FE and NE.

$$BS^{FE}-BS^{NE}=-4[(\theta^2-2)(\theta^2-6)(\theta^{15}+16\theta^{14}+86\theta^{13}+86\theta^{12}-832\theta^{11}-2760\theta^{10}+552\theta^9+14968\theta^8+16632\theta^7-25832\theta^6-60512\theta^5-10624\theta^4+58416\theta^3+51360\theta^2+13824\theta+1152)]/[\left(\theta^7+6\theta^6+4\theta^5-40\theta^4-64\theta^3+64\theta^2+132\theta+24\right)^2\left(\theta^3+2\theta^2-4\theta-6\right)^2(\theta+2)^2] \quad (76);$$

this is negative for all $0<\theta<1$.

Finally, consider breeders' profits under FE and RC.

$$BS^{FE}-BS^{RC}=2[(\beta^4\theta^4\begin{pmatrix}\theta^{12}+10\theta^{11}+20\theta^{10}-114\theta^9-432\theta^8\\-120\theta^7-364\theta^6+1520\theta^5+1464\theta^4\\+796\theta^3-1728\theta^2-1776\theta-288\end{pmatrix}+\beta^3\theta^2\begin{pmatrix}4\theta^{11}+22\theta^{10}-20\theta^9-320\theta^8-248\theta^7+1760\theta^6\\+2320\theta^5-4264\theta^4-6640\theta^3+3360\theta^2+6528\theta+1152\end{pmatrix}+\beta^2\theta\begin{pmatrix}-4\theta^{14}-38\theta^{13}-82\theta^{12}+311\theta^{11}+1516\theta^{10}\\+292\theta^9-7692\theta^8-9472\theta^7+13208\theta^6+29948\theta^5\\+4352\theta^4-25472\theta^3-23712\theta^2-9408\theta-1152\end{pmatrix}+\beta\theta\begin{pmatrix}-4\theta^{14}-30\theta^{13}-8\theta^{12}+472\theta^{11}+940\theta^{10}-2664\theta^9\\-8752\theta^8+5176\theta^7+35008\theta^6+6784\theta^5-65392\theta^4\\-40608\theta^3+43968\theta^2+43776\theta+6912\end{pmatrix}+\theta^{17}+10\theta^{16}+20\theta^{15}-116\theta^{14}-512\theta^{13}++192\theta^{12}+3864\theta^{11}+3104\theta^{10}-13728\theta^9-20096\theta^8+23328\theta^7+51648\theta^6-11828\theta^5-62432\theta^4-14784\theta^3+28992\theta^2+17280\theta+2304]/[\left(\theta^7+6\theta^6+4\theta^5-40\theta^4-64\theta^3+64\theta^2+132\theta+24\right)^2\left(\beta\theta(\beta+1)-2\beta-\theta^3-2\theta^2+4\theta+6\right)^2(\theta+2)^2]$$

(77); this is negative for all $0\leq\beta\leq1$ and $0<\theta<1$.

Proposition 4 Proof – Under farmer exemption, the price in the second period will be lower than the first period if

$$w_{i,1}^{FE}-w_{i,2}^{FE}=\frac{2\left(2\theta^5+\theta^4-15\theta^3-4\theta^2+24\theta+6\right)}{\left(\theta^7+6\theta^6+4\theta^5-40\theta^4-64\theta^3+64\theta^2+132\theta+24\right)^2}>0;i,j\in\{h,l\} \quad (78)$$

The above inequality holds for all $0<\theta<1$.

Proposition 5 Proof – Consider part i first. Comparing R&D undertaken by firm h under NE and RC, we can derive the following:

$$e_h^{NE}-e_h^{RC}=-\frac{k^2\theta\left(\theta^5+2\theta^4-8\theta^3-18\theta^2+16\theta+40\right)-k\left(2\theta^3+4\theta^2+8\theta+16\right)+4}{(k\theta^2+4k\theta+3k-1)(k\theta^6-12k\theta^4+44k\theta^2-4\theta^2-48k+12)} \quad (79);$$

with the following conditions:

a. $e_h^{NE}-e_h^{RC}>0$ iff $0.3593040860<\theta<1$ or

$$k>\frac{\theta^3+2\theta^2+4\theta+8+\begin{pmatrix}-3\theta^6-4\theta^5+44\theta^4+104\theta^3\\-16\theta^2-96\theta+64\end{pmatrix}^{\frac{1}{2}}}{\theta(\theta^5+2\theta^4-8\theta^3-18\theta^2+16\theta+40)}$$

b. $e_h^{NE}-e_h^{RC}\leq0$ iff $0<\theta\leq0.3593040860$ and

$$1<k\leq\frac{\theta^3+2\theta^2+4\theta+8+\begin{pmatrix}-3\theta^6-4\theta^5+44\theta^4+104\theta^3\\-16\theta^2-96\theta+64\end{pmatrix}^{\frac{1}{2}}}{\theta(\theta^5+2\theta^4-8\theta^3-18\theta^2+16\theta+40)}$$

