Public Investment Policy in Life-Science Research

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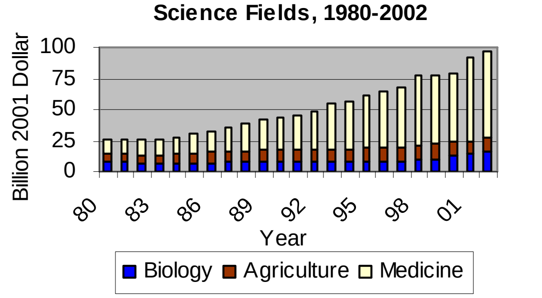
Abstract: The article presents a dynamic model of research investment. This model allows us to examine three important channels through which public investment policy can affect the private sector's research investment, that is, the productivity, replacement, and wage effects. Two alternative empirical approaches are introduced to implement the model. Through a unified examination of the productivity, replacement, and wage effects, the empirical estimation of this model will provide insight into whether public-sector research investment crowds in or crowds out private-sector research investment.

Key Words: Research Investment Demand, Adjustment Cost, Public Investment Policy

Public Investment Policy in Life-Science Research

Bioscience has become one of the promising forces of economic change. The total U.S. R&D spending in agricultural, medical and biological sciences has increased from $26 billion in 1980 to $97 billion in 2002, with an average annual growth rate of 6% (Fig. 1). The major contributors of this rapid growth are the private sector's expenditures in the fields of medicine (drugs) and agriculture, and the public sector's investment in general biological research, with an average annual growth rate of 12, 3, and 4%, respectively. In contrast with the private sector's increasing dominance of medical and agricultural R&D, the private sector maintained a roughly constant investment rate in these two fields.

Fig. 1: U.S. R&D Expenditures in Three Life Science Fields, 1980-2002



This dramatic structural change in life-science R&D investments raises policy questions government planners never faced in earlier years. With industry's increasing dominance of agricultural plant variety and drug development, should public monies continue to be spent in the applied research and developmental phases of life science research? How should government go about supporting basic research, given its impact on the productivity of applied research and hence on both consumer and industry welfare? Do investments in agricultural research bring long-run returns to pharmaceutical products, or pharmaceutical research to agricultural innovations?

Such questions touch on a government planner's budgeting problem: given the total research funds allocated to life science research, where to distribute the money on the basic-to-applied research continuum and in which field to focus (Xia and Buccola, 2005). A sound answer to these questions requires a good understanding of both the technical and behavioral aspects of the problem. The technical aspect bears on how the knowledge production processes of the two sectors interact, i.e., the mechanism of knowledge spillovers; while the behavioral aspect concerns how profit-seeking firms in the private sector determine their R&D investment in response to governmental R&D investment policy.

A large body of empirical literature has attempted to investigate public and private funding interactions (see David, Hall, and Toole (2000) for a review of this literature). The literature, however, has not reached a satisfying conclusive answer, both because the data sets and econometric models used to test the hypotheses are not comparable, and because the lack of a structural model to guide the empirical work. To fill the theoretical gap, David and Hall (2000) introduce a model that incorporates two important sets of channels through which the two sectors' knowledge production and research investment interact. The first set involves the interactions in the research input market, where the public sector's investment demand can change the investment good price, which in turn affects the private sector's investment and production decisions by altering the marginal investment cost. The second set involves the influence that the generation of new knowledge by the public sector may have upon the expected costs and benefits of research in the private sector. Comparative statics of the model provides insight into the effects on private-sector research investment of two policy instruments, the level of government research funding and the fraction of the funding devoted to basic research.

