R&D Spillovers in Agriculture: Results from a Trade Model

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Abstract

The objective of this study is to analyze technical change and the role of research and development (R&D) spillovers in this process for the U.S. agricultural sector. This study is composed of both a theoretical and an empirical analysis. In the theoretical analysis, a quality innovation model is used in which the R&D sector is the source of technological progress and is composed of a public and a private sector. The public R&D sector can serve either as a substitute to the private R&D sector or as a complement to it. Free trade is included in the next step of the analysis as a mechanism through which R&D spillovers are realized, along with increased market size for domestic R&D firms and increased competition from foreign R&D firms. Two different trade scenarios are utilized: a North-North and a North-South, as the United States has trade relations with both developed and developing countries. In the empirical analysis, the propositions of the model are tested for U.S. agricultural sector data. I find that R&D spillovers have a significant and positive effect on technical change as well as private R&D spending. The results indicate that the public R&D sector's complementary role outweighs its substitutability to the private R&D sector, as it is found to have a significantly positive effect on private R&D spending.

Keywords: productivity, R&D spillovers, technical change, trade.

R&D SPILLOVERS IN AGRICULTURE: RESULTS FROM A TRADE MODEL

Introduction

Extensive literature has focused on the determinants of productivity growth in agriculture, particularly on the roles of public and private research and development (R&D), human capital, and extension activities. There has been ample empirical evidence that these activities play an important role in productivity gains. A small fraction of this research has looked at the impact of R&D spillovers from other close geopolitical entities, whether it be the R&D spillovers between states in the United States or R&D spillovers between different countries. The results of these studies so far have shown the importance of accounting for R&D spillovers, as the variables included to capture these possible effects not only have been significant but also have changed the rates of return to research estimates for domestic variables, thus casting doubt on previous rates-of-return estimates.

Furthermore, a correct estimation of the impact of R&D spillovers is necessary in order to devise efficient agricultural policies on national and international levels. Alston (2002) notes that "…national benefits might be overestimated if the benefits from international spill-ins are attributed to domestic agricultural R&D, while spillovers among countries mean that the global benefits from a country's research will be underestimated by a study that measures only national benefits."

The objective of this paper is to analyze the impact of R&D spillovers from other countries on the U.S. agricultural R&D sector. First, the relationship between R&D and innovation in the U.S. agricultural sector is modeled with a focus on how the mechanism of the domestic R&D sector operates. Second, the model incorporates the impact of trade on the domestic R&D sector and innovation with an emphasis on R&D spillovers from foreign countries.

To this end, a quality innovation model is used in which both public and private sectors' R&D activities lead to technological progress. The public R&D sector conducts research and patents its research results in the same manner as the private R&D sector. This type of public sector R&D is a substitute for private sector R&D and may "crowd out" private sector R&D investments. Another public sector R&D activity is included through a subsidy that effectively lowers the cost of research for private firms, and through this mechanism the public R&D sector is a complement to the private R&D sector.

Including a public R&D sector is particularly important because in the United States, public R&D activities have been a major portion of the total agricultural R&D activities.[1] Although, the role of private R&D spending has increased considerably in the last two decades because of changes in the property rights structure and advances in biotechnology, the public sector is still a major contributor to agricultural R&D. The increasing role of private R&D combined with the stagnation in public R&D investments has spurred discussions on the optimal role of the public R&D sector. This model analyzes the dual effect of the public R&D sector on the private R&D sector, thus providing some theoretical framework for the latest discussions.

In the next step of the analysis, free trade is introduced into the model with two scenarios. The first scenario is a North-North trade model in which trade is between two developed and innovating countries. The second scenario is a North-South trade model in which trade is between a developed, innovating country and a less-developed, imitating country. The reason for presenting the two trade scenarios is that, although developed countries have been major spenders on public agricultural research in the past, in the 1990s developing countries have spent more on public agricultural research (Pardey and Beintema 2001). The U.S. agricultural sector will be affected not only by R&D investments in developed countries but also by R&D investments in developing countries, as its trade partners are both developed and developing countries.

It should be noted that the focus of this paper is not to explore the effects of trade on an economy, as this type of work has been done extensively before. The main focus is on analyzing how the flow of knowledge and the flow of goods between countries affect innovation and the R&D sector. Domestic R&D firms may benefit from access to research results in other countries and enjoy larger trade markets for their products, though there is a chance of losing their markets to foreign competition.

In the next part of the analysis, the implications of the model are tested using data for the U.S. agricultural sector for 1971 through 1994. A system of equations is estimated using the seemingly unrelated regressions technique. First, the link between total factor productivity (TFP) in the U.S. agricultural sector and technological change is explored, where agricultural patent data is used as a proxy for technological progress that benefits the agricultural sector. Second, the determinants of technological progress as measured by agricultural patents are examined. Finally, the factors that affect private agricultural R&D spending are analyzed.

This study proceeds as follows. First, a quality innovation model is presented, with autarky in the North, a North-North trade model, and finally a North-South trade model. Then, data source and variables are described. After a discussion of empirical specification and results of the empirical analysis, some concluding remarks are presented.

Quality Innovation Model

The quality innovation model used in this study is an endogenous growth model with an R&D sector that is the source of technical progress. The first contribution of the model is that the R&D sector is composed of two parts, a private sector and a public sector. Both of these sectors engage in research activities that lead to improvements in the quality of intermediate goods used in the production of a final good. The private sector represents the profit-maximizing behavior of entrepreneurs, whereas the public sector represents R&D conducted by public institutions that are not motivated by profit. The model is closely related to those of Barro and Sala-I-Martin (1995, Chap. 7) and Grossman and Helpman (1991, Chap. 4).

The link between public and private R&D consists of two channels. The public R&D sector is a substitute to the private R&D sector, as it not only engages in R&D but also earns exclusive property rights to the results of its research efforts and may drive an incumbent private sector firm out of business. The public sector also acts as a complement to the private sector by lowering the cost of research for private firms. This can be achieved through different tools, such as conducting “basic research” and making its results publicly available, providing incentives for private R&D through tax breaks or direct subsidies, and providing public funds to private firms through competitive grants.

