

R&D Spillovers in Agriculture:

Results from a North-South Trade Model

Simla Tokgoz

Center for Agricultural and Rural Development

Iowa State University

Ames, IA 50011

stokgoz@card.iastate.edu

*Paper prepared for presentation at the American Agricultural Economics Association Annual Meeting,
Montreal, Canada, July 27-30, 2003*

Abstract: This study attempts to analyze technical change and the role of R&D spillovers in this process using a quality innovation model. Domestic R&D sector consists of a public and a private R&D sector. Trade is the mechanism through which R&D spillovers are realized, along with increased market size and increased competition. Propositions of the model are tested for the U.S. agricultural sector data. It is found that R&D spillovers affect technological change as well as private R&D spending significantly and positively.

Keywords: R&D spillovers, Technical change, Trade, Productivity

Copyright 2003 by Simla Tokgoz. All rights reserved. Readers may make verbatim copies of this document for non-commercial purposes by any means, provided that this copyright notice appears on all such copies.

1. Introduction

There has been an extensive literature focusing on the determinants of productivity growth in agriculture with special interest on the roles of public and private research and development (R&D), human capital and extension activities. There has been ample empirical evidence that shows the important role these activities play in realizing gains in productivity. 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 U.S 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 the previous rates of return estimates.

The aim of this paper is to analyze the impact of R&D spillovers from other countries on the U.S. agricultural R&D sector. First, R&D sector and innovation in the U.S. agricultural sector is modeled with a focus on the mechanism of how domestic R&D sector operates. Secondly, the model incorporates the impact of trade on the domestic R&D sector and innovation, with an emphasis on the dual effect of trade through increased competition from foreign firms and through R&D spillovers from foreign countries.

To this end, a quality innovation model is used in which R&D activities increase the quality of intermediate goods and thereby lead to technological progress. To better reflect the characteristics of the U.S. agricultural sector, R&D sector is divided into two components: a public and a private sector. Public R&D sector also conducts research and patents its research results, thus decreasing the probability that it will be a private sector R&D firm that comes up with the next innovation. 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. 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. Through this channel, public R&D sector is a complement to private R&D sector.

Including a public R&D sector is particularly important, as in the U.S. public R&D activities have been a major portion of the total agricultural R&D activities. In the U.S., public R&D spending made up 54.4% of total agricultural R&D spending in 1971 although this ratio dropped to 46.7% in 1994 as public R&D investments stagnated after 1980s. Between 1971 and 1994, public R&D spending increased 73% in 1993 international dollars, whereas private R&D spending increased 176%. Although, the role of private R&D spending has increased considerably in the last two decades due to changes in the property rights structure and advances in biotechnology, 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 public R&D sector. This model analyzes the dual effect of public R&D sector on private R&D sector, thus providing some theoretical framework to the latest discussions.

In the next step of the analysis, free trade in final and intermediate goods is introduced into the model with two cases. The first case is a North-North trade model in which trade is between two developed and innovating countries. The second case is a North-South trade model in which trade is between a developed innovative country and a less developed imitative country. Both of these cases illustrate the effect of trade and through it the effects of R&D spillovers on a developed economy's agricultural R&D sector. The North-North trade model shows the possible benefits from economic integration as the two countries have similar factor endowments and production costs. The North-South trade model is based on Connolly (1996) and shows the impact of trade between an innovative country and an imitative country with lower production costs. In both of these models, opening up the economy to free trade affects the R&D sector through increased market size, increased competition and R&D spillovers.

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 how flow of knowledge and flow of goods between countries affect the R&D sector in an economy, and whether the domestic R&D sector benefits from R&D spillovers or whether it is worse due to increased competition from foreign R&D firms. If domestic R&D firms have access to research results in foreign countries, then R&D spillovers will be realized, and trade will be beneficial for domestic R&D firms. However, with free trade, domestic R&D firms will face competition from R&D firms in other countries. So, there is a negative impact of trade on domestic R&D firms as they now can lose their markets to foreign R&D firms.

The reason for presenting two trade models is that although developed countries have been major spenders on public agricultural research, in the 1990s developing countries have spent more on public agricultural research.¹ These developments will affect the U.S. agricultural sector and private R&D firms considerably. U.S. agricultural sector will be affected not only by R&D investments in developed countries, but also R&D investments in developing countries.

In the next part of the analysis, the implications of the model are tested using data for the U.S. agricultural sector for 1971-1994. A system of equations with three dependent variables is set up and

¹ Pardey and Beintema (2001)

estimated using seemingly unrelated regressions technique. The empirical analysis tests the main propositions of the model. First, it looks at the link between TFP in the U.S. agricultural sector and agricultural patents. Here, agricultural patents are used as a proxy for technological progress that benefits the agricultural sector. Secondly, it examines the determinants of technological progress, again measured by agricultural patents. Domestic public and private R&D stocks, and foreign R&D stock are included as possible determinants, along with a measure of available technology. Finally, the factors that affect private agricultural R&D spending are analyzed including domestic public R&D stock and foreign R&D stock. The country coverage in the foreign R&D stock calculation is based on PAGE Characterization of Global Agro ecosystems. The reason is that successful transfer of agricultural technologies depends on similar environmental factors, so only countries that have the same agroecological conditions as in the U.S. are included.