This microscopic approach provides a useful way to think of the research questions raised in this article. However, the David and Hall (henceforth D-H) model is restrictive in the following senses. First, it assumes that basic knowledge generated by the public sector has an unambiguously positive effect on the private-sector research productivity. But, basic knowledge borrowed from the public sector may well be a substitute for the private sector's research input, in which case, an increase in public-sector basic knowledge may inhibit the private sector's investment incentives (consider why many firms do not conduct any basic research at all). Second, the D-H model assumes that the applied research conducted by the public sector has no direct effect whatsoever on the private sector's knowledge production. This apparently is a strong assumption. Finally, this model does not allow for the adjustment process of investment towards equilibrium. However, both theoretical reasoning and empirical evidence (see Himmelberg and Peterson (1994) for a short literature review) suggest the existence of such an adjustment process.

In this article we introduce a dynamic model that generalizes the D-H model by overcoming the problems discussed above. Our model is based on the adjustment cost model of investment (see e.g., Caputo (2005), chap.17, pp.460-480).

Before we start to present the model, the scope of this article must be clearly stated. First, in this article we do not intend to address the issue of knowledge spillovers between different life science fields, because the mechanisms of these effects are relatively simple, and the one-field model can be readily extended to the case of several fields. Second, although in theory our model allows us to calculate the optimal rate of research investment and ratio of basic to applied research outputs for the public sector, the degree of precision of such results is still questionable given the quality of existing economic data on research inputs and outputs. Therefore, no attempt will be made to obtain such precise policy prescriptions; instead, our less ambitious but realistic goal is to detect the existence of some hypothetical channels of public and private interactions in research investment and knowledge production. Third, we are still in the stage of collecting data and therefore have no empirical results to show at this point. But a detailed data construction plan and the econometric model will be provided to explain how to implement our model.

Model

In our model research is viewed as a knowledge production process. There exist two sectors in the society engaged in research in a specific scientific field. The public research sector conducts both basic and applied research to enhance social welfare, while the private sector consists of research firms which conduct applied research to generate cash flow[1]. The knowledge production process is such that research capital—mainly human capital —is combined with existing knowledge stock to generate new knowledge. The knowledge stock, be it basic or applied, is accessible to anybody in the society for the research purposes[2]. It is assumed that research firms in the private sector sell the applied research output, for example, designs or patents, in a competitive market, i.e., they take price as given. But the equilibrium price reflects information on the rent that buyers of the applied research output can extract by commercializing it[3]. It is also assumed that there is a single homogeneous research investment good, and each research firm is taking its price as given. Since research firms are price takers in both input and output markets, in the ensuing analysis the private sector is viewed as a representative research firm[4].

Some notation is required to present the model formally. Throughout this article superscript 0 stands for the public sector, while no superscript for the private sector; subscript t denotes the time period and is suppressed when no confusion is created; capital and small letters are reserved for stock and flow variables, respectively.

Knowledge production functions

Define the public-sector knowledge production function $f^0 : \Re_+^4 \to \Re_+$ by

(1.1) $$a^0 = f^0(H^0, h^0, b^0; B);$$

and the private-sector knowledge production function $f : \Re_+^4 \to \Re_+$ by

(1.2) $$a = f(H, h; A^0, B^0);$$

where $H(h)$ denotes research capital stock (investment flow), $A(a)$ applied knowledge stock (flow), $B(b)$ basic knowledge stock (flow).

The accumulation processes of research capital and knowledge stocks are described by the perpetual inventory formulas:

(1.3) $$\dot{H}^0 = h^0 - \delta_H H^0, \ \dot{H} = h - \delta_H H,$$

(1.4) $$\dot{A}^0 = a^0 - \delta_A A^0, \ \dot{A} = a - \delta_A A,$$

(1.5) $$\dot{B}^0 = b^0 - \delta_B B^0,$$

where the dot notation represents the rate of change, δ_H is the depreciation rate of research capital, and δ_A and δ_B are the obsolescence rates of applied and basic knowledge, respectively.

Some assumptions on the production functions are required to proceed. Assume that f^0 and f are twice continuously differentiable with respect to all arguments; f^0 and f are strictly concave in (H^0, h^0, b^0) and (H, h), respectively; $f^0_{H^0} > 0$, $f_H > 0$, $f^0_{h^0} < 0$, $f_h < 0$, and $f^0_{b^0} < 0$.

