# The Strategic Role of Public R&D in Agriculture

**Alejandro Onofri**
Department of Agricultural Economics
University of Nebraska-Lincoln

**Konstantinos Giannakas**
Department of Agricultural Economics
University of Nebraska-Lincoln

**Abstract** - The role of public agricultural R&D is analyzed in a mixed oligopoly framework with strategic interaction among innovating firms and the government. Selective subsidization of innovating firms (i.e., targeted subsides) is also examined. Analytical results show that the existence of public applied research *can* enhance the arrival rate of innovations while mitigating the socially undesirable consequences of market power in applied R&D production. Under certain conditions, direct government involvement in applied R&D is equivalent to the provision of targeted subsides to less efficient firms.

American Agricultural Economics Association
Annual Meeting, August 2001
Chicago, Illinois

Preliminary Version, May 2001

# The Strategic Role of Public R&D in Agriculture

## *I. Introduction*

Public investment in research and development (R&D) is a key factor explaining agricultural growth before the '80s. The government involvement in R&D has been traditionally justified by the public good nature of R&D. Since the introduction of intellectual property rights (IPRs) in the '80s, however, U.S. private investment in R&D has been significantly increased (Moschini and Lapan (1997)). While the levels of public and private R&D expenditures before the early '80s were almost equal, private expenditures have been about 50% higher than public expenditures in the '90s. Given the incentives for private research provided by IPRs, is there a role for public R&D? Should the government allocate resources to appropriable (applied) R&D and, if yes, what form should the government involvement take? This paper will try to answer these questions.

The economic literature has pointed out that, in general, the government must subsidize research. Because of the public good nature of R&D, its benefits cannot be fully appropriated by a private firm. Hence, the social benefits from R&D exceed the private benefits and, consequently, the private sector underinvests in R&D (Tirole (1988), Link and Scott (2001)).

The patent race and endogenous growth literature have shown that with more than one innovating firms there can be costs associated with *duplication of research efforts* and *replacement effects* (Tirole (1988), Aghion and Howitt (1998)). Duplication of efforts occurs since more than one firms incur R&D expenditures but only one of them is granted a patent and appropriates the benefits from the innovation. In addition, the possibility of leapfrogging the technological leader implies that the technology of the leader becomes instantaneously obsolete. Firms do not internalize this 'replacement' or 'business-stealing' effect of their innovations over the existent technologies and the level of private research can, therefore, be less than, equal to, or higher than the socially optimum level.

The focus of the patent race literature has been on the strategic interaction among innovating firms without considering any potential role of the government.[1] This paper, in contrast, considers a strategic role of public research, namely, selective subsidization of specific innovating firms (targeted subsidies) and direct government involvement in applied R&D.[2] When firms and government make decisions about investments in R&D, there is strategic interdependence between them. In a patent race context, R&D expenditures by one firm affect its own probability of getting a patent and, thus, the probability of patent granting to its rivals - the level of R&D expenditures by a firm affects the other firms' expected profits. In this context, the government can affect private innovating firms' incentives for investment in R&D. At the same time, firms' investment decisions affect government's payoff (i.e., social welfare) because a private innovation implies improved productivity and/or deviations from marginal cost pricing. In addition to being directly involved in the production of applied research, the government can affect the behavior of innovating firms through subsidization of their investment activities. The objective of this paper is to shed light on this strategic role of the government and determine the socially optimal form of government involvement in applied R&D. It is assumed that the level of basic research necessary to make an appropriable discovery has already been implemented.[3]

The strategic interaction in R&D decisions is modeled as a sequential game between a government, the innovating firm(s), and the farmers. The government can subsidize private

[1] The patent race literature centers its analysis on two aspects: the incentives to innovate and the possibility of leapfrogging the leader. Examples of this literature are Fudenberg et al (1983), Grossman and Shapiro (1987), Delbono (1989), Aoki (1991) and Malueg and Tsutsui (1997).

[2] Recent Schumpeterian models of growth, like Davidson and Segerstrom (1998) and Aghion and Howitt (1992, 1997, and 1998), have analyzed the socially optimal research subsidization taking the market structure as given.

[3] Basic research complements applied research and is necessary for appropriable innovations to be realized.

research or directly produce applied research to maximize social welfare. Firms provide inputs to farmers and compete in applied research. A firm that makes a process innovation gains an advantage over its rivals that enables it to set price above marginal cost. Finally, farmers maximize profits demanding inputs from firms. The model is solved by backward induction. Different scenarios concerning the nature of competition between innovating firms (i.e. strategic or extensive games) and the nature of government intervention (subsidies to innovating firms versus direct involvement in R&D) are considered within this framework. Solution of the different formulations of the model determines the subgame perfect equilibrium investments in R&D, the pricing of farmers' input, and the productivity growth in the economy.

The rest of the paper is structured as follows. Section II presents the base model in which two firms compete in a market and undertake research activities protected by IPRs (i.e., they invest in appropriable or applied research). No government intervention is considered initially. Results agree with the ε-preemption result already found in the patent race literature: a firm that starts R&D activities before its rival does eventually becomes a monopolist. Having no potential competition, a monopolist might underinvest in R&D and the innovations would arrive slowly. Different subsidization strategies of the government and their implications for the equilibrium outcome and social welfare are considered within this framework. Section III introduces direct government involvement in the production of applied research. It is shown that in certain cases this kind of intervention can be optimal and, in the absence of agency problems, is equivalent to subsidizing the less efficient firm.

## II. *Base Model: Process Innovations, Deterministic Discoveries and No Direct Government Involvement in R&D.*

Consider two firms (Firm 1 and Firm 2) that produce and sell to farmers a homogeneous product X (e.g., a seed). At the beginning of period t=0, Firm 1 has unit variable costs of production $c_1^0$. The variable unit cost of production of Firm 2 is $c_2^0$. The two firms are engaged in research and development activities, which allow them to make process innovations, reduce their variable unit costs of production, and, *ceteris paribus*, gain a cost advantage over their rivals. The price of output X is dependent upon the firms' cost structure and, thus, the result of the firms' R&D activities.

The research levels of the firms are measured as effort intensities. For simplicity and without loss of generality, three possible research effort intensities are considered: zero (0), low (L) and high (H). Effort intensities are associated with different sizes of process innovations (or steps) and costs of research. Table 1 shows the three research efforts and their respective costs and size of innovations.

**Table 1**

| Research Effort | Research Cost | Innovation size ($\gamma$) |
|---|---|---|
| Zero (0) | 0 | $\gamma_0 = 1$ |
| Low (L) | $C_L > 0$ | $\gamma_L > 1$ |
| High (H) | $C_H > C_L$ | $\gamma_H = \gamma_L^2 > \gamma_L$ |

Assume now that firm 1 is initially the technological leader of the industry, i.e., at the beginning of period t=0, Firm 1 enjoys a cost advantage over Firm 2: $c_1^0 < c_2^0$. One reason for this difference can be that Firm 1 preempted Firm 2 - Firm 1 started R&D activities at t = -1, while

Firm 2 did not make any investment in R&D during that period.[4] Assuming that at the beginning of period t = -1 the two firms had the same cost structure $c_1^{-1} = c_2^{-1}$, low research effort by Firm 1 during that period resulted in a cost advantage of size $\gamma_L$ over its rival Firm 2. Put in a different way, the low research effort of Firm 1 in period t = -1 placed this firm one step ahead from Firm 2 in the technological race. Consequently, the relationship between the costs of the two firms at the beginning of period t=0 is $c_1^0 = c_2^0 / \gamma_L$.