This study proceeds as follows. Section 2 presents a quality innovation model, first autarky in the North, then a North-North trade model, and finally a North-South trade model. Section 3 describes data source and variables. Section 4 describes empirical specification, and section 5 discusses results of empirical analysis. Section 6 concludes.

2. 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 R&D sector is divided into two components, a private R&D sector and a public R&D sector. Both of these sectors engage in research activities that lead to improvements in the quality of intermediate goods used in the production of final good. The model is closely related to Barro and Sala-I-Martin (1995, Chapter 7) and Grossman and Helpman (1991, Chapter 4).

First, a closed economy model is presented where there is no trade and only intermediate goods designed by the domestic R&D sector are used. In the second part, 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. This part of the analysis is based on Connolly (1996) that set up a North-South trade model in a quality innovation model.²

² Grossman and Helpman (1991, Chapter 12) is the first that analyzed impacts of imitation in a quality innovation model.

Case 2.1. Autarky in the North

First the case of complete isolation is presented for a Northern country indexed by 1. The production function for the final good is specified as

$$Y_1 = A_1 \cdot L_1^{1-\alpha-\beta} \cdot H_1^\beta \cdot \sum_{j=1}^N (\tilde{X}_{1j})^\alpha \quad (2.1)$$

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.

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 . If the total number of improvements in the quality are κ_{1j} , then the available quality grades of an intermediate good are $1, q, q^2, q^3, \dots, q^{\kappa_{1j}}$. In this case, the quality-adjusted input from sector j can be written as $\tilde{X}_{1j} = \sum_{k=0}^{\kappa_j} q^k \cdot X_{1jk}$.

In equilibrium it will be assumed that only the highest quality goods are produced and used for tractability purposes. Then the production function can be written as

$$Y_1 = A_1 \cdot L_1^{1-\alpha-\beta} \cdot H_1^\beta \cdot \sum_{j=1}^N (q^{\kappa_{1j}} \cdot X_{1j\kappa_j})^\alpha \quad (2.2)$$

Final good industry is perfectly competitive and the price of final good (P_{1Y}) is set as the numéraire ($P_{1Y} = 1$). So the final good sector's profit maximization problem is

$$\max_{L, H, X_{j\kappa_j}} \pi^{FG} = P_{1Y} \cdot Y_1 - i \cdot L_1 - w \cdot H_1 - \sum_{j=1}^N P_{1j\kappa_j} \cdot X_{1j\kappa_j} \quad (2.3)$$

where i is the rental rate of land, and w is the wage rate of labor.

The marginal cost of production of the intermediate good is specified as equal to the price of final good. ($MC_1 = P_{1Y} = 1$). To derive the demand for the intermediate good, we need to look at the pricing strategy by the industry leader. The industry leader can use limit pricing strategy only in the case of $q \cdot \alpha > MC_1$. If the industry leader charges a price that is ε below ($q \cdot MC_1$), then it can drive the follower

out of the market. So the equilibrium price is $P_1 = q \cdot MC_1$ and only the leading edge quality intermediate goods will be produced and sold.³

If a quality index $Q_1 = \sum_{j=1}^N (q^{\kappa_{1j}})^{\alpha/(1-\alpha)}$ is defined, then aggregating over all intermediate good sectors will give us the equilibrium demand for intermediate goods in the North under autarky as

$$X_1 = \left(\frac{\alpha}{q} \right)^{1/(1-\alpha)} \cdot A_1^{1/(1-\alpha)} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot Q_1 \quad (2.4)$$

The equilibrium aggregate output in the North under autarky is derived as

$$Y_1 = \left(\frac{\alpha}{q} \right)^{\alpha/(1-\alpha)} \cdot A_1^{1/(1-\alpha)} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot Q_1 \quad (2.5)$$

Private Sector Resources devoted to Research in the North under Autarky

The behavior of the R&D sector is critical in this model, as it is the main force behind technological progress. The private and the public R&D sector are set up differently as the motivations behind their activities are quite different. The private sector is monopolistically competitive and its motivation behind innovation is profits. The profit for the successful private sector R&D firm that comes up with the κ_{1j} 'th innovation is

$$\pi_1^{RD} = (P_1 - MC_1) \cdot X_{1j\kappa_j} = (q \cdot MC_1 - MC_1) \cdot X_{1j\kappa_j} \quad (2.6)$$

The private sector researcher who innovates the κ_{1j} th quality of intermediate good j will accrue his profits until a new researcher comes up with the $(\kappa_{1j} + 1)$ th quality intermediate good j. The profit earned by the researcher from the latest innovation will be only through an interval of $T_{1j\kappa_j} = t_{1,\kappa_j+1} - t_{1\kappa_j}$. This random duration of this profit depends not only on the efforts of private R&D firms but also the efforts of public R&D sector.

To illustrate this relationship, let p_1^* be the probability per unit of time of an increase from κ_{1j} to $(\kappa_{1j} + 1)$. This is the society's total probability of innovation in the North. This value equals 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 private R&D firm is determined by p_1^* , not $p_{1j\kappa_j}^Z$. As

³ If $q \cdot \alpha < MC_1$, then monopoly pricing will prevail and the leader can again drive the producers of the lower quality intermediate good out of the market.

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 monopoly profits.