These are by and large standard assumptions on the production function. Noteworthy is the presence of the investment rate as an independent variable in the production functions. The intuition behind the negative effect of investment on the research outputs is that new research investment requires extra efforts to be transferred into productive research capital, i.e., investment incurs adjustment costs. For example, newly hired researchers need to be trained to be able to work effectively with other researchers in the same team, or when a firm initiates new projects, researchers need to acquire new skills, which takes resources away from ongoing projects. Usually, the adjustment cost is assumed to be increasing more than proportionally to the increase in the investment rate, i.e., f^0 and f are decreasing and strictly concave in h_0 and h, respectively[5].

Besides the above theoretical reasoning on the existence of adjustment costs in research investment, empirical evidence can also be found in the literature. Bernstein and Nadiri (1982 and 1989) show that the adjustment speed of R&D investment is even slower than that of physical investment.

Note that we have not specified the mechanism of knowledge spillovers between these two sectors, namely, how one sector's knowledge stocks affect another's knowledge production. In the theoretical literature, we can find two opposite hypotheses on this relationship. David and Hall (2000) assume that knowledge spillovers from the public sector can enhance the private sector's research productivity. In our model, this amounts to assuming that $\frac{\partial^2 f}{\partial H \partial A^0} > 0$ and $\frac{\partial^2 f}{\partial H \partial B^0} > 0$, namely, borrowed knowledge and own research capital are complements. On the other hand, Spence (1984) assumes that knowledge spillovers from outside are perfect substitutes for own research capital. Following his specification, in the present context the overall effective research capital available to the private sector can be assumed to be $H + g(A^0, B^0)$, where $g(\bullet)$ is a function strictly increasing in A^0 and B^0. In this case, we have $\frac{\partial^2 f}{\partial H \partial A^0} < 0$ and $\frac{\partial^2 f}{\partial H \partial B^0} < 0$, meaning that borrowed knowledge and own research capital are substitutes. The real situation might be in the middle of the two extremes, i.e., some borrowed knowledge is a perfect substitute for own research capital and some borrowed knowledge complements own research capital. In our model the specification of knowledge spillovers in the production function allows for both possibilities, leaving the answer to the empirical analysis.

Research investment good market

Another place where the two sectors interact is the market for the investment good. David and Hall (2000) argue that the two sectors compete in the research input market, and public-sector investment has a direct effect on the price of the research investment good, which in turn will affect the private sector's investment decision. Denote by $\hat{h} \in \Re_{+}$ and $\hat{w} \in \Re_{++}$ the total amount of research investment good supplied in the market, and its market price, respectively. Define the supply function of the research investment good by

(1.6) $$\hat{h} = s(\hat{w}) .$$

Following David and Hall (2000), we assume that this supply curve has a positive slope, i.e., $\frac{d\hat{h}}{d\hat{w}} = s'(\bullet) > 0$. The market clear condition is

(1.7) $$\hat{h} = h^0 + h .$$

Private-sector research investment demand

Next, we introduce a theory of the private sector's investment demand. Assume that the private sector maximizes the accumulated present value of profit flow over an infinite horizon. Denote the price for the applied research output by $p \in \Re_{++}$. Let $w = \hat{w} / p$ be the normalized price for the research investment good. The private sector finances by borrowing at a fixed, constant interest rate $r \in (0,1)$. For notational clarity, write in vector form all the exogenous parameters, i.e., $\boldsymbol{\theta} = (A^0, B^0, w, \delta_H, r)' \in \Re_{+}^{2} \times \Re_{++}^{1} \times (0,1)^2$.