The process through which public sector funds are allocated to R&D is taken as exogenous to the model as it is outside the scope of this paper.[2]

The main feature of the production technology assumed here is that capital is disaggregated into a finite number of distinct types of intermediate goods (indexed by $j=1 \ldots N$). Each intermediate good has a quality ladder along which improvements can occur. Research efforts are aimed at increasing the existing quality of each intermediate good and are based on the currently available technology.

When a product is improved, it tends to replace the lower-quality version in the market. In this study, it is assumed that a higher-quality product is a perfect substitute for its lower-quality counterpart, that is, it makes the older version obsolete. So, in the equilibrium, only the highest-quality intermediate goods are produced by the R&D sector and used by the producers of the final good to generate output.[3]

Each successful researcher, whether private or public, gains exclusive property rights over the use of the higher-quality intermediate good he or she creates. Private R&D firms operate in an imperfectly competitive market setting. When a private R&D firm is successful in upgrading the quality of an intermediate good, it receives a flow of monopoly profit. The researcher who succeeds in upgrading the quality of an intermediate good is different from the person who has invented the previously highest-quality intermediate good. So, the success of an innovator, whether public or private, terminates the profit flow to the previous private sector innovator. As it is uncertain whether the outcome of any research effort will be successful or not, the duration of this profit flow for the current patent holder is random. Hence, not only the size of the profit flow but also the duration of it determines the amount of resources devoted to research by private firms.

In this study, a closed economy model is presented where there is no trade and only intermediate goods designed by the domestic R&D sector are used. Then, free trade in final and intermediate goods is introduced into the model with two different scenarios. In the first scenario, trade between two Northern countries is analyzed, where countries are symmetrical in terms of their factor endowments and costs of production. In the second scenario, trade is between a developed country, i.e., North, and a less-developed country, i.e., South. The methodology to introduce a North-South trade into the model is based on

Connolly 1999.[4] The second contribution of this study is to analyze the impact of trade on innovation in a country and its domestic R&D sector.

Autarky in the North

First, the case of autarky is presented for a Northern country that is indexed by 1. The final good is produced in a perfectly competitive market using land, labor, and a set of N different intermediate goods. The production function is

$$Y_1 = A_1 \cdot L_1^{1-\alpha-\beta} \cdot H_1^{\beta} \cdot \sum_{j=1}^{N} \left(\tilde{X}_{1j}\right)^{\alpha} \tag{1}$$

where $0<\alpha<1$, $0<\beta<1$, $0<\alpha+\beta<1$, Y is agricultural output, L is land input, H is labor input, and $\tilde{X}_{1j}$ is the quality-adjusted amount employed of the *j*th type of intermediate good. The production function specifies diminishing marginal productivity of each input and constant returns to scale in all inputs together.[5]

The potential quality grades of each intermediate good are arrayed along a quality ladder with rungs spread proportionately at an interval of q (q>1). Innovations occur in the form of increases in the quality rungs of each intermediate good as a multiple of q. So, the quality-adjusted input from sector *j* can be written as $\tilde{X}_{1j} = \sum_{k=0}^{\kappa_j} q^k \cdot X_{1jk}$. κ_j—the total number of innovations in sector *j* is a proxy for the level of technology in that sector. When only the highest-quality goods are produced and used in equilibrium,[6] the production function takes the form $Y_1 = A_1 \cdot L_1^{1-\alpha-\beta} \cdot H_1^{\beta} \cdot \sum_{j=1}^{N} (q^{\kappa_{1j}} \cdot X_{1j\kappa_j})^{\alpha}$.

Behavior of Firms

The industry that produces the final good is perfectly competitive and the price of the final good (P_{1Y}) is set as *numéraire* ($P_{1Y}=1$). The private R&D sector is monopolistically competitive, and the marginal cost of producing an intermediate good is specified as equal to the price of the final good ($MC_1 = P_{1Y} = 1$). To understand how the industry leader captures the market, we need to look at its pricing strategy. If the industry leader uses limit-pricing strategy and charges a price that is ε below ($q \cdot MC_1$), then it can drive the follower that produces the lower-quality intermediate good out of the market. Therefore, the equilibrium price is $P_1 = q \cdot MC_1$, and only the leading edge quality intermediate goods will be produced and sold.[7]

If an aggregate quality index is defined as $Q_1 = \sum_{J=1}^{N} (q^{\kappa_{1j}})^{\alpha/(1-\alpha)}$, then the equilibrium level of output in the North under autarky is

$$Y_1 = \left(\frac{\alpha}{q}\right)^{\alpha/(1-\alpha)} \cdot A_1^{1/(1-\alpha)} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot Q_1 \tag{2}$$

Public and Private R&D Sectors in the North under Autarky

The private sector researcher who innovates the κ_{1j} th quality of intermediate good *j* will accrue his or her profits until a new researcher comes up with the ($\kappa_{1j} + 1$)th quality intermediate good *j*. The random duration of this profit depends not only on the efforts of private R&D firms but also on the efforts of the public R&D sector.

To illustrate this relationship, let p_1^* be the probability per unit of time of an increase in quality from κ_{1j} to ($\kappa_{1j} + 1$). This is the society's total probability of innovation in the North. This value is equal to the sum of the probability of innovation by the public sector, p_1^P, and the probability of innovation by the private sector, $p_{1j\kappa_j}^Z$. The duration of monopoly profits for the private R&D firm depends on p_1^*, not $p_{1j\kappa_j}^Z$. As both public and private R&D sectors can invent the next higher quality intermediate good, the probability of success of both of these sectors determines how long the current leader will accrue his or her monopoly profits.