This cost difference is assumed to be "non-drastic" in the sense that Firm 1 cannot charge a monopoly price – the monopoly price exceeds $c_2^0$ and, thus, the minimum price that can be charged by Firm 2. For Firm 1 to be able to charge a monopoly price, it must be two steps ahead of its rival in the technological race. This would happen if Firm 1 had exerted high efforts in the previous period, in which case the cost advantage over its rival would be "drastic" (i.e. $c_1^0 = c_2^0 / \gamma_H = c_2^0 / \gamma_L^2$).

As mentioned previously, at t = 0, the firms choose their R&D strategies, which affect their cost structure, the equilibrium price of X, and the level of their profits. Following Table 1, each firm has three possible strategies $S_i$ = 0, L, or H. Given the non-drastic cost advantage of Firm 1 and assuming no capacity constraints, in the absence of research activity in period t=0 (i.e., $S_1 = S_2 = 0$) the price of the (homogeneous) product X is $P_x = c_2^0 - \varepsilon$. With this price, Firm 1 gets positive profits while Firm 2 will find it optimal not to produce X. The *gross* benefits of the firms (i.e., the benefits associated with the production and commercialization of X) are:

[4] Another (probably more plausible) explanation can be that firm 1 was lucky at t = -1 and randomly made the first innovation. However, this argument implies that discoveries are stochastic. This assumption (although more realistic) would complicate the model without changing qualitative nature of the results. It can be shown that the model presented here is a particular case of the stochastic model when the probability of making a specific discovery with a given research effort is equal to one. A model with stochastic discoveries is available from the authors upon request.

$$\pi_1^0 = c_2^0 x(c_2^0) - c_1^0 x(c_2^0)$$

$$= (c_2^0 - c_1^0) x(c_2^0)$$

$$= c_2^0 (\frac{\gamma_L - 1}{\gamma_L}) x(c_2^0) > 0$$

$$\pi_2^0 = 0$$

where $x(P_x)$ is the farmers' demand for X.[5] Since no research effort is exerted in this case, the gross benefits correspond with the net benefits (payoff) of the two firms (the net benefits for Firm i, $\Pi_i$, equal its gross benefits less the costs of R&D activities, i.e., $\Pi_i = \pi_i^0 - C_j$).

Table 2 presents the payoff matrix (i.e., the payoffs of the two firms under different investment strategies), where $\pi^m(c_i)$ represents the gross benefit of Firm i when this firm can set a monopoly price and has unit variable cost of production equal to $c_i$.

**Table 2**

| | | Firm 2 | | |
|---|---|---|---|---|
| | | Zero ($S_2 = 0$) | Low ($S_2 = L$) | High ($S_2 = H$) |
| Firm 1 | Zero ($S_1 = 0$) | $((\gamma_L - 1)c_1^0 x(c_2^0), 0)$ | $(\frac{C_L}{2}, -\frac{C_L}{2})$ | $(0, (\gamma_L - 1)\frac{c_2^0}{\gamma_H} x(c_1^0) - C_H)$ |
| | Low ($S_1 = L$) | $(\pi^m(c_1^0/\gamma_L) - C_L, 0)$ | $((\gamma_L - 1)\frac{c_1^0}{\gamma_L} x(c_2^0/\gamma_L) - C_L, -C_L)$ | $(\frac{1}{2}(C_H - 2C_L), -\frac{C_H}{2})$ |
| | High ($S_1 = H$) | $(\pi^m(c_1^0/\gamma_H) - C_H, 0)$ | $(\pi^m(c_1^0/\gamma_H) - C_H, -C_L)$ | $((\gamma_L - 1)\frac{c_1^0}{\gamma_H} x(\frac{c_2^0}{\gamma_H}) - C_H, -C_H)$ |

---

[5] Farmers solve the following problem: $\text{Max}\Pi = P_y f(X) - P_x X$, where f(X) is the farmers' production function and $P_y$ is the price of their output, which is given.

At this point is important to remember three definitions.[6]

- Definition 1 (Best Response Functions): $S_i^* = S_i(S_j)$ is the best response of player i to the strategy $S_j$ chosen by player j if, when firm j chooses strategy $S_j$, strategy $S_i^*$ maximizes firm i's payoff, i.e., $\Pi_i(S_i^*, S_j) \geq \Pi_i(S_i, S_j), \forall S_i$.
- Definition 2 (Nash Equilibrium): A set of strategies ($S_i^*$, $S_j^*$) is a NE if, given the equilibrium strategy of its rival, a firm i cannot increase its profit by choosing a strategy $S_i$ different from the strategy $S_i^*$, i.e., ($S_i^*$, $S_j^*$) is a NE if $\Pi_i(S_i^*, S_j^*) \geq \Pi_i(S_i, S_j^*), \forall S_i$.
- Definition 3 (Strictly Dominated Strategies): Consider two feasible strategies of player i, $S_i^{'}$ and $S_i^{''}$. Strategy $S_i^{'}$ is strictly dominated by $S_i^{''}$ if for any strategy of firm j, firm i's payoff from playing $S_i^{'}$ is strictly less than its payoff from playing $S_i^{''}$, i.e., $\Pi_i(S_i^{'}, S_j) < \Pi_i(S_i^{''}, S_j), \forall S_j$.

*Nash Equilibrium of the Competition*

Note that for Firm 2 the strategy $S_2 = L$ is strictly dominated by strategy $S_2 = 0$. This means that for each feasible strategy of Firm 1, Firm 2 will always get higher payoffs by choosing zero research effort to low effort. The reason is that by making a low R&D effort the lowest variable unit cost of production Firm 2 can achieve equals Firm 1's original variable unit cost. Independently of the research effort exerted by Firm 1, the equilibrium price is less than or equal to the total unit cost of Firm 2. Thus, due to the fixed costs of R&D, Firm 2 cannot make positive profits when exerts low research effort.

[6] See Gibbons (1992) for details.

The following assumptions are useful in determining the Nash equilibrium strategies of the two firms.

- (A.1) $$C_H - C_L > \pi^m(c_1^0/\gamma_H) - \pi^m(c_1^0/\gamma_L) \text{ or}$$

$$\pi^m(c_1^0/\gamma_H) - C_H < \pi^m(c_1^0/\gamma_L) - C_L$$

Given that $\gamma_L^2 = \gamma_H$ and, consequently, $\pi^m(c_1^0/\gamma_L^2) = \pi^m(c_1^0/\gamma_H)$, (A.1) implies that when the technological leader faces no potential competition (i.e., Firm 2 plays $S_2 = 0$), it will always prefer low efforts to high efforts if $C_H > 2C_L$. This assumption is consistent with the argument that monopolists with no potential competition underinvest in R&D.[7]

- (A.2) $$\pi^m(c_1^0/\gamma_L) - C_L > (\gamma_L - 1)c_1^0 x(c_2^0) \text{ or}$$

$$C_L < \pi^m(c_1^0/\gamma_L) - (\gamma_L - 1)c_1^0 x(c_2^0)$$

This assumption implies that, when Firm 2 does not invest in R&D, the extra gross benefits from low research efforts to the innovator are higher than its costs ($C_L$). In this case, the technological leader will prefer low R&D effort to zero effort.