It is also assumed that these variables are time invariant, i.e. the private sector has static expectation. Thus, the private sector's problem is

(1.8) $$\max_{h(t)} \int_0^\infty e^{-rt} [f(H(t), h(t); A^0, B^0) - wh(t)]dt,$$

subject to (1.3) $\dot{H} = h - \delta_H H$ and $H(0) = H_0$, where H_0 is the fixed initial value of research capital.

Lucas (1967) shows that the closed-loop solution to the adjustment cost model such as (1.8) can be linearly approximated by (thus rationalize) the *ad hoc* flexible accelerator model, which in the present context takes the form:

(1.9) $$\dot{H}_t = m(\boldsymbol{\theta})[H_t - H^*(\boldsymbol{\theta})],$$

where H^* is the steady state or equilibrium stock of research capital, and

(1.10) $$m(\boldsymbol{\theta}) = \frac{1}{2}\left\{ r - \sqrt{r^2 + 4\frac{f_{HH}(H^*, h^*; A^o, B^0)}{f_{hh}(H^*, h^*; A^o, B^0)}} \right\},$$

is the adjustment parameter[6]. Note that since $f_{HH} < 0$ and $f_{hh} < 0$, m is always negative, implying that research capital stock H is always moving towards the steady-state level H^*. Also, $\frac{\partial |m|}{\partial r} < 0$, so that an increase in interest rate r always reduces the adjustment speed. Finally, if the adjustment cost increases quickly as investment increases, i.e., f_{hh} is relatively great in absolute value, then the adjustment speed is relatively slow.

Model (1.9) gives us the private sector's research investment demand, which explicitly describes the motion towards equilibrium. In the next section we shall conduct steady-state comparative statics of the model. Specifically, we shall study how the private sector's long-run equilibrium rate of investment responds to changes in the public sector's applied and basic knowledge stocks and other exogenous parameters. This will allow us to conduct some policy experiments considered by David and Hall (2000). Indeed, we shall show that in the long run our dynamic model reduces to a generalized version of the D-H model.

Steady State Comparative Statics and Policy Experiments

To begin our analysis, define the current value Hamiltonian function for (1.8) as:

(2.1) $$\mathcal{H}(H,\lambda_H;\boldsymbol{\theta}) = f(H,h;A^0,B^0) - wh + \lambda_H(h-\delta_H H).$$

The optimal solution to problem (1.8) must necessarily satisfies

(2.2) $$0 = \mathcal{H}_h = -w + f_h + \lambda_H \,,$$

(2.3) $$\dot{\lambda}_H = r\lambda_H - \mathcal{H}_H = \lambda_H(r+\delta_H) - f_H \,,$$

(2.4) $$\dot{H} = h - \delta_H H \;.$$

To simplify matters, let's reduce the above three equations down to two by eliminating the costate variable λ_H. Solve equations (2.2) for λ_H and substitute it into (2.3). Then differentiate (2.2) with respect to time, solve for $\dot{\lambda}_H$, and substitute it into (2.3). This leads us to two differential equations in (H,h), namely, (2.4) and

(2.5) $$\dot{h} = \frac{(r+\delta_H)(f_h - w) + f_H}{f_{hh}} \,.$$

At the steady state, $\dot{H} = \dot{h} = 0$. The long-run equilibrium $(H^*(\boldsymbol{\theta}), h^*(\boldsymbol{\theta}))$ is thus the solution of the following two nonlinear equations:

(2.6) $$(r+\delta_H)(f_h - w) + f_H = 0 \,,$$

(2.7) $$h - \delta_H H = 0 \,.$$

We are particularly interested in how $(H^*(\boldsymbol{\theta}), h^*(\boldsymbol{\theta}))$ changes in response to changes in $A_0, B_0,$ and w[7]. Applying Cramer's rule, we can arrive at following results:

(2.8) $$sign(\frac{\partial h^*(\boldsymbol{\theta})}{\partial Z}) = sign(\frac{\partial H^*(\boldsymbol{\theta})}{\partial Z}) = sign(\frac{\partial^2 f}{\partial H \partial Z}) \text{, for } Z = A^0, B^0;$$