This is clearer when the expected value of the next innovation to a private R&D firm is derived as

$$E(V_{1j\kappa_j}) = \frac{\pi_{1j\kappa_j}}{r_1 + p_1^*} = \frac{\pi_{1j\kappa_j}}{r_1 + p_1^P + p_{1j\kappa_j}^Z}$$

The expected value of the next innovation is lower with a public R&D sector as the society's probability of innovation is higher than the private sector's probability of innovation. The rationale for this result is that when both public and private sector researchers endeavor to come up with the next innovation, there is a higher probability that the next higher quality intermediate good will be invented. This increases the probability that the incumbent will be driven out of business by the next innovator, thus lowering the expected present value of profits from the next invention by a private sector researcher. That is why, in this model, the public sector may crowd out private sector R&D.

Private Sector Research Effort

The flow of resources expended by the aggregate of private potential inventors in intermediate good sector *j*, when the highest quality in that sector is κ_{1j}, is denoted as $Z_{1j\kappa_j}$. The relation between $p^Z_{1j\kappa_j}$ and $Z_{1j\kappa_j}$ is defined as

$$p^Z_{1j\kappa_j} = Z_{1j\kappa_j} \cdot \phi(\kappa_{1j}) . \tag{3}$$

As $Z_{1j\kappa_j}$ increases, the probability of successful innovation per unit of time in that sector by a private R&D firm increases. The second term, $\phi(\kappa_{1j})$, is added to reflect the complexity of a research project, and $\partial\phi(\kappa_{1j})/\partial\kappa_{1j} < 0$. In this model, it is assumed that p_1^* and $p^Z_{1j\kappa_j}$ follow a Poisson process.[8] Assuming free entry into the research business, the society's probability of innovation is derived as

$$p_1^* = \phi(\kappa_{1j}) \cdot q^{(\kappa_{1j}+1)\cdot\alpha/(1-\alpha)} \cdot (q-1) \cdot MC_1 \cdot A_1^{1/(1-\alpha)} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot \left(\frac{\alpha}{q}\right)^{1/(1-\alpha)} - r_1 . \tag{4}$$

If constant returns to R&D are assumed, the functional form for $\phi(\kappa_{1j})$ becomes $(1/s \cdot \zeta_1) \cdot q^{-(\kappa_{1j}+1)\cdot\alpha/(1-\alpha)}$.[9] The parameter $\zeta_1 > 0$ represents the fixed cost of research in the North: a higher ζ_1 lowers the probability of success for given values of $Z_{1j\kappa_j}$ and κ_{1j}. The parameter s takes a value between 0 and 1. This is the second channel through which public sector activities affect the private R&D sector of the model. Parameter s is a subsidy equivalent of public sector activities that effectively lowers the cost of private R&D sector, and here it lowers ζ_1, the fixed cost of research for private R&D firms. Through this channel, the public R&D sector acts as a complement to the private R&D sector.

After solving for the probability of an innovation per unit of time by the private R&D sector, the aggregate private sector R&D spending in the North under autarky is derived as

$$Z_1 = Q_1 \cdot q^{\alpha/(1-\alpha)} \cdot \left[\left(\frac{\alpha}{q} \right)^{1/(1-\alpha)} \cdot (q-1) \cdot MC_1 \cdot A_1^{1/(1-\alpha)} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} - (r_1 + p_1^P) \cdot (s \cdot \zeta_1) \right] . \qquad (5)$$

The above equation shows that private R&D spending is endogenously determined and depends on the decisions of economic agents and institutions that take part in the production and research process. It also gives information about which economic variables affect private R&D spending. First, the scale of demand positively affects private R&D spending, as a larger market size means higher profits from an innovation, which increases the R&D effort by private firms. Secondly, both the aggregate quality index (Q) and the productivity parameter (A) have a positive impact on private R&D spending. Through subsidy (0<*s*<1), the public R&D sector increases private R&D spending. However, the probability of innovation by the public R&D sector (p_1^P) decreases private R&D spending, as it increases the probability of being driven out of business. The net effect of public sector activities on the level of private R&D spending is ambiguous in the model: this is an empirical question that depends on the relative magnitude of these competing forces.

North-North Trade

In this step of the analysis, trade between two developed countries is incorporated into the model, where both of the countries engage in innovative R&D activities. These two countries have the same factor endowments and the same production costs. This part of the analysis shows the benefits from economic integration,[10] where trade in final and intermediate goods allows firms to benefit from larger markets, and increased competition in the R&D sector increases the probability of innovation in the sector.

To make the solution tractable, it is assumed that each country is the leader in half of the intermediate goods sectors and one quality below in the other half of the intermediate goods sectors. Thus, with free trade, half of the leader industries in each country will benefit from a larger market and the other half will lose their markets to the higher-quality intermediate good. After trade, each country will produce half of the intermediate goods domestically and start importing the other half. The focus in this scenario is on how the domestic R&D sector and innovation are affected by free trade with another developed country and the resulting R&D spillovers.

Again, the price of the final good is equal to the marginal cost of production of the intermediate good. As the countries have the same production costs and the same price of the final good, $P_{Y1} = MC_1 = P_{Y1}^* = MC_1^*$. The industry leader will use limit pricing strategy and charge a price that is ε below $q \cdot MC_1$ for the intermediate good, so the equilibrium price is $P_1 = q \cdot MC_1$. As there will be both domestic demand and import demand from the foreign country, profits of the industry leader under free trade will be twice the amount of its profits under autarky. However, from the perspective of the aggregate economy, only half of these firms can keep their markets, while the other half loses it to foreign industry leaders.

The expected present value of profits with trade is

$$E(V_{1j\kappa_j}^{TRADE}) = \frac{\pi_{1j\kappa_j}^{TRADE}}{r_1 + p_1^* + p_1^*} = \frac{2 \cdot \pi_{1j\kappa_j}^{AUTARKY}}{r_1 + 2 \cdot p_1^*}, \text{[11]}$$

which exceeds the expected present value of profits under autarky,

$$E(V_{1j\kappa_j}^{AUTARKY}) = \frac{\pi_{1j\kappa_j}^{AUTARKY}}{r_1 + p_1^*}.$$

There are two different impacts of trade on the expected present value of profits for an R&D firm. First, trade increases value through the increase in demand for intermediate goods. Second, trade decreases value through the lower duration of these profits after trade because then, R&D efforts double as firms in both countries try to come up with the next innovation and it is twice as probable that the incumbent will be driven out of business. In this scenario, the demand increase effect outweighs the lower duration effect from trade, increasing expected present value of profits from new innovations.