This is more clear 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 next innovation is lower with a public R&D sector as the duration of monopoly profit is determined by the society's probability of innovation, which is higher than private sector's probability of innovation. This occurs because as more researchers try to come up with the next innovation, it is a higher probability that next intermediate good will be innovated and the incumbent will be driven out of business.

Private R&D Spending

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

$p_{1j\kappa_j}^Z$ and $Z_{1j\kappa_j}$ is defined in a linear relationship as

$$p_{1j\kappa_j}^Z = Z_{1j\kappa_j} \cdot \phi(\kappa_{1j}) \quad (2.7)$$

As $Z_{1j\kappa_j}$ increases, the probability of successful innovation per unit 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. κ_{1j} is the total number of innovations in sector j and it is a proxy for the level of technology in that sector. As κ_{1j} increases, it will be harder for R&D firms to come up with a new idea. So,

$\partial\phi(\kappa_{1j})/\partial\kappa_{1j} < 0$ and $p_{1j\kappa_j}^Z$ decreases as κ_{1j} increases. In this model, it is assumed that p_1^* and $p_{1j\kappa_j}^Z$ follow a Poisson process. The public R&D sector is taken as exogenous to the model, and the public sector's probability of innovation, p^P , is taken as constant.

Assuming free entry into the research business, the society's probability of innovation is derived as

$$p_1^* = \phi(\kappa_{1j}) \cdot q^{(\kappa_{1j}+1)\alpha/(1-\alpha)} \cdot (q-1) \cdot MC_1 \cdot A_1^{1/(1-\alpha)} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot \left(\frac{\alpha}{q}\right)^{1/(1-\alpha)} - r_1 \quad (2.8)$$

κ_{1j} enters into the above equation in two ways. The probability of innovation increases as κ_{1j} and $q^{(\kappa_{1j}+1)\alpha/(1-\alpha)}$ increases. 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 this way, R&D exhibit constant returns. In the rest of the solution, it will be assumed that these two forces offset each other.

To this end, the functional form for $\phi(\kappa_{1j})$ is set as $(1/s \cdot \zeta_1) \cdot q^{-(\kappa_{1j}+1)\alpha/(1-\alpha)}$. 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 another channel through which public sector activities affect private R&D sector of the model. 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. This way, public R&D sector is a complement to private R&D sector.

The probability of an innovation per unit of time by private R&D sector (p_1^Z) is:

$$p_1^Z = \left\{ \left(\frac{1}{s \cdot \zeta_1} \right) \cdot (q-1) \cdot MC_1 \cdot A_1^{1/(1-\alpha)} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot \left(\frac{\alpha}{q} \right)^{1/(1-\alpha)} - p_1^P - r_1 \right\} \quad (2.9)$$

The public sector affects the private sector's probability of innovation in two opposite directions. Through subsidy (s), public sector increases private sector's probability of innovation. However, through conducting R&D (p_1^P), public sector decreases private sector's probability of innovation.

The aggregate private sector R&D spending in the North under autarky is derived as

$$Z_1 = Q_1 \cdot q^{\alpha/(1-\alpha)} \cdot \left[\left(\frac{\alpha}{q} \right)^{1/(1-\alpha)} \cdot (q-1) \cdot MC_1 \cdot A_1^{1/(1-\alpha)} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} - (r_1 + p_1^P) \cdot (s \cdot \zeta_1) \right] \quad (2.10)$$

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 in terms of 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 increase the R&D effort by the private firms. Secondly, both the quality index (Q) and the productivity parameter (A) have a positive impact on private R&D spending. Public R&D sector activities enter through two channels. The subsidy s takes a value between 0 and 1, and including it increases private R&D spending. Probability of innovation by public sector (p_1^P) decreases private R&D spending, as it increases the probability of being driven out of business. The theory does not tell which

effect dominates, so only empirical analysis can provide an answer to whether public R&D sector helps or “crowds out” private R&D investment.

Case 2.2. 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 where trade in final and intermediate goods allow firms to benefit from larger markets and increased competition in the R&D sector increases the probability of innovation.

To make the solution tractable, it will be assumed that each country is the leader in half of the intermediate goods sectors and one quality below in the other half of 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 how domestic R&D sector and innovation are affected by free trade with another developed country and the resulting R&D spillovers.

First, let's present the scale effect of trade through increased market size. The industry leaders that do not lose their markets will enjoy higher demand for their intermediate goods after trade; both domestic and foreign demand. The domestic demand for intermediate good j is

$$X_{1j\kappa_j} = \left(\frac{P_{Y1}}{P_{1j\kappa_j}} \right)^{1/(1-\alpha)} \cdot A_1^{1/(1-\alpha)} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot \alpha^{1/(1-\alpha)} \cdot (q^{\kappa_j})^{\alpha/(1-\alpha)} \quad (2.11)$$

The import demand from the foreign country for intermediate good j is⁴

$$X_{1j\kappa_j}^* = \left(\frac{P_{Y1}^*}{P_{1j\kappa_j}^*} \right)^{1/(1-\alpha)} \cdot A_1^{*1/(1-\alpha)} \cdot L_1^{*(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{*\beta/(1-\alpha)} \cdot \alpha^{1/(1-\alpha)} \cdot (q^{\kappa_j})^{\alpha/(1-\alpha)} \quad (2.12)$$