(2.9) $$\frac{\partial h^*(\boldsymbol{\theta})}{\partial w} < 0 \text{ and } \frac{\partial H^*(\boldsymbol{\theta})}{\partial w} < 0 .$$

(2.8) establishes an important result on how the private sector's research investment (and therefore research capital) is affected by knowledge generated by the public sector in the long run. Specifically, this effect is crucially determined by the mechanism of knowledge spillovers specified in the private sector's technology. For example, if the knowledge borrowed from the public sector complements the private sector's own research capital, i.e., $\frac{\partial^2 f}{\partial H \partial A^0} > 0$ and $\frac{\partial^2 f}{\partial H \partial B^0} > 0$, then the more knowledge is generated from the public sector the more will the private sector invest in research, other things being equal (we call this the *productivity effect*). On the other hand, if the knowledge borrowed from the public sector is a substitute for the private sector's own research capital, i.e., $\frac{\partial^2 f}{\partial H \partial A^0} < 0$ and $\frac{\partial^2 f}{\partial H \partial B^0} < 0$, an increase in the public sector's knowledge stocks will decrease the private sector's investment, other things being equal (we call this the *replacement effect*).

As shown in (2.9) the normalized price for the research investment good, w, has an unambiguously negative impact on the private sector's research investment rate and research capital stock (we call this the *wage effect*). This is not surprising because an increase in w either raises the marginal cost or reduces the marginal benefit of investment. In either situation, private-sector research investment will decline.

We now compare our model with the D-H model. The D-H model assumes that the basic knowledge generated by the public sector increases the private sector's productivity in knowledge production, but the applied knowledge has no direct effect whatsoever. Based on these assumptions, it was concluded that given the total research funds fixed, an increase in the ratio of basic to applied research outputs in the public sector will always increase private-sector research investment. In our notation, their assumptions can be expressed as $f_{HA^0} = 0$ and $f_{HB^0} > 0$. Since the total investment money remains the same, there is no wage effect in the research input market. Hence, their conclusion is immediate from (2.8). As we explained before the above assumptions made in the D-H model are quite restrictive. Therefore, our model allows for both the productivity and replacement effects for both basic and applied knowledge.

Consider now the question whether the public-sector research investment "crowds in" or "out" the private-sector research investment in the long run. Since there are two decision variables for the policy maker in this situation, i.e., how much to invest in total ,and how much basic/applied research to conduct, we have to fix one of the two research output rates, say b^0. This amounts to a long-term policy of conducting more applied research without affecting basic research, by increasing the investment rate. The impact of this policy on the private sector's investment demand can be seen from the long-run elasticity of the private sector's investment demand with respect to the public sector's, i.e.,

(2.10) $$e^l_{hh^0} = \frac{h^{0*}}{h^*}\frac{\partial h^*(\boldsymbol{\theta})}{\partial h^{0*}} \doteq \frac{h^{0*}}{h^*}\frac{\frac{1}{\delta_A}\frac{\partial h^*(\boldsymbol{\theta})}{\partial A^0}(\frac{1}{\delta_H}\frac{\partial f^0}{\partial H}+\frac{\partial f^0}{\partial h})+\frac{1}{ps'(\hat{w})}\frac{\partial h^*(\boldsymbol{\theta})}{\partial w}}{1-\frac{1}{ps'(\hat{w})}\frac{\partial h^*(\boldsymbol{\theta})}{\partial w}},$$