- (A.3) $$(\gamma_L - 1)\frac{c_1^0}{\gamma_H} x(\frac{c_2^0}{\gamma_H}) - C_H > \frac{1}{2}(C_H - 2C_L)$$

This assumption implies that, when Firm 2 exerts high R&D effort, the technological leader will find it optimal to also exert high R&D effort (rather than low effort).

[7] Note that assumption (A.1) implies that firm 1's payoff under strategies (L,H) is positive.

- (A.4) $(\gamma_L - 1)\frac{c_2^0}{\gamma_H} x(c_1^0) - C_H > 0$

This assumption implies that Firm 2 will make high R&D effort when Firm 1 makes no effort. Otherwise, playing "zero effort" is dominant for Firm 2 (Firm 2 will never invest in R&D).

Propositions about the Nash equilibrium outcome of this competition follow:

- (P.1) Under (A.1) and (A.2), $(S_1^*, S_2^*) = (L,0)$ is the unique NE in pure strategies.

  *Proof*: The best responses of Firm 2, $S_2(S_1)$, are:

  $S_2(0) = H$, if (A.4) holds

  $= 0$, if (A.4) does not hold.

  $S_2(L) = 0$

  $S_2(H) = 0$

  while the best responses of Firm 1, $S_1(S_2)$, are

  $S_1(0) = L$ (from (A.1) and (A.2))

  $S_1(H) = H$, if (A.3) holds.

  $S_1(H) = L$, if (A.3) does not hold.

  $S_1(L)$ has been ignored since low research effort is a strictly dominated strategy for Firm 2. Then, from the definition of NE, $(S_1^*, S_2^*) = (L,0)$ is the unique NE in pure strategies. ■

The intuition of this result is as follows. A low effort strategy is enough for Firm 1 to obtain monopoly profits when Firm 2 chooses not to invest in research. At the same time, when Firm 1 makes low research effort, Firm 2 will find it optimal to not invest in R&D efforts. Specifically, if Firm 2 also makes low effort, it will still be one step behind the technological leader who will set a price equal to Firm 2's *variable* unit cost. With the price set equal to its variable unit cost, Firm 2 incurs a loss given by the cost associated with its R&D effort ($C_L$). Similarly, if Firm 2 chooses high effort when $S_1$ = L, the two firms end up having the same variable unit costs of production. However, the higher R&D costs incurred by Firm 2 (relative to Firm 1), allow Firm 1 to set a price at which Firm 2 can only recoup part (half) of its (high) R&D costs. Consequently, the best Firm 2 can do when $S_1$ = L, is not to invest in R&D. On the other hand, for Firm 1 high R&D efforts will lower unit cost of production but the gain will be more than offset by the higher R&D cost (by (A.1)). Since low effort is more profitable than no effort (by (A.2)), the best strategy for Firm 1 is to make low R&D effort.

- (P.2) If (A.1) and (A.4) hold but (A.2) does not hold, there is no N.E. in pure strategies.

*Proof*: The best responses of Firm 2, $S_2(S_1)$, are:

$S_2(0)$ = H (from (A.4))

$S_2(L) = 0$

$S_2(H) = 0$

while the best responses of Firm 1, $S_1(S_2)$, are

$S_1(0) = 0$ (because (A.1) holds but (A.2) does not)

$S_1(H)$ = H if (A.3) holds, or

$S_1(H)$ = L if (A.3) does not hold.

Thus, when Firm 2 plays $S_2 = 0$, Firm 1 plays $S_1(0) = 0$. Then, Firm 2 plays $S_2(0)$ = H. However, the best response of player 1 then changes either to $S_1(H)$ = H or $S_1(H)$ = L, which makes Firm 2 to play $S_2 = 0$, and so on. There is no NE in pure strategies in this case. ■

- (P.3) If the elasticity of demand for X (η) is less than 1 and (A.4) holds, but (A.1) and (A.2) do not hold, then $(S_1^*, S_2^*) = (0, H)$ is the only NE in pure strategies. Note that this is the 'leapfrogging' case.

*Proof*: When η < 1 and (A.1) and (A.2) do not hold, it is dominant for Firm 1 to make no effort. The best response of Firm 2 to $S_1 = 0$ is to make high effort (using (A.4)). Then, from the definition of NE, $(S_1^*, S_2^*) = (0, H)$ is the unique NE in pure strategies. ■

Note then that the leapfrogging case is only possible when drastic innovations are not profitable. Drastic innovation has been defined as the innovation that allows the innovating firm to charge a monopoly price. Monopoly prices, however, are always at a point in the demand for which the price elasticity is higher than one, contradicting therefore one of the conditions for the leapfrogging case to be NE.

*Welfare Analysis*

This section analyzes the welfare level associated with the equilibrium $(S_1^*, S_2^*) = (L,0)$. Social welfare (W) is composed by the weighted sum of producer (firms') and consumer (farmers') surpluses. The weights are given by the preferences of the social planner (i.e., the government).

Producer surplus (PS) is given by the payoffs of Firms 1 and 2. Thus, the producer surplus for each combination of strategies is already presented in the payoff matrix (Table 2). For example, when firms are not engaged in R&D activities (i.e., $(S_1,S_2) = (0,0)$), the surpluses are

$$PS^{00} = (\gamma_L - 1)c_1^0 x(c_2^0)$$

$$CS^{00} = \int_{c_2^0}^{\infty} X(p)dp$$

and the total welfare equals

$$W^{00} = \theta_p PS^{00} + \theta_c CS^{00}$$

where $\theta_p$ and $\theta_c$ are the weights being placed by the government on PS and CS, respectively.

When the NE is $(S_1^*, S_2^*) = (L,0)$, PS and CS are given by

$$PS^{L0} = \pi^m (c_1^0/\gamma_L) - C_L$$

$$CS^{L0} = CS^{00} + \int_{p^m(c_1^0/\gamma_L)}^{c_2^0} X(p)dp$$

and total welfare equals

$$W^{L0} = \theta_p[\pi^m (c_1^0/\gamma_L) - C_L] + \theta_c[CS^{00} + \int_{p^m(c_1^0/\gamma_L)}^{c_2^0} X(p)dp].$$

Note the increase in social welfare when Firm 1 undertakes R&D activities. Producer surplus increases given assumption (A.2). Consumer surplus increases because Firm 1's innovation is "drastic" in the sense that the new price of X, although a monopolistic price, is lower than the price under no research activities (i.e., the unit cost of Firm 2). Therefore, this NE situation is Pareto superior relative to the situation with no R&D activities.

Although low investment by Firm 1 is Pareto superior to no investment, it has to be evaluated whether (L,0) represents a Pareto Optimum situation in the sense that there is no other combination of strategies under which both producers and consumers can be made better off. Two other possible situations are evaluated; $(S_1, S_2) = (H, 0)$ and $(S_1, S_2) = (H, H)$.