Again price of the final good is equal to the MC of production of the intermediate good. As the countries have the same production costs and the same price of 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. Thus the domestic demand and the import demand from foreign country will be respectively

⁴ * is used to denote foreign country.

$$X_{1j\kappa_j} = X_{1j\kappa_j}^* = \left(\frac{1}{q}\right)^{1/(1-\alpha)} \cdot A_1^{1/(1-\alpha)} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot \alpha^{1/(1-\alpha)} \cdot (q^{\kappa_j})^{\alpha/(1-\alpha)} \quad (2.13)$$

This makes profits of the industry leader under free trade 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.

$$\text{The expected present value of profits under free trade is } E(V_{1j\kappa_j}^{TRADE}) = \frac{\pi_{1j\kappa_j}^{TRADE}}{r_1 + p_I + p_I^*} = \frac{2 \cdot \pi_{1j\kappa_j}^{AUTARKY}}{r_1 + p_I + p_I^*},$$

which exceeds the expected present value of profits under autarky $E(V_{1j\kappa_j}^{AUTARKY}) = \frac{\pi_{1j\kappa_j}^{AUTARKY}}{r_1 + p_I^*}$. There are two

different impacts of trade on the expected present value of profits for an R&D firm. One of them is positive through the increase in demand for intermediate goods. The other one is negative through the lower duration of these profits after trade. The reason is that, after trade there is twice the number of R&D firms trying to come up with the next innovation. As the R&D efforts have doubled as firms in both countries try to come up with the next innovation, it is now twice the probability that the incumbent will be driven out of business. The demand increase effect outweighs the lower duration effect from trade, increasing expected present value of profits from new innovations.

The probability of innovation with trade, which is given below, is higher with trade.

$$p_I^{TRADE} = \left\{ \frac{1}{\frac{s}{2} \cdot \zeta_1} \right\} \cdot (q-1) \cdot MC_1 \cdot A_1^{1/(1-\alpha)} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot \left(\frac{\alpha}{q}\right)^{1/(1-\alpha)} - p_I^P - \frac{r_1}{2} \quad (2.14)$$

The above equation also includes the R&D spillover effects from trade. Note that, $\frac{s}{2}\zeta_1$ is used for the scenario with trade compared to $s \cdot \zeta_1$ in the autarky scenario. The subsidy variable, s , now enters the equation divided by two. 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 domestic probability of innovation. If a domestic R&D firm can benefit from R&D activities conducted in other countries, the effect would probably be in the form of decreasing fixed costs of research as now the R&D firm does not need to conduct research on its own, but merely use the available information. This specification assumes that the results of foreign R&D are publicly available to anyone who wants to access it, 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 increase as well with free trade, as now firms have higher expected profits for their research successes and benefit from foreign R&D activities. The equilibrium R&D spending with free trade is derived as

$$Z_1^{TRADE} = Q_1 \cdot q^{\alpha/(1-\alpha)} \cdot \left[\left(\frac{\alpha}{q} \right)^{1/(1-\alpha)} \cdot (q-1) \cdot MC_1 \cdot A_1^{1/(1-\alpha)} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot \alpha^{2/(1-\alpha)} - \left(\frac{r_1}{4} + \frac{p_1^P}{2} \right) \cdot (s \cdot \zeta_1) \right] \quad (2.15)$$

Case 2.3. North-South Trade

In this case, free trade is introduced between two countries where one of them is a developed country that is innovating, and the other one is a less developed country that is imitating. This part of the analysis is based on Connolly (1996), and is included to give a complete picture of the effects of trade on an economy. In this case, North is denoted by 1 and the 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. MC in the North is higher than the MC in the South, as now the South imitates the North and it is cheaper to imitate an intermediate good than innovating it.

With free trade, intermediate goods can be produced domestically or imported. In this case, 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 one is the Northern public R&D 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 South and the North can be so large that, with free trade the South only imports lead Northern goods and does not engage in any imitation as the expected costs outweigh 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 we need to look at 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 $q > \frac{MC_1}{MC_2} > 1$. 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 the limit price, i.e. $P = q \cdot MC_2$. Thus, it 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.

There will be two sources of demand for the Northern intermediate good sector: domestic demand ($X_{1\kappa_j}$) and imports of the South ($X_{1\kappa_j}^*$) given below respectively as

$$X_{1\kappa_j} = \left(\frac{MC_1}{q \cdot MC_2} \right)^{1/(1-\alpha)} \cdot A_1^{1/1-\alpha} \cdot L_1^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_1^{\beta/(1-\alpha)} \cdot \alpha^{1/(1-\alpha)} \cdot (q^{K_{1j}})^{\alpha/(1-\alpha)} \quad (2.16)$$

$$X_{1\kappa_j}^* = \left(\frac{MC_2}{q \cdot MC_2} \right)^{1/(1-\alpha)} \cdot A_2^{1/1-\alpha} \cdot L_2^{(1-\alpha-\beta)/(1-\alpha)} \cdot H_2^{\beta/(1-\alpha)} \cdot \alpha^{1/(1-\alpha)} \cdot (q^{K_{1j}})^{\alpha/(1-\alpha)} \quad (2.17)$$