where all the derivatives are evaluated at equilibrium levels and the second-round effects running from the private to public sector through knowledge spillovers are ignored for simplicity. Since $\frac{\partial h^*(\boldsymbol{\theta})}{\partial w} < 0$ as shown in (2.9) and $s'(\hat{w}) > 0$ as assumed in (1.6), we have $\frac{1}{ps'(\hat{w})}\frac{\partial h^*(\boldsymbol{\theta})}{\partial w} < 0$ and $1 - \frac{1}{ps'(\hat{w})}\frac{\partial h^*(\boldsymbol{\theta})}{\partial w} > 0$. In other words, the wage effect of this policy is unambiguously negative. Also, $\frac{1}{\delta_H}\frac{\partial f^0}{\partial H} + \frac{\partial f^0}{\partial h}$ should be always positive since at equilibrium the marginal adjustment cost of investment should not exceed the marginal product value of research capital. If the replacement effect dominates the productivity effect, i.e., $\frac{\partial h}{\partial A^0} < 0$, the public research investment will crowd out some of the private sector's. But, if the productivity effect dominates the replacement effect, i.e., $\frac{\partial h}{\partial A^0} > 0$, whether the public sector' research investment crowds in or out the private sector's hinges on the relative magnitudes of the wage, productivity, and replacement effects.

This is consistent with the conclusion drawn by David and Hall (2000) in considering a similar policy experiment (though they do not take into consideration the replacement effect). In passing, we note that another policy experiment, i.e., conducting more applied research while keeping the same level of basic research by increasing investment rate, can be carried out analogously. Also, how the public research policy will affect the applied knowledge generated by the private sector can be understood by looking at the elasticities of private-sector applied knowledge supply. These results are not shown here owing to the space constraint.

In summary, our dynamic model generalizes the D-H model in three dimensions: 1) our model takes into consideration the evolution towards equilibrium of the private sector's investment demand; 2) our model allows for both replacement and productivity effects while theirs only considers the latter; 3) our model takes into account the spillover effects of both basic and applied knowledge generated by the public sector, while their model only accommodates that of basic knowledge. We have also shown that it is difficult to draw any definitive conclusion on the "crowding in or out" question based on theoretical deduction, and careful empirical analysis is necessary for a satisfactory answer. However, the usefulness of a structural model, as we have seen, is helping to single out some important channels of forces in the complex of public and private interactions.

Implementation of the Model

In this section, we consider how to implement the theoretical model proposed above. To begin, we assume that the public- and private-sector knowledge production functions take the following quadratic forms:

$$f^0(H^0, h^0, b^0; A) =$$

$$\alpha^0 + \begin{bmatrix} \alpha_{H^0} & \alpha_{h^0} & \alpha_{b^0} \end{bmatrix} \begin{bmatrix} H^0 \\ h^0 \\ b^0 \end{bmatrix} + \frac{1}{2} \begin{bmatrix} H^0 & h^0 & b^0 \end{bmatrix} \begin{bmatrix} \beta_{H^0H^0} & 0 & 0 \\ 0 & \beta_{h^0h^0} & 0 \\ 0 & 0 & \beta_{b^0b^0} \end{bmatrix} \begin{bmatrix} H^0 \\ h^0 \\ b^0 \end{bmatrix} + \gamma_{H^0A} H^0 A \tag{3.1}$$

and

$$f(H, h; A^0, B^0) = \alpha + \begin{bmatrix} \alpha_H & \alpha_h \end{bmatrix} \begin{bmatrix} H \\ h \end{bmatrix} + \frac{1}{2} \begin{bmatrix} H & h \end{bmatrix} \begin{bmatrix} \beta_{HH} & 0 \\ 0 & \beta_{hh} \end{bmatrix} \begin{bmatrix} H \\ h \end{bmatrix} + H \begin{bmatrix} \gamma_{HA^0} & \gamma_{HB^0} \end{bmatrix} \begin{bmatrix} A^0 \\ B^0 \end{bmatrix}, \tag{3.2}$$

respectively; where those $\alpha's, \beta's,$ and $\gamma's$ are parameters to be estimated.