1. Under $(S_1, S_2) = (H, 0)$ total welfare is

$$W^{H0} = \theta_p[\pi^m (c_1^0/\gamma_H) - C_H] + \theta_c[CS^{00} + \int_{p^m(c_1^0/\gamma_H)}^{c_2^0} X(p)dp]$$

The consumer surplus is higher under (H,0) than that under (L,0) due to the reduction in price from $p^m(c_1^0/\gamma_L)$ to $p^m(c_1^0/\gamma_H)$. Gross monopoly profits are also higher (i.e., $\pi^m(c_1^0/\gamma_H) > \pi^m(c_1^0/\gamma_L)$) given that the monopoly operates in the elastic part of the demand curve.

If (A.1) does not hold, then (H,0) is Pareto superior with respect to (L,0). In this situation, (L,0) is not a NE. Instead, (H,0) is the only NE and both producers and consumers are better off. If (A.1) holds, however, producers are worse off due to costs associated with high R&D efforts, and (H,0) is not Pareto superior with respect to (L,0). Nevertheless, total welfare can still be higher if

$$\theta_p[\pi^m(c_1^0/\gamma_H) - \pi^m(c_1^0/\gamma_L)] + \theta_c[\int_{p^m(c_1^0/\gamma_H)}^{p^m(c_1^0/\gamma_L)} X(p)dp] > \theta_p[C_H - C_L]$$

Therefore, the lower is the incremental cost of R&D efforts ($C_H - C_L$); and/or the greater is the size of the innovations ($\gamma_L$ and, thus, $\gamma_H = \gamma_L^2$); and/or the higher is the elasticity of demand (i.e., the greater is the increase in consumer surplus for a given price reduction); the greater is the likelihood that total welfare increases with high research efforts by the technological leader. In addition, the higher is the relative weight placed by the government on consumer surplus, the higher are the welfare gains from high R&D efforts.

2. Under $(S_1, S_2)$ = (H, H) total welfare is:

$$W^{HH} = \theta_p[(\gamma_L - 1)\frac{c_1^0}{\gamma_H} x(\frac{c_2^0}{\gamma_H}) - 2C_H] + \theta_c[CS^{00} + \int_{c_2^0/\gamma_H}^{c_2^0} X(p)dp]$$

This situation is not Pareto superior with respect to (L, 0) since Firm 2 exhibits a loss equal to $C_H$ compared to zero net benefits under both (L,0) or (H,0). However, total welfare can still be higher because consumers experience a welfare gain due to a reduced price of X. This price reduction occurs because both firms reduce their variable unit costs of production by two steps, and the cost difference between firms is non-drastic. Price competition then results in farmers paying a lower price than the prices under (L, 0) and (H, 0).

The total welfare under (H, H), $W^{HH}$, is higher than $W^{L0}$ if

$$\theta_c[\int_{c_2^0/\gamma_H}^{p^m(c_1^0/\gamma_L)} X(p)dp] > \theta_p[\pi^m(c_1^0/\gamma_L) - (\gamma_L - 1)\frac{c_1^0}{\gamma_H}x(\frac{c_2^0}{\gamma_H})] - \theta_p[2C_H - C_L]$$

The relationship between $W^{HH}$ and $W^{L0}$ as well as the magnitude of their difference depends on the incremental cost of R&D efforts, the elasticity of demand, and the weight being placed by the government on the welfare of the interest groups.

Comparing (H, H) against (H, 0), consumers are better off given the reduction in price from $p^m(c_1^0/\gamma_H)$ to $c_2^0/\gamma_H$. This price reduction is due to both higher size of innovation and higher competitive pressures to the leader. Producers, however, are worse off for two reasons. First, gross profits of Firm 1 are reduced from monopoly profits to profits arising from non-drastic-cost difference. Second, Firm 2 exhibits a loss because it incurs high R&D efforts without getting a competitive advantage. For the society, Firm 2’s loss represents resources wasted in duplication of research efforts.

Recall, however, that, given assumptions (A.1) and (A.2), (L,0) is Pareto Optimum in the sense that there is no other combination of strategies that can increase welfare of at least one player without making other players worse off. Nevertheless, if the increase in payoffs for a (some) player(s) is larger than the reduction in other players’ payoffs, then appropriate policies can be implemented to achieve the highest possible social welfare. Since the prevailing NE depends on the costs of research activities, the government can influence the firms' payoffs and, thus, their equilibrium strategies by subsidizing their research activities.

*Targeted Subsidies to Innovating Firms*

This subsection considers the implications of a subsidy to R&D activities. The purpose of the subsidy is to make the firms to incur high R&D efforts when this is socially desirable. With higher R&D efforts, innovations of size $\gamma_H = \gamma_L^2$ occur. That increases both productivity of the firms and farmer (consumer) surplus. In addition, the subsidy might allow achieving higher welfare levels if $W^{H0}$ and/or $W^{HH}$ are higher than $W^{L0}$.

Two possible subsidies are evaluated: a subsidy to the technological leader (Firm 1) and a subsidy to Firm 2. The subsidization of Firm 2 purports to keep this firm competing with the leader. When facing a competitive situation, the leader has incentives to incur high R&D efforts if (A.3) holds. However, there is a loss associated with duplication of research efforts.

Specifically, the subsidy that makes Firm 2 keep competing with the technological leader must be of size $C_H$. Under assumption (A.3), this subsidy makes the high research efforts by both firms (H, H) a NE. Total welfare in this case is

$$W^{SF} = \theta_p[(\gamma_L - 1)\frac{c_1^0}{\gamma_H} x(\frac{c_2^0}{\gamma_H}) - C_H] + \theta_c[CS^{00} + \int_{c_1^0/\gamma_L}^{c_2^0} X(p)dp] - \theta_g C_H$$

where $W^{SF}$ represents total welfare when the government subsidizes Firm 2 and $\theta_g \geq 1$ represents the government cost of collecting funds for the subsidy. It is easy to see that

$$W^{SF} = W^{HH} - (\theta_g - 1)C_H$$

when $\theta_p = \theta_c = 1$ is assumed. Obviously, the more efficient is the government in raising funds for the subsidy (i.e., the closer is $\theta_g$ to 1) and the lower is $C_H$, the closer is the correspondence between $W^{SF}$ and $W^{HH}$. In such a case, if $W^{HH} > W^{L0}$, a subsidy to the follower firm will constitute a Pareto improvement relative to the equilibrium (L, 0).

The idea of subsidizing inefficient firms might seem counterintuitive. In order to show that this policy can be appropriate under certain circumstances, its potential welfare gains must be compared to those under a subsidy to the (more efficient) technological leader.

A subsidy to the technological leader is a subsidy aimed at solving the problem of low R&D incentives associated with lack of competition. The advantage of this subsidy is that it does not involve duplication of efforts. The disadvantage, however, is that, as a result of being the only firm making innovations, a higher (monopoly) price results.