The profit of the Northern innovator is with trade is

$$\pi_{1\kappa_j}^{TRADE} = (P_{1j} - MC_1) \cdot (X_{1\kappa_j} + X_{1\kappa_j}^*) = (q \cdot MC_2 - MC_1) \cdot \left(\frac{\alpha}{q} \right)^{1/(1-\alpha)} \cdot (q^{K_{1j}})^{\alpha/(1-\alpha)} \cdot \psi \quad (2.18)$$

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

The first impact of trade on the Northern R&D sector is through increased demand as now the lead R&D firm can sell its products in two markets as seen in equation 2.16. The second impact of trade on the Northern firms is through the duration of its profits. The expected present value of profits now depends on the probability of imitation by the South, the probability of innovation by the public R&D sector, and the probability of innovation by the other Northern R&D firms. The expected present value of

profits is derived as $E(V_{1\kappa_j}) = \frac{\pi_{1\kappa_j}^{TRADE}}{r_1 + p_l^* + p_c - p_l^* \cdot p_c}$, where $p_l^* = p_{l,j\kappa_j} + p_l^p$. 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 probability of innovation for the Northern firm under free trade is

$$p_1^{TRADE} = \left\{ \left(\frac{1}{s^{Trade} \cdot \zeta_1} \right) \cdot (q \cdot MC_2 - MC_1) \cdot \psi \cdot \left(\frac{\alpha}{q} \right)^{1/(1-\alpha)} - (r_1 + p^p + p_c - p^p \cdot p_c) \right\} / (1 - p_c) \quad (2.19)$$

We see that the probability of a successful imitation by a Southern R&D firm decreases the probability of innovation by a Northern firm just the same way as a public R&D sector decreases it, i.e.

p_1^{TRADE} and p_c are negatively related. Also, with free trade the Northern R&D firm can benefit from

R&D spillovers from the South. To include this effect, s^{Trade} is used, where $s^{Trade} < s^{Autarky}$. R&D spillovers decrease the fixed cost of research for the Northern R&D firm and increase the probability of innovation. Additionally trade increases p_1^{TRADE} through increased market size as seen in ψ . The net effect of trade on p_1^{TRADE} is ambiguous in the model.

The private sector's R&D spending under free trade is derived as

$$Z_1^{TRADE} = Q_1 \cdot q^{\alpha/(1-\alpha)} \cdot \left[\left(\frac{\alpha}{q} \right)^{1/(1-\alpha)} \cdot (q \cdot MC_2 - MC_1) \cdot \psi - (r_1 + p^p + p_c - p^p \cdot p_c) \cdot (s^{Trade} \cdot \zeta_1) \right] / (1 - p_c) \quad (2.20)$$

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 increase in demand for the intermediate goods it produces, 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, expected present value of profits decreases as now 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_c . The last effect is R&D spillovers included through s^{Trade} . With opening up of economy to trade, the Northern R&D firms may not only benefit from research activities in the North, but also 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.

3. Data Source and Variables

Data used in this study is for the U.S. agricultural sector for the period 1971-1994, and all data are in logs. The summary statistics for the data are given in Table 1.

Public R&D Stock ($R_{t,i}$) is a stock variable calculated from total public agricultural R&D spending in 1993 international dollars using Perpetual Inventory Method (PIM) method with a depreciation rate of 12%. Public R&D spending data were taken from a study by Day and are provided by USDA ERS. Data for federal and state R&D expenditures were derived from USDA Inventory of Current Research.

Private R&D Stock ($S_{t,i}$) is a stock variable calculated from private sector's agricultural R&D spending in 1993 international dollars using PIM method with a depreciation rate of 12% obtained from USDA ERS estimates. Private R&D Spending (Z_t) is Agricultural Research Expenditures by Private Sector (Agricultural Inputs plus Food & Kindred Products R&D) in 1993 international dollars.

Extension Stock (E_{t-i}) is a stock variable created from funds for cooperative extension service in 1993 international dollars using perpetual inventory method (PIM) with a depreciation rate of 12%.

Foreign R&D stock (F_{t-i}) is a stock variable calculated from total foreign public agricultural R&D spending in 1993 international dollars using PIM method with a depreciation rate of 12%, i.e. both government and higher education spending. Countries included are Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, UK, Australia, Japan, New Zealand, China, Canada, and South Korea. The criteria for the choice of countries included in the coverage were availability as well as having the same agroecological zones as the U.S. 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)). That is why, the coverage of foreign R&D is based on PAGE Characterization of Global Agro ecosystems and only countries that have the same agroecological conditions as in the U.S. are included.

Total Factor Productivity (TFP_t) is a multifactor productivity index of the ratio of aggregate crop and livestock production to aggregate production inputs from USDA ERS estimates. Agricultural Patents (P_{t-i}) denote total number of patents granted in the U.S. by sector of use chosen as the agricultural sector. Quality Index (Q_t) is a stock variable calculated from agricultural patents using PIM with a depreciation rate of 12%.

Price received ($P_{AGR,t}$) is an index of prices received for all farm products deflated by the GDP deflator. Real Interest Rate (r_t) is annual interest rate on 1 year Treasury Bills minus ex post inflation rate from Consumer Price Index.

4. Empirical Specification

The empirical specification in this part of the study is based on the theoretical model. The aim in this part is to understand the impacts of domestic R&D and R&D spillovers on the technological progress and TFP in the U.S. agricultural sector.