After solving for the probability of innovation per unit of time by the private R&D sector, which is higher with trade, the equilibrium private R&D spending with trade is derived as

$$Z_1^{TRADE} = Q_1 \cdot q^{\alpha/(1-\alpha)} \cdot \left[\left(\frac{\alpha}{q} \right)^{1/(1-\alpha)} \cdot (q-1) \cdot MC_1 \cdot A_1^{1/(1-\alpha)} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} - (\frac{r_1}{2} + p_1^P) \cdot (s^{TRADE} \cdot \zeta_1) \right]. \quad (6)$$

Note that, $s^{TRADE} \cdot \zeta_1$ is used for the scenario with trade compared to $s \cdot \zeta_1$ in the autarky scenario. The subsidy variable with trade, s^{TRADE}, is less than the subsidy variable in autarky, s. The reason for this specification is to include the possible R&D spillover effects after the economy opens up. This specification demonstrates the positive effects of foreign R&D on the domestic R&D sector. If a domestic R&D firm can benefit from R&D activities conducted in other countries, the effect probably would be in the form of decreasing fixed costs of research, because the R&D firm would not need to conduct research on its own, but merely would use the available information. This specification assumes that the results of foreign R&D are publicly available to anyone who wants to access them, which is a rather implausible assumption. This might be a better representation of reality for public and higher education R&D conducted in foreign countries, as their results are more likely to be accessible than a private firm's research findings. R&D spending by private firms increases as well under free trade, as firms have higher expected profits for their research successes and benefit from foreign R&D activities.

North-South Trade

Because this part of the model follows Connolly 1999 closely, it will be presented in condensed form. In this case, free trade is introduced between two countries, in which one of them is a developed country that is innovating and the other is a less-developed country that is imitating. In this case, North is denoted by 1 and South is denoted by 2. The main assumptions of the model are the same, but now the marginal cost of producing intermediate goods is different between the two countries. Marginal cost in the North is higher than in the South, as now the South imitates the North, and it is cheaper to imitate an intermediate good than to innovate it.

In this scenario, the lead Northern firms have three sets of competitors. The first set is the other Northern R&D firms investing in R&D to innovate the next higher quality intermediate good. The second set is the Southern R&D firms that are investing to imitate the lead Northern good and sell it at a lower price. The third set is the Northern public sector that can conduct R&D.

In terms of the technology gap between the North and the South, there are two possible situations. The gap between the North and the South can be so large that, with free trade, the South only imports leading Northern goods and does not engage in any imitation, as the expected costs outweigh the expected benefits. However, the gap can also be minimal and the Southern intermediate good sectors could have succeeded at imitating the lead Northern goods prior to trade. In this case, the Southern R&D firms continue their activities of imitation and are still competing with the lead Northern R&D firms to capture their market. In this study, only the second case is presented, as the aim is to understand the impacts of imitation in the South on the Northern R&D sector.

The other issue is whether the Northern R&D firm with a higher-quality intermediate good will be able to capture the market from a Southern copy. If the quality improvements are large enough, then with a single innovation, the Northern firm can capture the market from the Southern copy. This can happen only in the case of $q > MC_1/MC_2 > 1$. Here the size of the quality innovation, q, is large enough to be able to sell an intermediate good at a higher price. In this case, the Northern R&D firm will set the price at ε below $q \cdot MC_2$, that is, $P = q \cdot MC_2$. Thus, the Northern firm will be able to undercut all sales of the Southern copy and cover its own cost (MC_1) as well. If this condition does not hold, then the Northern firm cannot underprice the Southern firm.

In this trade scenario, the expected present value of profits for the Northern R&D firm depends on the probability of imitation by the Southern firm (p_2), the probability of innovation by the public R&D sector (p_1^P), and the probability of innovation by the other Northern R&D firms ($p_{1,j\kappa_j}^Z$). The expected present value of profits is derived as

$$E(V_{1j\kappa_j}^{TRADE}) = \frac{\pi_{1j\kappa_j}^{TRADE}}{r_1 + p_1^* + p_2 - p_1^* \cdot p_2}[12],$$

where $p_1^* = p_{1,j\kappa_j}^Z + p_1^P$. The net effect on expected value of profits is ambiguous, as it depends on the relative size of higher profits due to new market demand to the lower duration of these profits.

The net effect of trade on the probability of innovation per unit of time by the private R&D sector in the North is ambiguous in the model. The private sector's R&D spending under free trade is derived as

$$Z_1^{TRADE} = Q_1 \cdot q^{\alpha/(1-\alpha)} \cdot \left[\left(\frac{\alpha}{q}\right)^{1/(1-\alpha)} \cdot (q \cdot MC_2 - MC_1) \cdot \psi - (r_1 + p_1^p + p_2 - p_1^p \cdot p_2) \cdot (s^{Trade} \cdot \zeta_1) \right] / (1 - p_2) \quad (7)$$

where $\psi = A_1^{1/1-\alpha} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot \left(\frac{MC_1}{MC_2}\right)^{1/(1-\alpha)} + A_2^{1/1-\alpha} \cdot L_2^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_2^{\beta/(1-\alpha)}$.

Opening up to trade has three effects on the Northern R&D sector. Through an increase in demand for the North's intermediate goods, as seen in ψ, trade increases the expected present value of profits, the probability of innovation, and the R&D effort of Northern R&D firms. However, because of imitation in the South, the expected present value of profits decreases, because the duration of these profits is shorter. This effect operates in the same way that the public sector R&D does. This is seen in the negative relation between Z_1^{TRADE} and p_2. The last effect is R&D spillovers included through s^{Trade}. With opening up of the economy to trade, the Northern R&D firms may not only benefit from research activities in the North but also from those in the South. Naturally, this effect will be realized to the extent that Northern R&D firms have access to the R&D results in the South, which is more probable with public sector activities.