Assuming that the government can perfectly monitor the firms, the subsidy that induces the technological leader to make high R&D efforts must be of size $C_H$-$C_L$. Then, total welfare is

$$W^{SL} = \theta_p[\pi^m(c_1^0/\gamma_H) - C_L] + \theta_c[CS^{00} + \int_{p^m(c_1^0/\gamma_H)}^{c_2^0} X(p)dp] - \theta_g(C_H - C_L)$$

where $W^{SL}$ represents total welfare when the government subsidizes Firm 1. The relationship between $W^{SL}$ and $W^{H0}$ is

$$W^{SL} = W^{H0} - (\theta_g - 1)(C_H - C_L)$$

Similarly to the case examined previously, if $\theta_g$ is close to one and/or the incremental cost of R&D efforts is not too high, the welfare achieved with a subsidy to the leader is close to $W^{H0}$. If this is the case and social welfare under (H, 0) is higher than that under (L, 0), the subsidy to the technological leader can be (social) welfare enhancing.

Since both kinds of subsidies can induce high R&D efforts and improve social welfare, the question that naturally arises is “what is the socially optimal subsidization strategy of the government?” Should the government subsidize the technological leader or the (less efficient) follower in the technological race? Some interesting tradeoffs occur.

Specifically, when compared to subsidization of the follower, a subsidy to the leader increases producer surplus while reducing the surplus of consumers (farmers). The social cost is also lower due to the elimination of duplication of efforts. On the other hand, the subsidization of the less efficient firm enhances consumer welfare and introduces competitive pressures to the technological leader that, as a consequence, is induced to invest heavily in research. Firm 1’s payoffs are reduced due to both a reduction in monopoly profits and an increase in its R&D costs. Consumer surplus increases due to the reduction in the price of X.

As a consequence of these tradeoffs, the optimal government strategy will depend on the relative weights being placed on producer and consumer surplus and the level of government (budgetary) costs. Specifically, if $\theta_p = \theta_c = 1$, a subsidy to the follower will constitute a Pareto-superior policy if consumer gains exceed the reduction in Firm 1’s payoff plus the government cost of duplicating research efforts.

*Sequential Game: Firm 1 is the Leader of the Game*

In order to evaluate the robustness of the results of the base model, assume now that the technological leader (Firm 1) is also the leader in the game. This means that Firm 1 moves first and determines its optimal investment strategy knowing Firm 2’s best response function. The game can then be solved by backward induction, determining first the best responses of Firm 2 and then analyzing the optimal decision of the technological leader. This way, non-credible strategies are eliminated and a subgame perfect Nash equilibrium (SPNE) is obtained.

Figure 1 presents the relevant game tree. Payoffs to Firm 1 under the different investment scenarios are those above the dotted line at the bottom of the figure. Payoffs to Firm 2 are those below the dotted line. Note that the payoffs are the same as those in the payoff matrix of the simultaneous game.

- (P.4) Under (A.1) and (A.4), $(S_1^*, S_2^*) = (L,0)$ is SPNE.

*Proof*: The best response function of Firm 2, $S_2(S_1)$, is:

$S_2(0) = H$ (from (A.4))

$S_2(L) = 0$

$S_2(H) = 0$

Knowing how the follower will react to each of its choices, Firm 1 will find it optimal to exert low research efforts (from (A.1)). Therefore, $(S_1^*, S_2^*) = (L,0)$ is SPNE. ■

Thus, the same equilibrium emerges no matter if the firms make their choices simultaneously or the technological leader moves first. Note that in this case assumption (A.3) is not required for the equilibrium (L, 0) to emerge. This assumption is required, however, for the subsidization of Firm 2 to have the same effect in stimulating the technological leader's willingness to exert high research efforts. Hence, under assumptions (A.1), (A.3) and (A.4), the welfare analysis and policy implications are the same as those in the simultaneous move case.

### *III. Modified Model: The Government as Firm 2*

Consider now the case where the government is directly involved in the production of applied R&D research, i.e., the government is one of the players. In this case, there are still two players:

Firm 1 (the technological leader) and the government. The government invests in R&D activities and its output is a public good. It is not necessary to interpret the government as a producer of X. The government can be interpreted as an intermediary producing new technologies that are freely available to firms that want to adopt them. Thus, if the government develops a technology that lowers the cost of production of X, all firms will adopt this technology and the resulting price of X will be equal to the new unit cost of production. The research efforts, R&D costs and the corresponding process innovations for the government are those presented in Table 1.

This modified game is a kind of mixed oligopoly model. Mixed oligopoly models are those in which the players have different objectives and, thus, different payoff functions. Similar to the previous case, Firm 1's objective is to maximize profits. The government's objective is to maximize social welfare. The relevant payoff matrix is presented in Table 3.

Note that Firm 1's payoffs are the same as those in the previous section with two exceptions; namely, its payoffs under (0, L) and (L, H). The payoffs in these two cases are different because the equilibrium price is altered by the public provision of R&D. While the variable unit costs of production are the same for the two competitors, the government cost of R&D activities is not transferred to the price of the product.

While the payoffs to Firm 1 differ from those in the previous section, the best responses to the research efforts of its rival (here the government) are not modified. However, since the payoff function of the government is different from that of Firm 2 in the base model, the best response functions to Firm 1's strategies are different and, therefore, the NE can differ as well.

Consider then the best responses of the government. Assume that one dollar to consumers worth as much as one dollar to producers ($\theta_p = \theta_c = 1$). The best response to $S_1 = 0$, for instance, depends upon the potential consumer gains from public R&D, the producer losses, and the government costs of financing research. Note that consumer welfare increases more than the reduction in producer profits because the firm sets a price above marginal cost that implies a deadweight welfare loss. When the government makes low R&D efforts, this welfare loss becomes part of the consumer surplus. Therefore, if the cost of making low public R&D efforts ($\theta_g C_L$) is less than the welfare loss when there is no public research, then $S_g$ = L is preferred to $S_g$ = 0. Note that the welfare loss depends positively on both the initial cost difference between the leader firm and the government ($\gamma_L$) and the elasticity of demand ($\eta$). Specifically, the government has higher incentives to exert high research efforts when the initial cost difference and/or the elasticity of demand are high.

If the government makes high R&D investments when $S_1 = 0$, the gross welfare gain is given by the deadweight loss plus the consumer surplus increase due to an additional reduction in price (costs of production are reduced one more step $\gamma_L$). Therefore, it is optimal for the government to exert high R&D efforts if the incremental cost of public research ($\theta_g(C_H - C_L)$) is less than the additional increase in consumer surplus.

The following assumptions are useful in determining the equilibrium conditions of this competition. To simplify notation, $W^{ij}$ refers to government's payoff when the firm plays $S_1$ = i, i = 0, L, H, and the government plays $S_g$ = j, j = 0, L, H.

- (A.5) $W^{0H} > 0$. This assumption implies that high public R&D efforts result in positive social welfare when no private firm is involved in applied research.

- (A.6) $S_g$ = H is a strictly dominant strategy. This happens when $\theta_g C_H$ is low and/or consumer surplus is weighted highly in the social welfare function.[8]

- (A.7) $(\gamma_L - 1)\frac{c_1^0}{\gamma_H} x(\frac{c_2^0}{\gamma_H}) - C_H > 0$

  Firm 1 will get positive net profits even if it has a non-drastic cost difference and has made high R&D efforts. Thus, Firm 1 will get positive profits when incurring high research efforts.