The first equation decomposes TFP into different components.

$$TFP_t = f(\text{trend}, E_{t-i}, P_{t-i}, R_{t-i}) \quad (4.1)$$

Extension stock variable is included to capture the effect of adoption and spread of new technology, as extension activities in the U.S. are focused on connecting farmers with new technology and training them to use it. The second variable is agricultural patents used as a proxy for the inventions in the U.S. that will benefit agricultural sector. This variable is added to capture the link between new

technology and productivity. 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.

$$P_t = g(\text{trend}, R_{t-i}, S_{t-i}, F_{t-i}, TFP_t) \text{ and } P_t = g(\text{trend}, R_{t-i}, S_{t-i}, F_{t-i}, Q_t) \quad (4.2)$$

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 U.S. pertaining to the agricultural sector are used. Public, private and foreign R&D stocks are included as explanatory variables, but with lags as R&D activities can have an effect on the number of patents with at least one period lag. This equation will show the combined effect of domestic and foreign R&D on the U.S.'s ability to invent. There are two different specifications in which the final explanatory variable is TFP or Quality index. These variables are included as a proxy for the level of available technology in the sector (or stock of past technological achievements). Although in the model constant returns to R&D are assumed to keep the solution tractable, this is a restrictive assumption which needs to be released in the empirical analysis. 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?

$$Z_t = h(\text{trend}, R_{t-i}, F_{t-i}, P_{AGRt}, r_t) \quad (4.3)$$

The last equation has the dependent variable as private agricultural spending directly from the model. 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 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 public R&D sector (p^p). The model showed that public R&D sector helps private R&D sector through subsidy, but at the same time it may “crowd out” part of private R&D spending by decreasing the duration of profits. The effect of R&D spillovers is included with foreign R&D stock variable. This specification will show how R&D activities in other countries affect the private R&D sector in the U.S. An index of prices received by farmers is included as a proxy for the demand conditions for the products of research firms as their market consists of farmers. 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 as Dickey-Fuller tests revealed that variables are non-stationary. So a trend variable is added to de-trend the data. Extension stock, patents and public R&D stock, private R&D stock and foreign R&D stock variables are included in the equations with lags. The choice of these lags for each variable in each equation is based on the AIC and SBC results from the ordinary least squares estimation (OLS) results. The above three equations is estimated as a system of equations using seemingly unrelated regression (SUR) technique.

5. Empirical Analysis Results

In Table 2, the first set of results is presented for the system of equations. In the TFP equation, it is seen that the trend variable has a negative coefficient estimate which is significant at the 0.05 level. 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 due to the large scope and diversity of public R&D activities.

The next equation examines the forces determining the creation of new technology, i.e. inventions as measured by patents. The trend variable is negative and significant. The coefficient of public R&D stock variable is positive, but insignificant. This reason for this finding may be the fact that most of public R&D results are not patented but kept in the public domain. This also shows the necessity of estimating the direct effect of public R&D on the TFP as in the previous equation. The next variable, private R&D stock variable has a positive and significant coefficient estimate which is in line with the main implication of the model, i.e. R&D activities drive technological progress. R&D spillovers are measured by the foreign R&D stock variable, which has a positive and significant coefficient estimate. This result shows that the U.S. agricultural sector benefits from R&D activities in other countries through more inventions. 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. In Table 3, Quality Index is used as a measure of stock of past technological achievements in place of TFP. Again, this variable has a positive and significant coefficient estimate showing that past research successes facilitate present research successes. However, in this second specification, both public and private R&D stock variables are insignificant as now the quality index captures the results of past public and private R&D activities.

The final equation analyzes the determinants of private agricultural R&D spending in the U.S. The model was ambiguous in terms of the net effects of public R&D sector on the private R&D sector. These results show that the complementary effect of public R&D outweighs the substitute effect as the public R&D stock variable has a positive and significant coefficient estimate. This finding combined with the above finding of 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 it indirectly benefiting the agricultural sector by increasing the knowledge stock that private R&D sector benefits from. The next variable, foreign R&D stock is included to understand the effects of R&D spillovers on private R&D firms in the U.S. 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 competitor force. The coefficient of interest rate is negative and significant as predicted in the model, showing the higher the opportunity cost, the lesser the private R&D spending. 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 discussed when interpreting the above empirical results. The first one is that the presented results used a depreciation rate of 12% to generate stock variables. A depreciation rate of 5% was used to generate stock variables as well, and the empirical results are robust to using a different depreciation rate. The other issue is about the calculation of the foreign R&D stock variable. This stock variable is created from the sum of all foreign R&D of countries that have the same agroecological attributes as the U.S. as spread of new technology in the agricultural sector depends on the suitability of these inventions to be used in the U.S. On the other hand, merely adding up all foreign R&D spending gives equal weight to all countries included in the data set. However, the model shows that trade is the channel through which two economies interact with each other and learn from each other. So, for future work, relative trade shares of these countries with the U.S. will be used as weights for foreign R&D spending. This may provide a better picture of the relative significance of foreign R&D with respect to domestic R&D, as it is more plausible that U.S. firms benefit more from R&D activities in countries where they have a better means of interaction.