Given the above specification for the private-sector production function, the discrete-time version of research investment demand (1.9) is:

$$h_t = m(\boldsymbol{\theta})[H_{t-1} - H^*(\boldsymbol{\theta})] + \delta_H H_{t-1}, \tag{3.3}$$

where

$$H^*(\boldsymbol{\theta}) = \frac{(r+\delta_H)(w-\alpha_h) - \gamma_{HA^0} A^0 - \gamma_{HB^0} B^0 - \alpha_H}{\beta_{HH} + \beta_{hh}(r+\delta_H)\delta_H} ,$$

and

$$m(\boldsymbol{\theta}) = \frac{1}{2}\left\{ r - \sqrt{r^2 + 4\frac{\beta_{HH}}{\beta_{hh}}} \right\}.$$

The supply of the research investment good (1.6) is specified as

(3.4) $$\hat{h} = \phi_0 + \phi_1 \hat{w} + \phi_2 \hat{w}^2 .$$

where $\phi_1, \phi_2,$ and ϕ_3 are parameters to be estimated. Along with the market clearing condition (1.7), equations (3.1-4) constitute a non-linear simultaneous equation system. Maximum Likelihood Estimation procedures can be combined with Simultaneous Equation System estimation techniques to estimate the parameters of interest.

The hypotheses on the structure of adjustment cost of investment can be tested by examining the estimates of α_{h^0}, α_h, $\beta_{h^0 h^0}$ and β_{hh}. If there is evidence of adjustment cost, $m(\boldsymbol{\theta})$ can be readily calculated to tell us the adjustment speed of research investment. The estimates of γ_{HA^0} and γ_{HB^0} can tell us whether the productivity effect dominates the replacement effect, or vice versa. To evaluate the long-run effect of increasing basic research, other things being equal, we can calculate the long-run elasticity of the private sector's basic research supply with respect to the public sector's basic knowledge stock, i.e.,

(3.5) $$e^l_{hB^0} = \frac{-\gamma_{HB^0}}{\beta_{HH} + \beta_{hh}(r+\delta_H)\delta_H} \frac{B^0}{h} .$$

Note that if β_{HH} and β_{hh} behave normally, i.e., both are negative, $e^l_{hB^0}$ always has the same sign with γ_{HB^0}, which verifies result (2.8). The effect of other public research policy regimes can be evaluated by estimating the corresponding elasticities in a similar manner. For example, whether public-sector research investment in applied research crowds in or out the private-sector research investment can be understood by calculating elasticity (2.10).

We have described an empirical model in which the private sector's research demand is directly derived from the intertemporal profit maximization problem (1.8). Alternatively, we can also estimate a dual system based on the value function of (1.8). The intertemporal duality theory is due to Epstein (1981) and McLaren and Cooper (1980). The key idea is to use as a bridge the Hamilton-Jacobi-Bellman equation to transform the dynamic optimization problem into a static one. Then, the standard duality theory can be applied to establish the dual relationship between the value and production functions. The dynamic factor demands can be readily obtained by way of an analogue of Shephard's lemma. This approach can reduce the aggregation bias problem to the extent that independent variables of the value function include the investment good price, which is the same for every firm in the private sector (Epstein and Denny, 1983).

Data

Aggregate time-series data from 1980 to 2004 are going to be used in this study. Till now, we have collected data on research expenditures by the public and private sectors for three life science fields, medicine, agriculture and biology, and some agricultural subfields. Data on public spending in medical and biological research were obtained from NSF's annual R&D Funds Survey, and data on public spending in agricultural research were from USDA's Current Research Information System Funding Summaries.

Data on industry R&D spending are based on the Compustat database. An effort has been made to identify the scientific fields of R&D conducted by each of the Compustat firms based on the SIC system and a textual review of firms' businesses at the business segment level.

To get a measure of the quantity of the investment good, these expenditures data should be deflated using an appropriate price index, which can also serve as the price of the investment good. NIH's Biomedical Research and Development Price Index measures changes in the weighted-average of the prices of inputs (e.g., personnel services, various supplies and equipment) purchased with NIH budget to support research, and therefore can serve as the price index for biological and medical research investments. The agricultural research deflator published in USDA's website can be used for the price index of agricultural research investment.