The equilibrium conditions can then be established.

- (P.5) If (A.6) and (A.7) hold, $(S_1^*, S_2^*) = (H, H)$ is a unique NE.

*Proof*: The government always plays the dominant strategy H. Given

$$(\gamma_L - 1)\frac{c_1^0}{\gamma_H} x(\frac{c_2^0}{\gamma_H}) - C_H > 0$$

from (A.7), $S_1(H)$=H. Therefore, $(S_1^*, S_2^*) = (H, H)$ is NE. ■

Note that the strategy $S_g$ = H results in the same NE (and has, therefore, the same welfare effects) as a subsidy to the follower firm (Firm 2) in our base model.[9]

---

[8] When this assumption holds, assumption (A.5) also holds.

[9] The preference of direct public production of R&D over such a subsidy depends upon factors that are not considered in this paper. For instance, one of the assumptions is that the government and firms are equally efficient in the production of innovations. In other words, the costs associated with low and high efforts are the same for the firms and government. In addition, potential costs of monitoring firms' R&D activities are assumed away from the welfare effects of subsidies. Thus, it is implicitly assumed that firms can neither transfer subsidy funds toward alternative activities nor substitute own research resources with public funds. The introduction of these considerations is the subject of on-going research.

The situation (0, H) is another possible equilibrium when different assumptions are considered.

- (P.6) If (A.6) holds, but (A.7) does not hold, $(S_1^*, S_2^*) = (0, H)$ is the only NE.[10]

This proposition implies that when the private cost of high R&D efforts is less than the profits associated with a non drastic cost difference, government research completely crowds out private research.

Although strict dominance of $S_g$ = H has been assumed in (P.5), this assumption is not required for (H, H) to be a NE. Specifically,

- (P.7) If (A.1), (A.2) and (A.7) hold, $W^{LL}>W^{LH}$ and $W^{HH}>W^{H0}$, $(S_1^*, S_2^*) = (H, H)$ is the only NE in pure strategies.

*Proof*: The best responses of the firm are

$$S_1(0) = L$$

$$S_1(L) = H$$

$$S_1(H) = H$$

while the best responses of the government are

$$S_g(0) = H$$

$$S_g(L) = L$$

$$S_g(H) = H$$

Thus, the only NE in pure strategies is (H,H). ■

[10] The proof of this proposition is obvious and is left to the reader.

Note that $S_g = H$ is not dominant because $W^{LL} > W^{LH}$, that is, the incremental cost of public R&D plus the cost of duplication of efforts is high relative to the deadweight welfare loss when the firm has a nondrastic cost difference.

Finally, note that if $W^{HH} < W^{H0}$, there is no NE in pure strategies. Nevertheless, $W^{H0}$ (the highest aggregate welfare in this case) can be achieved through subsidizing the monopolist if

$$W^{H0} - \theta_g (C_H - C_L) > W^{HH}$$

i.e., if total welfare less the cost of the subsidy is higher than the welfare achieved with direct government production (or with a subsidy to the follower firm).

*Sequential Games with the Government*

This section considers a sequential game in which the government is the leader that moves first knowing the best responses of the firm. Observing public research, the firm then determines its optimal R&D investment.

Figure 2 presents the game tree of this competition. $CS^{ij}$ and $\Pi^{ij}$ represent the consumer surplus and firm's payoff, respectively, when the firm plays $S_1 = i$, and the government plays $S_g = j$, with i, j = 0, L, H. The payoffs are the same as those in Table 3. Those above the dotted line are the payoffs of the firm, while the payoffs below the dotted line are those of the government.

The model is solved by backward induction. The best responses of the firm to different investment strategies of the government are

$S_1(0) = L$

$S_1(L) = H$

$S_1(H) = H$

Knowing the optimal responses of the firm, the government will choose $S_g$ = H if $W^{HH}$ > $W^{H0}$. Therefore, a proposition equivalent to (P.7) can be established for the extensive game.

- (P. 8) In an extensive game in which the government moves first, if (A.1), (A.2) and (A.7) hold, and $W^{HH}$>$W^{H0}$, $(S_1^*, S_2^*) = (H, H)$ is the only SPNE.

Note that, similar to the simultaneous game, if $W^{H0}$ is the highest level of welfare, it can only be achieved through subsidizing the technological leader.

Figure 3 shows the extensive form of a game in which the firm moves first and chooses its optimal investment strategy knowing the reactions of the government to each of its investment decisions.

- (P.9) In an extensive game in which the firm moves first, if (A.7) holds and $S_g$ = H is strictly dominant, $(S_1^*, S_g^*) = (H, H)$ is the only SPNE.

However, (H, H) is SPNE only under the condition of strict dominance.

- (P.10) In an extensive game in which the firm moves first, if (A.7) holds and $W^{LL}$>$W^{LH}$, $(S_1^*, S_g^*) = (L, L)$ is the only SPNE.

Finally, (H, 0) can also be SPNE. Specifically,

- (P.11) In an extensive game in which the firm moves first, if $W^{HH}<W^{H0}$ and $S_g(L) = H$, then $(S_1^*, S_g^*) = (H,0)$ is the only SPNE.

(P.11) indicates that, even though the firm obtains the highest payoff under (L,0), the fact that the government maximizes social welfare induces the firm to undertake high R&D efforts. This happens because the government's best response to any firm's strategy other than $S_1$ = H is to play high R&D effort. If the firm exerts high effort, however, the government does not invest in R&D. Knowing this, Firm 1 finds it optimal to exert high R&D effort.

Overall, the equilibria obtained from the sequential games are similar to those obtained from the simultaneous-move game. This implies that the strategic role of public R&D is not affected by the nature of competition between the firm and the government. Direct public production of applied research can stimulate high R&D effort of a technological leader and potential monopolist. Conclusions drawn from this paper are then robust.

## *IV. Conclusions*

This paper examines the strategic role of the government in the production of appropriable applied research. Private and public R&D activities are strategically related. Without public provision of research, private R&D races can end up in a monopolistic situation with reduced incentives for investment in R&D. In these cases, public production of applied research can create the competitive pressures necessary for inducing private firms to exert the (socially desirable) high R&D effort. Stimulation of private research effort can also be achieved through government subsidization of private investment activities.

High public R&D efforts are shown to be equivalent to subsidizing the ‘lagged’ or ‘inefficient’ firm in a model with no direct government involvement in applied research. The provision of targeted subsides to less efficient firms can be Pareto superior relative to the subsidization of the more efficient firm if deadweight welfare losses from a monopoly are considerable and/or if farmer welfare is weighted highly by the government. Though counterintuitive, the optimality of subsidies to less efficient firms is consistent with recent findings of the research-incentives literature that highlight the role of small firms in a market and the necessity of reducing entry costs to stimulate competition.

Overall, analytical results show that government involvement in applied R&D can be welfare enhancing and, thus, socially desirable. The socially optimal form of government involvement is case-specific and depends on market conditions, the costs of research and development, the efficiency of the government in raising taxes to finance research, and the political preferences of the government (i.e., the weights being placed on the welfare of interest groups).