6. Conclusion

This study utilizes a quality innovation model, in which technical progress is the result of commercially motivated efforts of researchers responding to economic incentives, and a public research and development sector. First, a closed economy model is presented to show the mechanism of how domestic R&D sector operates. In the model, both public and private R&D sectors directly affect creation of new technology, which in turn leads to higher productivity growth. Public sector directly affects

private R&D sector and contributes indirectly to inventions and productivity, as well. This is different from the previous research, as not only are public and private R&D sectors both included, but also the liaison between these two sectors is examined.

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 private R&D sector is included through a subsidy that decreases the cost of private R&D firms. Public R&D sector is also modeled as a substitute to private R&D sector as it engages in activities that attempt to create higher quality intermediate goods and thereby potentially "crowding out" private R&D spending. Overall, the net effect of public R&D spending on private R&D spending is ambiguous in the 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 that have the same production costs and the same factor endowments. 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 one, in which the less developed country has lower production costs. This scenario analyzes the impacts of imitative R&D activity in a less developed country on the R&D sector and innovation in a developed country. In both of these scenarios, trade affects the R&D sector of a developed country through three channels. First, through trade R&D firms realize increased market size for their products. Secondly, with trade R&D firms face increased competition from foreign R&D firms that can capture their market either through a lower cost imitation or through a higher quality intermediate good. Finally, with the opening up of 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. A system of equations is set up based on the model. First, the impact of technological progress on TFP in the agricultural sector is tested using agricultural patents as a proxy for technological progress. It is found that agricultural patents have a significant and positive impact on TFP which is consistent with the model. Extension stock is included as extension activities in the U.S. are crucial for adoption and spread of new technology. 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. The other variable in the equation is public R&D stock, and is included to capture the direct effect of public R&D activities on TFP, as these results are not always patented. It is found that public R&D stock has a positive and significant coefficient estimate.

The second equation is directly in the spirit of the model as the dynamics of technological progress is analyzed. It is found that domestic private R&D stock affects agricultural patents significantly and positively as previously expected. Foreign R&D stock is included to measure the impacts of R&D spillovers on the technological progress in the U.S. It is found that foreign R&D stock is as critical as domestic private R&D stock to creation new technology, as it has a positive and significant parameter estimate as well. Surprisingly, domestic public R&D stock does not have a significant impact on agricultural patents. This may be due to low patenting of public R&D research results as the results are mostly in public good nature.

The third equation has private R&D spending as the dependent variable. 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 public R&D sector on the private R&D spending was ambiguous. This finding combined with the above result that public R&D stock affects TFP positively and significantly shows that continuation of public R&D activities are 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 private R&D sector in the U.S. which is in line with the prediction of the model. However, caution should be exerted when interpreting this result as all foreign R&D spending is given an equal weight when calculating foreign R&D stock and an appropriate weighting according to relative trade shares is necessary to better reflect the main proposition of the model, i.e. trade is the channel through which R&D spillovers occur. Interest rate serves as a measure of opportunity cost and has a negative and significant coefficient estimate as predicted by the model.

This study attempts to analyze technical change and the role of R&D spillovers in this process using a quality innovation model. In order to better reflect the characteristics of the U.S. agricultural sector, both a private and a public R&D sector is included into the model. Trade is the mechanism through which R&D spillovers are realized, along with increased market size and increased competition. Propositions of the model are tested for the U.S. agricultural sector data. The results are fairly consistent with the model, and though a more detailed empirical analysis may be necessary; this is a first step towards that aim.

Table 1. Summary Statistics

Variable	N	Mean	Std. Deviation	Minimum	Maximum
Foreign R&D Spending	24	6867.12	1294.91	4767.15	8947.90
US Public R&D Spending	24	2438.91	399.87	1837.15	3109.35
US 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

Table 2. Regression Results^a

Variable	Dependent 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

a. These are seemingly unrelated regression estimates. Standard errors are in parentheses. ** denote significance at the 0.05 level. System weighted $R^2 = 0.960$.

Table 3. Regression Results^a

Variable	Dependent Variable		
	TFP	Patents	Private R&D Spending
Intercept	-2.042 (1.710)	-164.140** (82.628)	-89.075** (29.497)
Trend	-0.005** (0.002)	-0.422** (0.180)	-0.216** (0.078)
Extension Stock _{t-3}	1.049* (0.590)		
Patents _{t-1}	0.030** (0.005)		
Public R&D Stock _{t-1}	0.179* (0.099)		5.735** (2.346)
Public R&D Stock _{t-3}		1.405 (5.271)	
Private R&D Stock _{t-3}		0.952 (3.529)	
Foreign R&D Stock _{t-2}			4.126** (1.177)
Foreign R&D Stock _{t-3}		11.144** (5.108)	
Quality _t		3.760** (0.871)	
Interest Rate _t			-1.010** (0.423)
Price _t			-0.069 (0.193)
N	21	21	21

a. These are seemingly unrelated regression estimates. Standard errors are in parentheses. ** denote significance at the 0.05 level. * denotes significance at the 0.10 level. System weighted $R^2 = 0.954$.