Data Source and Variables

The study uses U.S. agricultural sector data for the 1971–1994 period, all of which are logarithms. The summary statistics for the data are given in Table 1.

Public R&D stock (R_t) is a stock variable calculated from total public agricultural R&D spending in 1993 international dollars using the Perpetual Inventory Method (PIM). Public R&D spending data are provided by the U.S. Department of Agriculture. Private R&D stock (S_t) is a stock variable calculated from the private sector's agricultural R&D spending in 1993 international dollars using the PIM. Private agricultural R&D spending (Z_t), estimated by Klotz, Fuglie, and Pray (1995), includes R&D of agricultural inputs plus food and kindred products. Extension stock (E_t) is a stock variable created from funds for cooperative extension service in 1993 international dollars using the PIM obtained from Alston and Pardey (1996).

TABLE 1. Summary statistics

Variable	N	Mean	Std. Deviation	Minimum	Maximum
Foreign R&D spending	24	6867.12	1294.91	4767.15	8947.90
U.S. Public R&D spending	24	2438.91	399.87	1837.15	3109.35
U.S. private R&D spending	24	2531.36	667.46	1536.21	3554.09
Agricultural patents	24	1500.65	231.20	1103.72	1906.31
TFP	24	82.92	14.09	64.86	112.52
Extension spending	24	1218.10	194.39	570.66	1461.91
Price index	24	135.52	29.54	96.58	194.58
Interest rate	24	0.0150	0.0330	-0.0387	0.0788

Foreign R&D stock (F_t) is a stock variable calculated from total foreign public agricultural R&D spending in 1993 international dollars using the PIM method, that is, both government and higher education spending.[13] The criteria for the choice of countries included in the coverage were their availability as well as whether they were in the same agroecological zones as the United States. The reason is that it is crucial to adjust agricultural technologies to local conditions. "The more similar countries are in terms of their agroecological attributes, the more likely it is that research done in one country will be applicable, with comparatively little adaptation, in the other country" (Pardey and Beintema 2001). The coverage of foreign R&D is based on the Pilot Analysis of Global Ecosystems study conducted by Wood, Sebastian, and Scherr (2001).

Total factor productivity (TFP_t) is a multifactor productivity index of the ratio of aggregate crop and livestock production to aggregate production inputs from U.S. Department of Agriculture estimates. The agricultural patents (P_t) variable denotes the total number of agricultural sector patents granted in the United States and is from a study by Johnson (1999). Price received ($P_{AGR,t}$) is an index of prices received for all farm products deflated by the GDP (gross domestic product) deflator. Real interest rate (r_t) is the annual interest rate on one-year Treasury bills minus the *ex post* inflation rate from the Consumer Price Index.

Empirical Specification

The empirical specification in this part of the study is loosely based on the theoretical model. The conceptual model for the TFP equation is based on equation (2), and it decomposes TFP into different components.

$$TFP_t = f(trend, E_{t-i}, P_{t-i}, R_{t-i}) \tag{8}$$

(?) (+) (+) (+)

The extension stock variable is included as a proxy for the variable A, the level of TFP not accounted for by the quality index. It captures the effect of adoption and the spread of new technology, as extension activities in the United States are focused on connecting farmers with new technology and training them to use it.[14] The second variable is agricultural patents used as a proxy for the inventions in the United States that will benefit the agricultural sector. This variable is added to capture the link between new technology and productivity, that is, the aggregate quality index, Q. The third variable is Public R&D stock, which is included to analyze the direct effects of public R&D activities that are not reflected in the patents variable. The reason for this specification is the fact that only a small percentage of public R&D results are patented, given the public service nature of these agencies. The omission of such a variable may cause omitted variable bias.

The second equation uses patents as a proxy for innovations and attempts to understand the dynamics of technological progress, that is, the forces governing the behavior of aggregate quality index, Q, in the model.

$$P_t = g(trend, R_{t-i}, S_{t-i}, F_{t-i}, TFP_t)\,. \tag{9}$$

(?) (+) (+) (?) (?)

In the model, technological progress is described as quality upgrades of intermediate goods. As a proxy for innovations in the agricultural sector, patents granted in the United

States pertaining to the agricultural sector are used. Public, private, and foreign R&D stocks are included as explanatory variables but with lags, because R&D activities can have an effect on the number of patents with at least a one-period lag. This equation will show the combined effect of domestic and foreign R&D on the ability of researchers in the United States to invent. TFP is included as a proxy for the level of available technology in the sector (or stock of past technological achievements). This variable will show how technological know-how affects creation of new technology. In other words, does past success help present success or does each invention reduce the size of the pool of possible inventions?

$$Z_t = h(trend, \underset{(?)}{R_{t-i}}, \underset{(?)}{F_{t-i}}, \underset{(?)}{P_{AGRt}}, \underset{(+)}{r_t}) \, . \quad (-) \tag{10}$$

In the last equation, the dependent variable is private agricultural R&D spending.[15] One of the main propositions of the model was the endogeneity of technological progress and the R&D effort of the private agents in the economy. This equation, as well as the patent equation, is directly modeled in the spirit of this proposition. Domestic public R&D stock is included to capture the combined effect of subsidy (s) and the probability of innovation by the public R&D sector (p^p). The effect of R&D spillovers (s^{TRADE}) is included with the foreign R&D stock variable. An index of prices received by farmers is included as a proxy for the demand conditions for the research firms' products, as their market consists of farmers. The interest rate is the opportunity cost of these firms that have the option of investing their funds elsewhere instead of engaging in agricultural R&D.

All three equations include a trend variable; Dickey-Fuller tests revealed that the variables are non-stationary, so a trend variable is added to de-trend the data.[16] Creation and adoption of new technology takes time. To incorporate this fact into the empirical analysis, extension stock, patents, public R&D stock, private R&D stock, and foreign R&D stock variables are incorporated into the equations with lags. The choice of these lags for each variable in each equation is based on the AIC and SBC tests from the ordinary least squares estimation results. The previous three equations are estimated as a system of equations using the seemingly unrelated regression technique.