***References***

Aghion, P. and P. Howitt (1992). "A Model of Growth through Creative Destruction," *Econometrica*, Vol. 60, No. 2 (March): 323-351.

Aghion, P. and P. Howitt (1997). "A Schumpeterian Perspective on Growth and Competition," in *Advances in Economics and Econometrics: Theory and Applications*, Seventh World Congress, Vol. II, edited by D. Kreps and K. Wallis, Econometric Society Monograph No 27, Cambridge University Press.

Aghion, P. and P. Howitt (1998). *Endogenous Growth Theory*, The MIT Press.

Aoki, R. (1991). "R&D Competition for Product Innovation: An Endless Race," *American Economic Review*, Papers and Proceedings, 81, No. 2 (May): 252-256.

Audretsch, D., W. Baumol, and A. Burke (2001a). "Competition Policy in Dynamic Markets," *International Journal of Industrial Organization*, Vol. 19, No 5 (April): 613-634.

Audretsch, D., G. Leeuwen, B. Menkveld, and R. Thurik (2001b). "Market Dynamics in the Netherlands: Competition Policy and the Role of Small Firms," *International Journal of Industrial Organization*, Vol. 19, No 5 (April): 795-821.

Cabral, L. and M. Riordan (1994). "The Learning Curve, Market Dominance, and Predatory Pricing," *Econometrica*, 62, No. 5 (Winter): 1115-1140.

Dasgupta, P. and J. Stiglitz (1988). "Learning-by-Doing, Market Structure and Industrial and Trade Policies," *Oxford Economic Papers*, 40: 246-268.

Davidson, C. and P. Segerstrom (1998). "R&D Subsidies and Economic Growth," *Rand Journal of Economics*, Vol. 29, No. 3 (Autumn): 548-577.

Delbono, F. (1989). "Market Leadership with a Sequence of History Dependent Patent Races," *Journal of Industrial Economics*, XXXVIII, No. 1 (September): 95-101.

Fudenberg, D., R. Gilbert, J. Stiglitz, and J. Tirole (1983). "Preemption, Leapfrogging and Competition in Patent Races," *European Economic Review* 22: 3-31.

Gibbons, R. (1992). *Game Theory for Applied Economists*, Princeton University Press, Princeton, New Jersey.

Gilbert, R. and R. Harris (1981). "Investment Decisions with Economies of Scale and Learning," *American Economic Review*, Papers and Proceedings, 71: 172-177.

Grossman, G. and C. Shapiro (1987). "Dynamic R&D Competition," *The Economic Journal*, 97 (June): 372-387.

Gruber, H. (1992). "Persistence of Leadership in Product Innovation," *Journal of Industrial Economics*, XL, No. 4 (December): 359-375.

Link, A. and J. Scott (2001). "Public/private Partnerships: Stimulating Competition in a Dynamic Market," *International Journal of Industrial Organization*, Vol. 19, No. 5 (April): 763-794.

Malueg, D. and S. Tsutsui (1997). "Dynamic R&D Competition with Learning," *Rand Journal of Economics*, Vol. 28, No. 4 (Winter): 751-772.

Moschini, G. and H. Lapan (1997). "Intellectual Property Rights and the Welfare Effects of Agricultural R&D," *American Journal of Agricultural Economics* 79 (November): 1229-1242.

Reinganum, J. (1989). "The Timing of Innovation: Research, Development, and Diffusion," in *Handbook of Industrial Organization*, Vol. I, ed. by R. Schmalensee and R. D. Willig. Elsiever Science Publishers.

Ross, D. (1986). "Learning to Dominate," *Journal of Industrial Economics*, 34: 337-353.

Sutton, J. (1998). *Technology and Market Structure*. The MIT Press.

Tirole, J. (1988). *The Theory of Industrial Organization*. The MIT Press.