7. References

- Agricultural Outlook (1999). 'Biotechnology Research: Weighing the Options for a New Public-Private Balance', USDA Economic Research Service.
- Aghion, P. and P. Howitt (1992). 'A Model of Growth through Creative Destruction' *Econometrica*, vol. 60, no. 2, pp. 323-351.
- Alafranca, O. and W. E. Huffman (1999). 'Private R&D Investments in Agriculture: The Role of Incentives and Institutions', Staff Paper # 332, Iowa State University.
- Alston, J., G. W. Norton and P. G. Pardey (1995). 'Science Under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting', Ithaca, NY: Cornell University Press,
- Alston, J. and P. G. Pardey (1996), 'Making Science Pay: The Economics of Agricultural R&D Policy', Washington D.C., The AEI Press.
- Alston, J., P. G. Pardey and J. Roseboom (1998). 'Financing Agricultural Research: International Investment Patterns and Policy Perspectives', *World Development*, vol. 26, no.6, pp.1057-71.
- Alston, J., P. G. Pardey and V. H. Smith (1999). 'Paying for Agricultural Productivity', The Johns Hopkins University Press.
- Alston J. (2002) 'Spillovers', *The Australian Journal of Agricultural and Resource Economics* vol. 46(3), pp.315-346.
- Ball, E. (1992). 'Sources of Agricultural Economic Growth and Productivity: Discussion', *American Journal of Agricultural economics*, vol. 74, no. 3, pp. 764-765.
- Ball, E., J. C. Bureau, R. Nehring, A. Somwaru (1997). 'Agricultural Productivity Revisited', *American Journal of Agricultural Economics*, no. 79, pp. 1045-1063.
- 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*, vol. 39, pp. 859-87.
- Coe, D. T., E. Helpman and A. Hoffmaister (1995). 'North-South Research and Development Spillovers', NBER Working Paper no. 5048.
- Connolly M. P. (1996) 'Technology, Trade and Growth', Ph.D. Dissertation, Yale University.
- Fuglie, K., N. Ballenger, K. Day, C. A. Klotz, M. Ohlinger, J. Reilly, U. Vasavada and J. Yee (1996) 'Agricultural Research and Development: Public and Private Investments under Alternative Markets and Institutions', USDA ERS, AER 735.
- Griliches Z. (1964). 'Research Expenditure, Education and the Aggregate Agricultural Production Function', *American Economic Review*, vol. 54, no. 6, pp. 961-74.
- Griliches, Z. (1988). 'Technology, Education, and Productivity: Early Papers with Notes to Subsequent

- Literature', Oxford and New York, Blackwell.
- Griliches, Z. (1992). 'Sources of Agricultural Economic Growth and Productivity: Discussion', *American Journal of Agricultural Economics*, vol. 74(3), pp. 762-766.
- Griliches, Z. (1996). 'The Discovery of the Residual: A Historical Note', *Journal of Economic Literature*, vol.34(3), pp.1324-1330.
- Griliches Z. (1998). 'R&D and Productivity', The University of Chicago Press, Chicago.
- Grossman, G. M. and E. Helpman (1991). 'Innovation and Growth in the Global Economy', The MIT Press, Cambridge, Massachusetts.
- Hayami Y. and V. W. Ruttan (1985). 'Agricultural Development; An International Perspective', The Johns Hopkins University Press, Baltimore.
- Huffman, W. E. and R. E. Evenson (1992). 'Contributions of Public and Private Science and Technology to U.S. Agricultural Productivity', *American Journal of Agricultural Economics*, vol. 74(3), pp. 751-756.
- Huffman, W. E. and R. E. Evenson (1993a). 'Science for Agriculture: A Long Term Perspective', Iowa State University Press, AMES.
- Huffman, W. E. and R. E. Evenson (1993b). 'The Effects of R&D on Farm Size, Specialization, and Productivity' in Johnson and Martin eds., 'Industrial Policy for Agriculture in the Global Economy', Chapter 3, Iowa State University Press, Ames.
- Johnson, D. (1999). '150 Years of American Invention: Methodology and a First Geographical Application', Wellesley College Working Paper 99-01, January.
- Johnson, D. and R. E. Evenson (1997). 'Introduction: Invention Input-Output Analysis' *Economic Systems Research*, June, vol. 9, issue 2.
- Johnson, D. and R. E. Evenson (1999). 'R&D Spillovers to Agriculture: Measurement and Application', *Contemporary Economic Policy*, vol.17, no.4, October, pp. 432-450.
- 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*, vol. 76(2), pp. 267-277.
- Klotz, C. A., K. O. Fuglie and C. E. Pray (1995). 'Private Sector Agricultural Research Expenditures in the U.S., 1960-1992', USDA ERS, AGES-9525.
- 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*, vol. 21(2), pp.185-211.
- McCunn, A. and W. E. Huffman (2000), 'Convergence in U.S. Productivity Growth for Agriculture: Implications of Interstate Research Spillovers for funding Agricultural Research', *American Journal of Agricultural Economics*, vol.82 (2), pp. 371-388.
- Pardey P.G. and N. Beintema (2001) 'Slow Magic: Agricultural R&D a Century after Mendel' IFPRI

- Rivera-Batiz L.A. and P. M. Romer (1991) 'Economic Integration and Endogenous Growth', *The Quarterly Journal of Agricultural Economics*, vol. 106(2), pp.531-55.
- Schimmelfennig, 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*, vol. 17(4), pp. 457-468.
- Wood S. and P.G. Pardey (1997) 'Agroecological Aspects of Evaluating Agricultural R&D' EPTD Discussion Paper. No. 23.