Empirical Analysis Results

In Table 2, the first set of results is presented for the system of equations in which import shares are used as weights while constructing the foreign R&D variable. The theoretical model utilizes trade as the mechanism through which R&D spillovers are realized between countries; thus, it is plausible to say that the more trade relations the

TABLE 2. Regression results

	Dependent Variable		
Variable	**TFP**	**Patents**	**Private R&D Spending**
Intercept	-2.135 (1.675)	-197.240** (43.127)	-84.082** (31.614)
Trend	-0.006** (0.002)	-0.466** (0.112)	-0.218** (0.087)
E_{t-3}	1.062* (0.565)		
P_{t-1}	0.037** (0.004)		
R_{t-1}	0.186* (0.101)		8.348** (2.950)
R_{t-2}		0.764 (2.848)	
Z_{t-1}		6.916** (1.628)	
F_{t-2}		4.777** (1.156)	1.917** (0.804)
TFP_t		44.274** (5.328)	
r_t			-0.856** (0.381)
P_{Yt}			-0.324 (0.186)
N	21	21	21

Note: These are seemingly unrelated regression estimates. Standard errors are in parentheses. ** denotes significance at the 0.05 level. * denotes significance at the 0.10 level. System weighted $R^2 = 0.9673$. The depreciation rate for stock variables is 12 percent. Import shares are used as weights in the calculation of foreign R&D stock.

countries have with each other, the greater are the possibilities of technology transfer among them (Coe and Helpman 1995). The depreciation rate used to construct stock variable is 12 percent.

In the TFP equation, the trend variable has a negative coefficient estimate, which is significant at the 0.05 level. The extension stock variable has a positive and significant effect on TFP, which is in line with prior expectations and studies, showing that dissemination and adoption of new technology is a critical factor in increasing TFP in the agricultural sector. The next variable, agricultural patents lagged one period, has a coefficient estimate that is positive and significant, showing the impact of new technology measured by patents on the TFP. This is in accordance with the model's predictions. The last variable, public R&D stock, has a positive and significant effect on TFP, showing that public R&D activities have a significant effect on TFP separate from technological progress measured by agricultural patents. This may be because of the large scope and diversity of public R&D activities.

The next equation examines the forces determining the creation of new technology, that is, inventions as measured by patents. The trend variable is negative and significant. The coefficient of public R&D stock variable is positive but insignificant. The reason for this finding may be the fact that most public R&D results are not patented but are kept in the public domain.[17] This also shows the necessity of estimating the direct effect of public R&D on the TFP in the previous equation. The next variable, private R&D stock, has a positive and significant coefficient estimate, which is in line with the main implication of the model, namely, that R&D activities drive technological progress. R&D spillovers measured by the foreign R&D stock variable have a positive and significant coefficient estimate. This result shows that the U.S. agricultural sector benefits from knowledge created by the R&D activities in other countries through more inventions. It should be noted again that foreign R&D stock is calculated from foreign public R&D spending, that is, foreign government and higher education spending, which has more accessible results compared to the private R&D sector.[18] The last variable, TFP, has a positive and significant effect on agricultural patents. This result can be interpreted as evidence that currently available technology in an economy helps researchers create new technology.

The final equation analyzes the determinants of private agricultural R&D spending in the United States. The model was ambiguous in terms of the net effects of the public R&D sector on the private R&D sector. The empirical analysis shows that the complementary effect of the public R&D sector outweighs the substitutability effect on private R&D spending, as the public R&D stock variable has a positive and significant coefficient estimate. This finding combined with the public R&D stock's significant positive effect on TFP provides evidence that public R&D sector activities are not only helping increase TFP in the agricultural sector directly but also are indirectly benefiting the agricultural sector by increasing the knowledge stock that the private R&D sector benefits from. This result provides some context for discussions of the optimal role of the U.S. public R&D sector. The next variable, foreign R&D stock, is included to better understand the effects of R&D spillovers on private R&D firms in the United States. The positive and significant coefficient estimate shows that the benefits of R&D spillovers on the private agricultural R&D sector outweigh the negative effect of foreign R&D as a competing force. The coefficient of the interest rate is negative and significant as predicted in the model, showing that the higher the opportunity cost, the lower the private R&D spending. The index of prices received by farmers is insignificant, which shows that a better proxy for demand conditions may need to be included in this specification.

There are two points that need to be addressed when interpreting the study's empirical results. The first is that the presented results used a depreciation rate of 12 percent to generate stock variables. Another depreciation rate of 5 percent was used to generate stock variables as well; the empirical results are presented in Appendix Table A.1. The results are robust to using a different depreciation rate, except for the private R&D spending equation in which the coefficients of public R&D stock, foreign R&D stock, and interest rate are insignificant.

The other issue is about the calculation of the foreign R&D stock variable. Table A.2 in the Appendix presents the results of the empirical analysis in which a depreciation rate of 12 percent and a simple sum of foreign R&D stock are used for illustrative purposes. Using a simple sum while constructing foreign R&D stock does not make a difference in the empirical analysis, except for the magnitude of the coefficient estimates. The conclusions drawn from the empirical analysis are essentially the same.

Concluding Remarks

This study utilizes a quality innovation model, in which technological progress is the result of commercially motivated efforts of researchers responding to economic incentives and a public R&D sector. First, a closed economy model is presented to show the mechanism of how the domestic R&D sector operates. In the model, both public and private R&D sectors directly affect the creation of new technology, which in turn leads to more output and higher productivity growth. The public sector directly affects the private R&D sector and contributes indirectly to inventions and productivity as well. The inclusion of both public and private R&D sectors and the examination of the liaison between these two sectors in a quality innovation model is a departure from the previous research.