These quantities of investment can then be used to construct research capital using the perpetual inventory formula. Jaffe (1986) and Bernstein and Nadiri (1989) assume a depreciation rate of 0.15 and 0.1, respectively. They also find that varying the depreciation rate did not alter the estimation results significantly.

Construction of research output data is still in progress. Publication and patent counts, appropriately adjusted for quality variation, will be used to measure basic and applied research outputs, respectively. Such data can be constructed for both private and public sectors by sorting publications and patents by institution of authors and assignees, respectively.

Knowledge stocks can be constructed again using the perpetual inventory formula. Blundell, et al. (1995) adopts this approach to construct knowledge stock with patent data.

They also experiment with different depreciation rates (15, 25, and 50%), and find that the depreciation rate made little difference to the estimation results.

The remaining two data items that we need to estimate the model are the interest rate and the applied research output price. Many different measures for the former exist in the literature. For example, Bernstein and Nadiri (1989) use the mean of the preferred dividend rate for medium-risk companies. There exist no good economic data for the average price of patents, and we have to find a proxy for it. One possibility is to estimate the contribution to the market value of the number of owned patents after accounting for the total physical asset for each industry (Griliches, 1981).

Conclusion

In this article, we have proposed a dynamic model to guide our empirical analysis of public investment policy in life science research. The model allows us to examine three important channels through which public investment policy can affect the private sector's research investment, that is, the productivity, replacement, and wage effects. We have shown that our model is a generalization of David and Hall (2000)'s model in that at the steady state, our dynamic model encompasses their static model as a special case. Two alternative empirical approaches were then introduced to test the hypotheses underlying our model and estimate the impacts of several research policy regimes on the private-sector research investment. In addition, through a unified examination of the productivity, replacement, and wage effects, the empirical estimation of our model will provide insight into whether public-sector research investment crowds in or crowds out private-sector research investment. Future research will continue our data construction and extend the one-field model into a multi-field one allowing for private-sector production of basic research.

[1] This assumption can be relaxed to accommodate the situation where research firms also conduct basic research. Our final data analysis will adopt such a model. But, to focus ideas we do not present it here.

[2] Note that this hypothesis holds even though there exist certain legal restrictions on the scope of using ideas generated by others, since it is practically impossible to exclude the use of existing ideas completely, especially for the research purposes.

[3] The assumptions on the abstract research firms and the competitive output market are borrowed from Romer (1990). It might be justifiable to abstract a sector of research firms from the private industry, but it is more difficult to defend the competitive market assumption because theorists in industrial organization suggest that R&D investment can be a strategic variable to the firm, that is, the internal price of the research output may well be endogenous to the firm's R&D investment decision. A model discarding this assumption has not yet been developed. A similar situation has been encountered by Bernstein and Nadiri (1989), but no solution was provided in that study.

[4] Empirically, the aggregation bias can be reduced in estimating a value function whose independent variables include prices, rather than a production function whose independent variables are all quantities (see pp. 16 for a detailed discussion of this approach). We also note that the knowledge spillovers among firms are completely ignored in our model, because this study is focused on public and private R&D interactions, and the presence of knowledge spillovers among firms should not alter our results qualitatively.

[5] This assumption is the backbone of the adjustment cost model. Without it, the dynamic model would collapse to a static one.

[6] This result is based on the assumption that the production function is separable in research capital and investment, i.e., $f_{Hh} = 0$. This assumption will be maintained throughout the rest of the paper, and we also assume that $f_{hA^0} = 0$ and $f_{hB^0} = 0$.

[7] We do not show results of steady state comparative statics associated with δ_H and r because these variables are not in direct relevance to our policy analysis, and treated as constants in our empirical analysis.

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