Now let's consider part ii.

$$e_l^{NE}-e_l^{RC}=-\frac{k(\theta^6+2\theta^5-8\theta^4-18\theta^3+12\theta^2+24\theta-12)-2\theta(\theta^2-4)}{(k\theta^2+4k\theta+3k-1)(k\theta^6-12k\theta^4+44k\theta^2-4\theta^2-48k+12)}$$

(80); with the following conditions:

a. $e_l^{NE}-e_l^{RC}>0$ iff

- $0.4833419210<\theta<1$ or
- $0.3593040860<\theta<0.4833419210$ and $1<k<\dfrac{2\theta(\theta^2-4)}{\theta^6+2\theta^5-8\theta^4-18\theta^3+12\theta^2+24\theta-12)}$

b. $e_l^{NE}-e_l^{RC}\leq0$ iff

- $0<\theta\leq0.3593040860$ or
- $0.3593040860<\theta<0.4833419210$ and $k\geq\dfrac{2\theta(\theta^2-4)}{\theta^6+2\theta^5-8\theta^4-18\theta^3+12\theta^2+24\theta-12)}$

Proposition 6 Proof – Consider part i first. Comparing R&D undertaken by firm h under NE and RC, we can derive the following:

$$e_h^{NE}-e_h^{RC}=\frac{\tau\begin{pmatrix}2\theta^7+7\theta^6-8\theta^5-56\theta^4-32\theta^3\\+112\theta^2+120\theta-12\end{pmatrix}-\theta^8-4\theta^7+5\theta^6+36\theta^5+12\theta^4-80\theta^3-52\theta^2+8\theta-36}{(\theta-2)(\theta+2)(\theta^2+4\theta+2)(\theta^3-2\theta^2-4\theta+6)(\theta^3+2\theta^2-4\theta-6)}$$ (81); with the following conditions:

a. $e_h^{NE}-e_h^{RC}>0$ iff $\theta>0.3593040860$ or

$$\frac{\theta^8+4\theta^7-5\theta^6-36\theta^5-12\theta^4+80\theta^3+52\theta^2-8\theta+36}{2\theta^7+7\theta^6-8\theta^5-56\theta^4-32\theta^3+112\theta^2+120\theta-12}<\breve{\tau}<\breve{\tau}$$

b. $e_h^{NE}-e_h^{RC}\le 0$ iff $\theta\le 0.3593040860$ and

$$1<\tau\le\frac{\theta^8+4\theta^7-5\theta^6-36\theta^5-12\theta^4+80\theta^3+52\theta^2-8\theta+36}{2\theta^7+7\theta^6-8\theta^5-56\theta^4-32\theta^3+112\theta^2+120\theta-12}.$$

Now let's consider part ii.

$$e_l^{NE}-e_l^{RC}=-\frac{\tau\begin{pmatrix}\theta^8+4\theta^7-5\theta^6-36\theta^5-12\theta^4\\+80\theta^3+52\theta^2-8\theta+36\end{pmatrix}-2\theta^7-7\theta^6+8\theta^5+56\theta^4+32\theta^3-112\theta^2-120\theta+12}{(\theta-2)(\theta+2)(\theta^2+4\theta+2)(\theta^3-2\theta^2-4\theta+6)(\theta^3+2\theta^2-4\theta-6)}$$ (82); with the following conditions:

a. $e_l^{NE}-e_l^{RC}<0$ iff $\theta<0.3593040860$ or

$$\frac{2\theta^7+7\theta^6-8\theta^5-56\theta^4-32\theta^3+112\theta^2+120\theta-12}{\theta^8+4\theta^7-5\theta^6-36\theta^5-12\theta^4+80\theta^3+52\theta^2-8\theta+36}<\breve{\tau}<\breve{\tau}$$

b. $e_l^{NE}-e_l^{RC}\ge 0$ iff $\theta\ge 0.3593040860$ and

$$1<\tau\le\frac{2\theta^7+7\theta^6-8\theta^5-56\theta^4-32\theta^3+112\theta^2+120\theta-12}{\theta^8+4\theta^7-5\theta^6-36\theta^5-12\theta^4+80\theta^3+52\theta^2-8\theta+36}.$$