The model developed here makes a contribution to the literature on endogenous growth theory by incorporating a role for a public R&D sector. Public R&D's complementary role to the private R&D sector is included through a subsidy that decreases the cost of private R&D firms. The public R&D sector is modeled also as a substitute for the private R&D sector, as it engages in activities that attempt to create higher-quality intermediate goods and thereby potentially can "crowd out" private R&D spending. Overall, the net effect of public R&D spending on private R&D spending is ambiguous in the theoretical model.

In the next step, the economy is opened up to free trade in two different scenarios. In the first scenario, trade is between two developed, innovative countries. This scenario analyzes the scale effects from economic integration on the domestic R&D sector and innovation of a developed country. In the second scenario, trade is between a developed, innovative country and a less-developed, imitative country. This scenario analyzes the impacts of imitative R&D activity in a less-developed country on the R&D sector and on innovation in the developed country. In both of these scenarios, trade affects the R&D sector of a developed country through three channels. First, R&D firms realize increased market size for their products. Second, R&D firms face increased competition from foreign R&D firms that can capture their market. Finally, with the opening up of an economy, domestic R&D firms can benefit from the R&D activities conducted in foreign countries, and this may decrease their cost of research.

In the empirical analysis, the implications of the model are tested for the U.S. agricultural sector using 1971-1994 data. The analysis finds that agricultural patents have a significant and positive impact on TFP, which is consistent with the model. The results point to a positive and significant relationship between extension stock and TFP, which is in line with prior expectations and previous empirical studies.

Then, the dynamics of technological progress is analyzed. The analysis finds that domestic private R&D stock affects agricultural patents significantly and positively as previously expected. Also, foreign R&D stock is found to be as critical as domestic private R&D stock to the creation of new technology, as it has a positive and significant parameter estimate as well. Surprisingly, public R&D stock does not have a significant impact on agricultural patents. This may be because of low patenting of public R&D research results, as the results are mostly in the public domain.

Evidence was found of a significant positive relationship between private R&D spending and public R&D stock. This result answers a question in the model, as the net effect of the public R&D sector on private R&D spending was ambiguous. This finding, combined with the previously noted result that public R&D stock affects TFP positively and significantly, shows that continuation of public R&D activities is crucial, as it affects TFP both directly and indirectly through private R&D spending. Evidence was found of a significant, positive relationship between private R&D spending and foreign R&D stock. This finding shows that R&D spillovers aid the private R&D sector in the United States.

This study shows that there may be considerable gains from R&D spillovers for the rate of innovation and private R&D spending in an economy, which in turn results in higher output levels and TFP growth. This demonstrates the possible gains from coordination and cooperation of countries when they are designing national and international agricultural research and development policies. The second conclusion from this study is the importance of a public R&D sector in terms of realizing TFP gains directly and indirectly. The beneficial effect of the public R&D sector on the private R&D sector is also a significant outcome of this study and may prove helpful to policymakers in designing an optimal role for the public R&D sector in the next decades.

Appendix

Alternative Specifications

Table A.1. Regression results with a depreciation rate of 5 percent for stock variables

	Dependent Variable		
Variable	**TFP**	**Patents**	**Private R&D Spending**
Intercept	-4.470** (2.093)	-194.517** (76.653)	-49.533 (83.119)
Trend	-0.013** (0.004)	-0.564** (0.201)	-0.102 (0.202)
E_{t-3}	0.154** (0.053)		
P_{t-1}	0.027** (0.004)		
R_{t-1}	0.498** (0.190)		4.939 (7.236)
R_{t-2}		-2.695 (5.728)	
Z_{t-1}		11.407** (3.367)	
F_{t-2}		5.169** (1.925)	0.919 (1.713)
TFP_t		34.296** (5.187)	
r_t			-0.324 (0.422)
P_{Yt}			-0.118 (0.220)
N	21	21	21

Note: These are seemingly unrelated regression estimates. Standard errors are in parentheses. ** denotes significance at the 0.05 level. * denotes significance at the 0.10 level. System weighted R^2 = 0.9644. Import shares are used as weights in calculation of foreign R&D stock.

TABLE A.2. Regression results with a simple sum of foreign R&D stock

	Dependent Variable		
Variable	**TFP**	**Patents**	**Private R&D Spending**
Intercept	-2.452 (1.691)	-261.151** (73.810)	-99.546** (29.187)
Trend	-0.006** (0.002)	-0.585** (0.172)	-0.243** (0.077)
Extension Stock $_{t-3}$	1.032** (0.585)		
Patents$_{t-1}$	0.032** (0.005)		
Public R&D Stock$_{t-1}$	0.225** (0.098)		6.708** (2.318)
Public R&D Stock$_{t-3}$		1.616 (3.505)	
Private R&D Stock$_{t-1}$		5.183** (2.083)	
Foreign R&D Stock$_{t-2}$			4.263** (1.168)
Foreign R&D Stock$_{t-3}$		10.404** (3.182)	
TFP$_t$		44.386** (7.796)	
Interest Rate$_t$			-1.028** (0.415)
Price$_t$			-0.096 (0.185)
N	21	21	21

Note: These are seemingly unrelated regression estimates. Standard errors are in parentheses. ** denotes significance at the 0.05 level. * denotes significance at the 0.10 level. System weighted R^2 = 0.960. The depreciation rate for stock variables is 12 percent. A simple sum of R&D stock is used to calculate foreign R&D stock.

Endnotes

1. In the United States, public R&D spending made up 54.4 percent of total agricultural R&D spending in 1971, although this ratio dropped to 46.7 percent in 1994 as public R&D investments stagnated after the 1980s. Between 1971 and 1994, public R&D spending increased 73 percent in 1993 international dollars, whereas private R&D spending increased 176 percent.

2. Khanna, Huffman, and Sandler (1994) set up a model where agricultural R&D is a public good and derived the demand for it.

3. In other words, instantaneous adoption of new technology is assumed.

4. Grossman and Helpman (1991, Chap. 12) also analyzed the impacts of imitation in a quality innovation model.

5. The additively separable form for $(\tilde{X}_{1j})^{\alpha}$ implies that the marginal product of intermediate good $X_{1j\kappa_j}$ is independent of the quantity employed of intermediate good $X_{1l\kappa_l}$ where $j \neq l$.