**Figure 1**
**Sequential Game: the technological leader moves first**

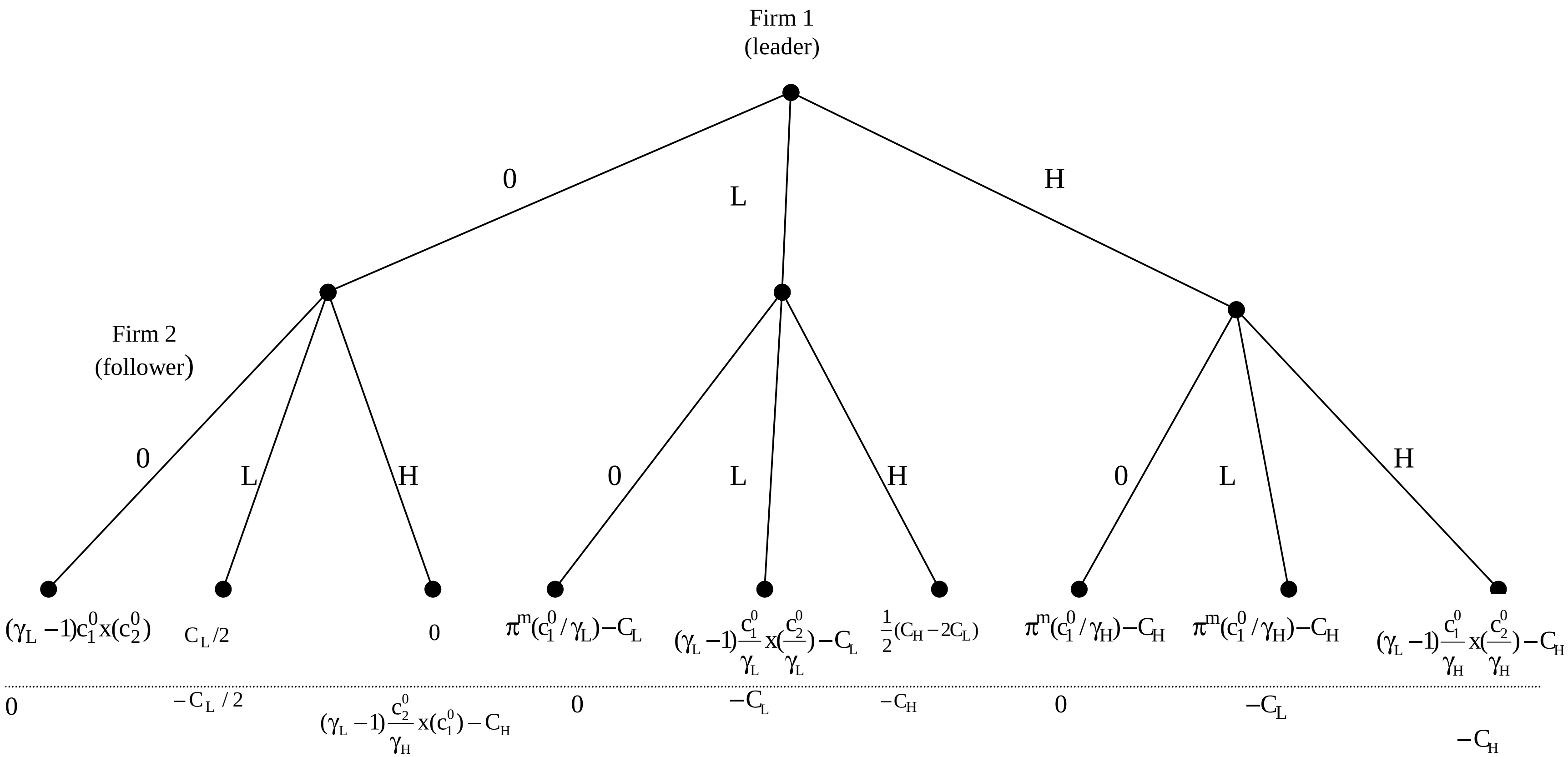

**Table 3**

| | | Government | | |
|---|---|---|---|---|
| | | Zero ($S_2 = 0$) | Low ($S_2 = L$) | High ($S_2 = H$) |
| Firm 1 | Zero ($S_1 = 0$) | $((\gamma_L - 1)c_1^0 x(c_g^0),$<br>$\theta_p[(\gamma_L - 1)c_1^0 x(c_g^0)] + \theta_c CS^{00})$ | $(0,$<br>$\theta_c[CS^{00} + \int_{c_1^0}^{c_g^0} X(p)dp] - \theta_g c_L)$ | $(0,$<br>$\theta_c[CS^{00} + \int_{c_1^0/\gamma_L}^{c_g^0} X(p)dp] - \theta_g c_H)$ |
| | Low ($S_1 = L$) | $(\pi^m(c_1^0/\gamma_L) - c_L,$<br>$\theta_p[\pi^m(c_1^0/\gamma_L) - c_L] +$<br>$+\theta_c[CS^{00} + \int_{p^m(c_1^0/\gamma_L)}^{c_g^0} X(p)dp])$ | $((\gamma_L - 1)\frac{c_1^0}{\gamma_L} x(\frac{c_g^0}{\gamma_L}) - c_L,$<br>$\theta_p[(\gamma_L - 1)\frac{c_1^0}{\gamma_L} x(\frac{c_g^0}{\gamma_L}) - c_L] +$<br>$+\theta_c[CS^{00} + \int_{c_1^0}^{c_g^0} X(p)dp] - \theta_g c_L)$ | $(-c_L,$<br>$-\theta_p c_L +$<br>$+\theta_c[CS^{00} + \int_{c_1^0/\gamma_L}^{c_g^0} X(p)dp] - \theta_g c_H)$ |
| | High ($S_1 = H$) | $(\pi^m(c_1^0/\gamma_H) - c_H,$<br>$\theta_p[\pi^m(c_1^0/\gamma_H) - c_H] +$<br>$+\theta_c[CS^{00} + \int_{p^m(c_1^0/\gamma_H)}^{c_g^0} X(p)dp)])$ | $(\pi^m(c_1^0/\gamma_H) - c_H,$<br>$\theta_p[\pi^m(c_1^0/\gamma_H) - c_H] +$<br>$+\theta_c[CS^{00} + \int_{c_1^0}^{c_g^0} X(p)dp] - \theta_g c_L)$ | $((\gamma_L - 1)\frac{c_1^0}{\gamma_H} x(\frac{c_g^0}{\gamma_H}) - c_H,$<br>$\theta_p[(\gamma_L - 1)\frac{c_1^0}{\gamma_H} x(\frac{c_g^0}{\gamma_H}) - c_H] +$<br>$+\theta_c[CS^{00} + \int_{c_1^0/\gamma_L}^{c_g^0} X(p)dp] - \theta_g c_H)$ |

**Figure 2**
**Sequential Game: The government is the leader**

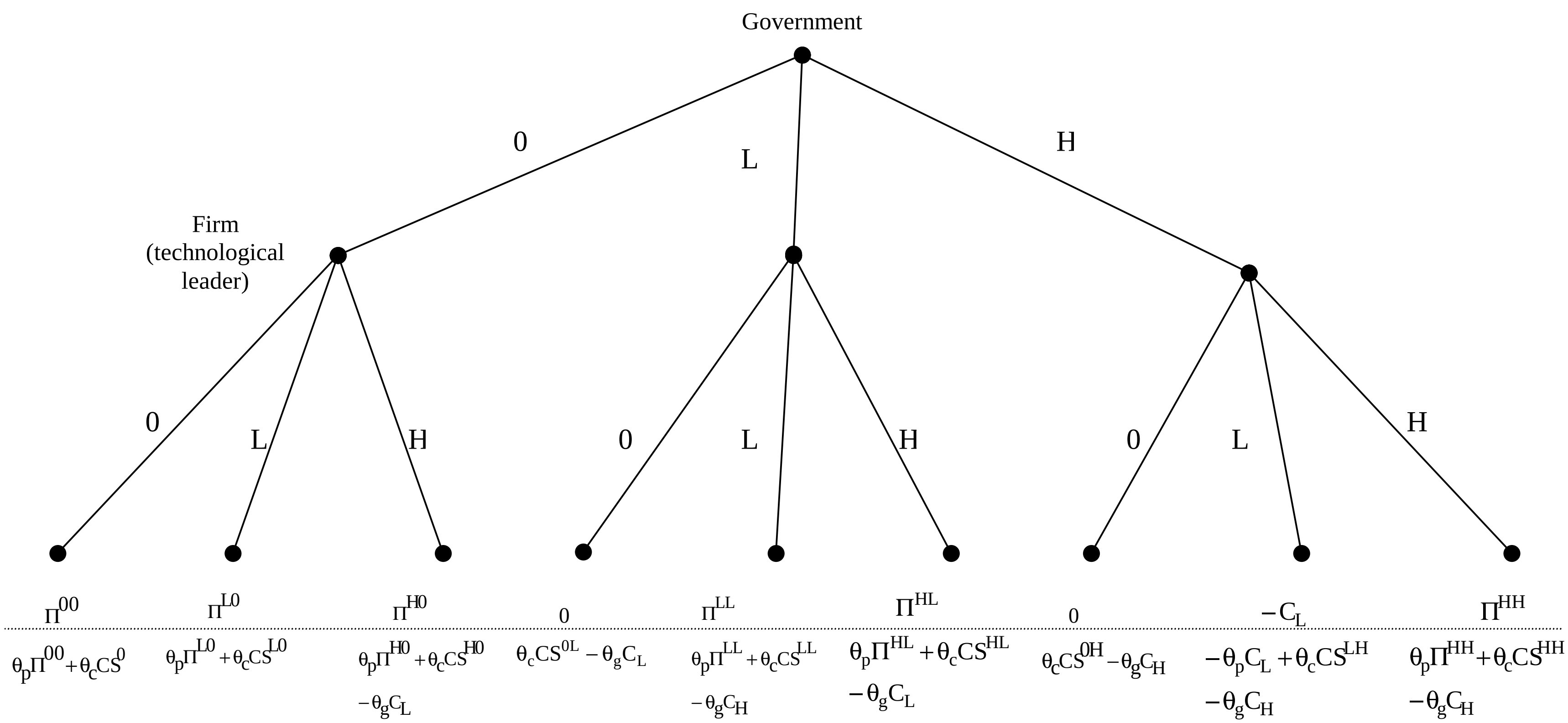

**Figure 3**
**Sequential Game: The Firm is the leader**