6. Otherwise, there is no closed-form solution for X (intermediate goods) and Y (output).

7. This strategy holds in the case of $q \cdot \alpha > MC_1$. If $q \cdot \alpha < MC_1$, then the leader can drive the producers of the lower-quality intermediate good out of the market by monopoly pricing. See Barro and Sala-I-Martin (1995) for a discussion of these two strategies.

8. In equation (3), only the current level of private R&D spending is included through $Z_{1j\kappa_j}$ and past R&D investments enter indirectly through κ_{1j}. As κ_{1j} is the total number of innovations in intermediate good sector j, it is directly related to all past research successes.

9. In equation (4), the probability of innovation increases as κ_{1j} and $q^{(\kappa_{1j}+1)\cdot\alpha/(1-\alpha)}$ increase. The probability of innovation decreases as κ_{1j} increases and $\phi(\kappa_{1j})$ decreases. If the first effect dominates, the more advanced sectors will grow faster. If the second effect dominates, the more advanced sectors will grow slower. If the two forces offset each other, then all intermediate good sectors will grow at the same rate and the growth rate of the agricultural sector will be constant over time and across

intermediate-good sectors. In the rest of the solution, it will be assumed that these two forces offset each other.

10. See Rivera-Batiz and Romer 1994 for a discussion of economic integration in an endogenous growth model.

11. In this equation, the probability of losing the market is ($p_1 + p_1$), as the leader loses its market to the next innovation either in its country or in the foreign country.

12. In this equation, the probability of losing the market is ($p_1 + p_2 - p_1 \cdot p_2$), as now imitation and innovation are two independent events and the leader either loses the market to a new invention or to an imitation.

13. Countries included are Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, United Kingdom, Australia, Japan, New Zealand, China, Canada, and South Korea.

14. This is also in line with previous empirical work that found the positive impact of extension funds (Huffman and Evenson 1993).

15. Equations (6) and (7) are the basis for this empirical specification.

16. Another method for dealing with non-stationarity is first differencing the data, which was implemented in Makki, Thraen, and Tweeten 1999. However, the stock variables used in this study are not stationary even when first differenced. One solution would have been to use levels of R&D spending that would require lags to account for the time necessary to create new technology and for it to have an effect on TFP. This approach was not adopted here because of the short time span of the available foreign R&D spending data.

17. The State Agricultural Experiment Systems-U.S. Department of Agriculture (SAES-USDA) system has generated far fewer intellectual property rights protected inventions per dollar expended on research than the private sector has. In the post-harvest technology field of international patent classification, the ratio of patents granted to public institutions was 2.5 percent for the 1971-80 period. For six production technology fields, one modern biotechnology field, and an aggregate post-harvest technology field, the ratio of patents granted to public institutions was 10 percent for 1975-80 period and 10 percent for 1980-84 period. For the period of 1971-1990, USDA-SAES obtained only 11 percent of plant variety protection certificates (Huffman and Evenson 1993).

18. Schimmelpfennig and Thirtle (1999) have used international patent data to capture the effect of international spillovers of private foreign R&D. However, adding such a variable creates issues of accessibility of research results of foreign R&D firms and how much of these research activities are transformed into patents in the country of origin. The specification used in this study is more in line with the accessibility issue for the domestic country firms.

References

Alston, J. 2002. "Spillovers." *The Australian Journal of Agricultural and Resource Economics* 46: 315-46.

Alston, J., and P.G. Pardey. 1996. *Making Science Pay: The Economics of Agricultural R&D Policy*. Washington, D.C.: The AEI Press.

Barro, R.J., and X. Sala-I-Martin. 1995. *Economic Growth*. New York: McGraw-Hill.

Coe, D.T., and E. Helpman. 1995. "International R&D Spillovers." *European Economic Review* 39: 859-87.

Connolly, M.P. 1999. "North-South Technological Diffusion: A New Case for Dynamic Gains from Trade." Working paper. Department of Economics, Duke University.

Grossman, G.M., and E. Helpman. 1991. *Innovation and Growth in the Global Economy*. Cambridge, MA: The MIT Press.

Johnson, D. 1999. "150 Years of American Invention: Methodology and a First Geographical Application." Working Paper. Department of Economics, Wellesley College.

Huffman, W.E., and R.E. Evenson. 1993. *Science for Agriculture: A Long Term Perspective*, Ames, IA: Iowa State University Press.

Khanna, J., W.E. Huffman, and T. Sandler. 1994. "Agricultural Research Expenditures in the U.S.: A Public Goods Perspective." *Review of Economics and Statistics* 76: 267-77.

Klotz, C.A., K.O. Fuglie, and C.E. Pray. 1995. *Private Sector Agricultural Research Expenditures in the U.S. 1960-1992*. ERS AGES-9525. Economic Research Service, U.S. Department of Agriculture, Washington, D.C.

Makki, S.S., C.S. Thraen, and L.G. Tweeten. 1999. "Returns to American Agricultural Research: Results from a Cointegration Model." *Journal of Policy Modeling* 21: 185-211.

Pardey, P.G., and N. Beintema. 2001. "Slow Magic: Agricultural R&D a Century after Mendel." IFPRI Food Policy Report. International Food Policy Research Institute, Washington, D.C.

Rivera-Batiz, L.A., and P.M. Romer. 1994. "Economic Integration and Endogenous Growth." *Quarterly Journal of Economics* 106: 531-55.

Schimmelpfennig, D., and C. Thirtle. 1999. "The Internationalization of Agricultural Technology: Patents, R&D Spillovers, and Their Effect on Productivity in the European Union and United States." *Contemporary Economic Policy* 17: 457-68.

Wood, S., K. Sebastian, and S.J. Scherr. 2001. *Pilot Analysis of Global Ecosystems*. International Food Policy Research Institute and World Resources Institute, Washington, D.C.